Lecture Notes in Mobility

Domokos Esztergár-Kiss
András Munkácsy
Ádám Török *Editors*

Re-Generation in Transport

Proceedings of the 11th TRA Conference, 2026, Budapest, Hungary - Volume 3: Zero Emission Vehicles, Electrification and Alternative Fuels, and Circular Economy

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Lecture Notes in Mobility

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Domokos Esztergár-Kiss · András Munkácsy · Ádám Török
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TRA 2026 – Preface

We are pleased to present the conference proceedings of the 11th Transport Research Arena (TRA) conference held in Budapest in May 2026. TRA is a flagship event co-organized by the European Commission and various stakeholders. Previous editions of the conference took place in Gothenburg (2006), Ljubljana (2008), Brussels (2010), Athens (2012), Paris (2014), Warsaw (2016), Vienna (2018), Helsinki (2020), Lisbon (2022), and Dublin (2024). After these successful events the 11th Transport Research Arena was organized under the overarching theme of "Regeneration in Transport."

The conference addressed key areas of transportation research with specific focus on User Centered Mobility, Green Mobility and Decarbonization, Planning and Operation, and Transport Digitalization. Its aim was to connect academics with practitioners, bring together leading experts, and provide opportunities for promising young researchers. The conference program was complemented by demonstrations, innovative exhibitions, technical tours, and social events.

As part of the conference, researchers were invited to submit research papers aligned with the conference themes. The best contributions were presented at technical sessions or as posters, and selected submissions are included in the conference proceedings.

The submission process was organized in two stages. In the first round, abstracts of maximum 200 words were invited by 30 June 2025 via the online submission system accessible through the conference website. A total of 1573 abstracts were received, of which 48 were rejected based on a review by members of the local program committee.

In the second round, full papers of maximum 3000 words were invited to be submitted by 30 September 2025. A total of 1274 full papers were submitted, of which 112 papers were rejected. Each paper was reviewed by at least two independent experts and by members of the local program committee.

The conference papers typically describe research goals, literature review, methodologies, results, and discussion, enabling the scientific committee to assess their quality. The highest-scoring papers were invited to special issues of international peer-reviewed journals. In total 865 final papers (68% of the submitted papers) were accepted and included in the conference proceedings based on the preferences of the authors, the evaluation of the reviewers, and the decision of the editors.

Papers authored by early-stage researchers as first authors and selected for a TRA VISIONS Award have been highlighted. Their achievements may serve as an inspiration to young researchers and future generations of academics.

The editors would like to express their sincere appreciation for the strong dedication and scientific excellence of the technological platforms, the program committee, the local program committee, the reviewers, the session chairs, the sponsors, and of course the authors, who contributed to the successful organization of TRA2026 and the publication of this conference proceedings.

Domokos Esztergár-Kiss
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Zero Emission Vehicles

Evaluating Flexibility and Assets in Battery-Powered Train Operations: A Simulation Approach

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Abstract. The transition to decarbonized railway rolling stock fleets, such as battery-powered regional trains, presents significant challenges for rail operations, yet offers substantial benefits, including reductions in CO_2 emissions and energy gains through direct brake energy recovery. Their operational benefits are often undervalued. This research aims to perform a comprehensive analysis of the flexibility provided by battery trains amidst operational uncertainties, such as discontinuity or total absence of electrification in contrast to conventional Electrical Multiple Units (EMU) trains. A state-of-the-art review of these operational uncertainties has been conducted to define test scenarios. The analysis is grounded in simulations using a validated energy model and applies a numerical simulation prediction model for range estimation, which integrates the conditions of rolling stock, infrastructure, and operational elements within the railway system. The analysis conducted herein validates a single Battery Electrical Multiple Units (BEMU) significant operational flexibility across the simulated cases, especially its ability to ensure operational continuity during power supply failures and simultaneously recover from delays, a key advantage over conventional EMUs. These findings warrant the initiation of furthermore structured and operationally oriented research aimed at bridging the gap between simulation and real-world deployment.

Keywords: Battery-Powered Trains · Operational Flexibility · Simulation Modeling

1 Introduction

The decarbonization of railway activities is a main objective for the railway sector. EMU, while ideal for short trips with frequent stops, face high electrification costs, limiting their use to heavily traffic routes [1]. The shift from fossil fuel has made major progress in the past few years, through technological improvements on energy storage systems. In 2025, almost 1000 alternatives drivetrain are expected to be in service, twice as many in comparison to 2022 [2]. This strong dynamic shows the railway sector moving up towards low emission passenger transportation. Beyond these numbers, the full battery train, so called BEMU, is leading the technology, by around 2/3 of the market share.

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With the introduction of alternative drive technologies on rolling stock, new challenges should be faced, especially concerning operation. These innovative solutions bringing on rail may fail and significantly impact the traffic. Some recent experiences unfortunately show such events on battery trains and hydrogen trains, involving delays, stops and in worst cases, replacement by diesel trains or buses [3, 4].

One major change compared to diesel trains is the limited energy capacity on board. While battery trains commit an average range of 100 km, diesel trains have an autonomy around 10 times higher. A deep analysis of operational uncertainties is mandatory to estimate the flexibility to adapt to such events, contributing to enhance the service robustness and trust in the technology for transportation authorities and passengers. Therefore, this study specifically focuses on the BEMU's performance in critical degraded scenarios.

2 State of the Art Regarding Operational Uncertainties

The operation of conventional rolling stock (Diesel trains, Diesel/Electric bi-mode, Electrical trains) is directly influenced by unplanned events, with the probability and severity of such events varying according to the type of rolling stock and, most importantly, the primary power source (catenary, diesel). The uncertainties in the railway system can be divided into three main areas:

2.1 Infrastructure

The railway infrastructure can be divided into different subsystems:

- Tracks/guideways,
- Power supply,
- Signaling.

Some events, such signaling failures affect all types of rolling stock and can slow or stop traffic, increasing energy consumption due to speed restrictions and stops. While this generally has no operational impact on diesel or EMU trains, it can deplete the limited energy of battery trains before the next electrified section, causing additional disruption and extending traffic disturbance.

Electric trains are sensitive to power supply issues, such as overhead lines or substation failures and voltage drops that limit current, reduce tractive performance, and lower charging power for energy-storage trains. For battery trains, high-current charging at standstill makes pantograph–catenary contact a critical point, requiring care to prevent accelerated ageing and cracks [5].

2.2 Vehicle

Concerning diesel trains traction system, failures might happen in several parts, such as pneumatic system, electrical components, diesel engine, cooling systems, etc. Several studies have been published on railway diesel vehicles to analyze the structure of the failures [6, 7].

At vehicle level, electrical failures may occur in different components of the power and auxiliary conversion systems, such as short-circuits, over-currents, over-temperatures or insulation faults. Depending on the traction and auxiliary architecture, these failures can have no operational impact when redundancy and design margins are sufficient, or, on the contrary, lead to major service consequences by limiting tractive performance (e.g. reduced power, speed restrictions) or stopping the rolling stock on line (e.g. pantograph drops, main transformer failures).

For trains with traction batteries, specific failures are linked to battery technology. A Rail Safety and Standards Board (RSSB) study in 2020/2021 identified 61 hazards, including failures related to infrastructure (battery charging, plugs, etc.) [8]. In addition to electrical failures, fire and explosion hazards must be considered. While new failure modes may arise, battery technology enables more redundant architectures using multiple battery packs: if one pack fails, the others can continue operating. By contrast, diesel architecture offers far less redundancy, so failures on the diesel engine have more severe consequences.

2.3 Operation

The uncertainties related to train operation may have several types and different consequences. These events are applicable to all train types and create a degradation of the service. A list of uncertainties has been produced based on France and SNCF Voyageurs experience [9]:

- Passengers (Unaccompanied luggage, Illness on-board, Fraud, Exceptional attendance),
- Environmental conditions (Flooding, Dead leaves and lack of adhesion, Extreme weather),
- External conditions (Animals along the track, Fatalities, Fire along the track
- Traffic (Radio alert, Traffic regulation)
- Train operator (Crew member delay or missing, Strike)

Impacts may include longer running times (dwell, delays, rescheduling), changes in passenger flows and information quality. For trains with limited onboard energy, higher consumption can also reduce onboard comfort if available energy becomes insufficient. Because alternative drive trains have less onboard energy than diesel or externally supplied electric trains, their energy consumption impacts must be analyzed and assessed to anticipate adverse operating conditions. This requires modelling BEMU trains with detailed energy performance, including traction/braking and charging/discharging; a case study follows in the next chapter.

3 Simulation Tool for Battery Train Evaluation

To study the specification of a BEMU train, a modeling/simulation tool is used. This tool allows for detailed simulation of rolling stock energy consumption based on various parameters (driving styles, rolling stock status, etc.). The methodology is based on an organized architecture (system approach) with power links by effort-flow (derived from the bond graph) and a Forward approach (from the energy source to the movement) [10].

This approach allows for detailed consideration of the specific characteristics of the Energy Storage System (ESS) architecture and its partial availability, which significantly impacts traction performance and energy efficiency and speed profile [11].

The simulation approach closely approximates real-world conditions, enabling testing of various scenarios involving partial ESS availability and the development of adaptive operational strategies. By modeling interactions among power systems, traction demands, and energy management algorithms, accurate performance predictions under degraded conditions are possible, facilitating optimization of system resilience.

Research focuses on a realistic implementation scenario of BEMU technology on a regional train line with partial electrification, providing a comprehensive evaluation of hybrid powertrain solutions that combine traditional electric traction with advanced battery systems, for operation across electrified and non-electrified sections.

3.1 Recharging Infrastructure

The study evaluates two complementary recharging methods:

- Dynamic Recharging: The train draws power directly from overhead catenary systems while in motion on the electrified sects. (42 km of the total 110 km route), simultaneously powering the train and recharging its ESS.
- Fast Static Recharging: A dedicated fast-charging facility is strategically positioned at a station located approximately midway along the route. This allows for battery replenishment during scheduled passenger stops (Table 1).

Table 1. Recharging infrastructure parameters

Train speed	Location	Length	Maximum available power	Maximum Allowed Power*
>0 km/h	Partial electrification of the line	42 km	1,8 MW	1,5 MW
0 km/h	Partial electrification of the line	42 km	0,45 MW	0,45 MW
0 km/h	Station L (Static Fast Charging)	0,2 km	1,8 MW	1,5 MW

* Due to limitations of current at standstill in 1.5 kV DC (300 A DC), the power available at the catenary is low. Therefore, the power supply is consumed to provide energy to the auxiliary loads and to the traction batteries charging. So, the allowable power for the traction batteries charging will depend on the auxiliary loads power.

3.2 Route Characteristics

The regional line spans a total distance of 110 km with the following key features:

- 13 intermediate passenger stops distributed throughout the route,

– Total journey time of approximately 2 h,
– 42 km (38%) of the route is electrified,
– 1 station (station "L") with fast charging at standstill (rated power 1.5 MW).

3.3 Battery Management Parameters

The operational battery constraints include the State Of Charge (SoC) and the State of Health (SoH) (Table 2).

Table 2. Battery management parameters table

SoC MAX (%)	SoC MIN* (%)	SoH (%)
100	0	80

* The SoC in this table is usable capacity, with a reserved margin to preserve battery life that is only used when usable SoC goes below 0% in degraded situations.

4 Focus Study

The main goal of the study case is to evaluate how various operational disruptions impact the train's SoC throughout the journey profile. These disruptions might include:

– Infrastructure failures limiting electrification availability,
– Timetable deviations affecting charging opportunities,
– Vehicle performance degradation altering energy consumption.

The analysis aims to determine whether the BEMU solution provides sufficient operational robustness to maintain reliable service despite these challenges while keeping battery levels within safe operating parameters which enables the return journey in both cases of Nominal Operation (NOp) and All-Out (the maximum allowed speed).

Table 3. Comparison of different BEMU train operations

Line stations	All-Out [Margin/SoC]	NOp [Delay/SoC]	NOp ½ ESS* [Delay/SoC]	NOp Degraded mode Infra [Delay/SoC]
A	+0 s 100%	+0 s 100%	+0 s 100%	+0 s 100%
B	+35 s 100%	+1 s 100%	+1 s 100%	+1 s 100%
…	…	…	…	…
K	+75 s 92%	+1 s 93%	+1 s 86%	+1 s 52%

(*continued*)

Table 3. (*continued*)

Line stations	All-Out [Margin/SoC]	NOp [Delay/SoC]	NOp ½ ESS* [Delay/SoC]	NOp Degraded mode Infra [Delay/SoC]
L	+206 s 78%	+3 s 82%	+3 s 67%	+3 s 41%
M	+195 s 60%	+2 s 68%	+2 s 40%	+2 s 29%
…	…	…	…	…
O	+88 s 66%	+4 s 86%	+4 s 46%	+4 s 48%
O + 20	–	–	–	–
Min	100%**	100%	72%	74%

* In degraded mode, the ESS loses 50% of its capacity (a SoC of 70% then corresponds to 35% under nominal conditions).

** This case represents the SoC reached at the end of all-out mode, including both the cumulative margin throughout the journey and the turnaround period.

Table 3 highlights two key points: the margins between tight scheduling and the planned timetable, and the train's ability to consistently meet the expected schedule. It also evaluates SoC at each stop and the remaining margin while operating at maximum traction power within speed limits and stop durations.

Under normal conditions, the train reaches about 85% SoC at destination, allowing a 100% SoC departure after the 20-min turnaround. The analysis confirms that, in all cases including degraded ESS or partially unavailable energy infrastructure, the train can still respect the timetable.

However, in degraded scenarios, the final State of Charge (SoC) after turnaround falls short of 100%. With half the ESS available, the SoC reaches only 72% (equivalent to 36% under nominal conditions, as the ESS loses 50% of its capacity in degraded mode), or around 74% with limited electrification. In both cases, this is insufficient for the next journey, indicating that degradation limits despite margin relaxations prevent achieving a full SoC, potentially impacting subsequent operations. Still, the scenario where only half the ESS is available remains extremely rare, due to the inherent redundancy in the ESS cell-to-pack architecture.

4.1 Nominal Operation

The graphic below illustrates the nominal operation scenario over time evolution, with electrification represented by the green line (from station A to J, station L, and finally from N to O). The red line indicates the catenary free zone operation mode. During this normal journey, the final SoC at the destination reaches 85%, and it is restored to 100% after 12 min within the scheduled 20-min turnaround period (Fig. 1).

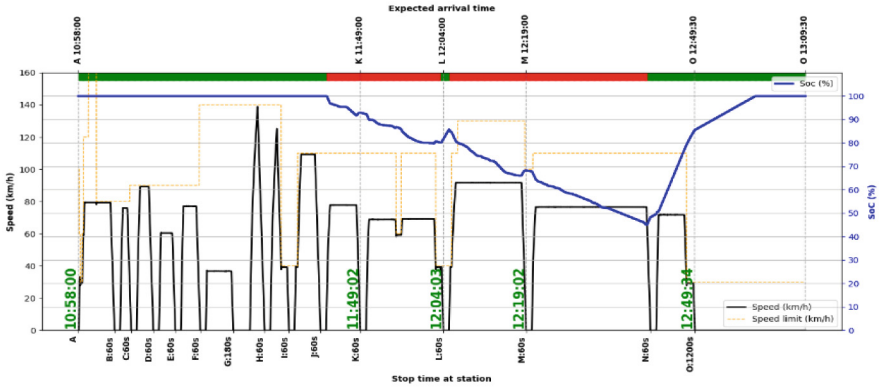


Fig. 1. Battery train ESS SoC and Vehicle's speed in nominal operation condition

4.2 Degraded Infrastructure Conditions

Case 1: Power Supply Failure Between Station B and J

In this scenario, an infrastructure accident between stops B and J forced the train to operate in catenary-free mode, significantly affecting the state of charge. The minimum SoC fell to about 6% at station N. As a result, the final SoC at the destination was only 48%, insufficient to reach the 100% required for the next journey.

This situation allows testing and analyzing potential adaptations to ensure normal operation during later trips. The goal is to minimize journey disruptions and avoid constraints for other trains running on the same line (Fig. 2).

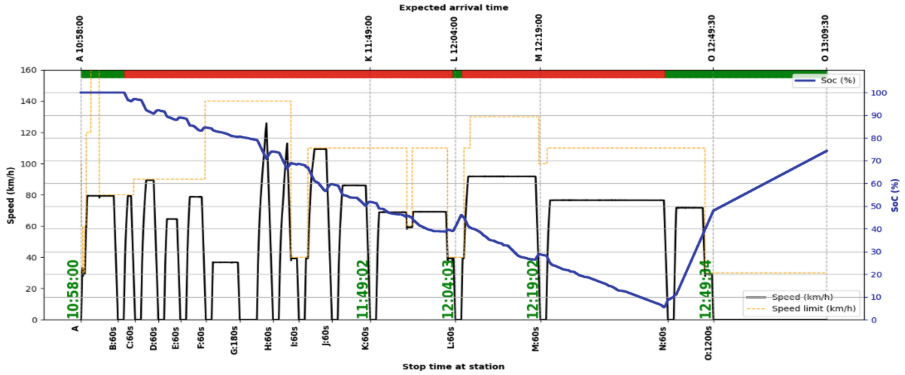


Fig. 2. ESS SoC and train speed under degraded infrastructure

Case 2: Adapting the Speed Profile to Ensure the Subsequent Programmed Journey: 100% of SoC at the Stop O After the Turnaround Period

In this scenario, the available inter-stop margins were used to allow additional fast

charging time at stop L, ensuring that the target SoC could be achieved by the end of the journey. The timetable was adjusted only between stops K-L and L-M, providing an extended charging duration of approximately 7 min, exceeding the originally scheduled 1 min.

By running at the maximum allowed speed before and after stop L, the train reached L about 4 min early, allowing extra charging. Departure from L was delayed by about 3 min, while keeping the train on time at station M and for the rest of the trip. The SoC reached 100% after the turnaround, avoiding disruption before the next departure. Both scenarios can be illustrated with a Minkowski space–time diagram (Fig. 3).

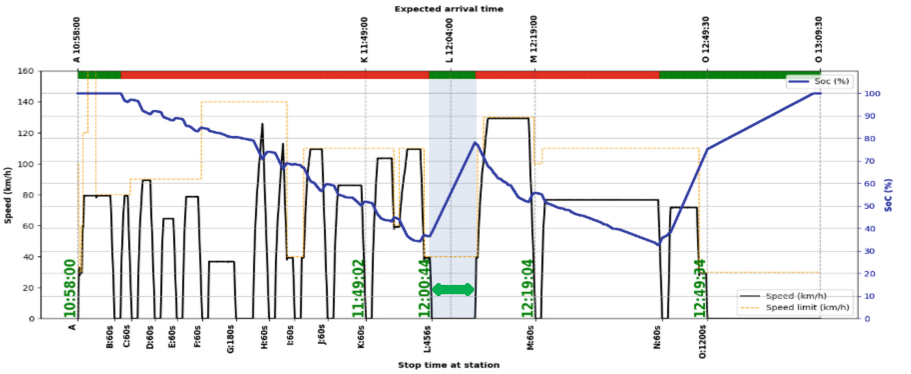


Fig. 3. Battery train ESS SoC and Vehicle's speed in degraded infrastructure condition and adapted speed profile & timetable

5 Conclusion and Outlook

This study has presented an initial evaluation of the flexibility and assets of a single battery train by adapting a numerical model to simulate its performance within its operational environment. The analysis, while limited to a single vehicle, has highlighted the potential of this technology under nominal conditions. The results show the capability of the battery trains to operate under normal and degraded conditions, by using different strategies, such as adjusting the speed profile or timetable. However, outcomes may vary across different line profiles. Future research should extend this analysis to a multi-train context to assess the limits of flexibility and resilience at a network level, which will require modeling complex interactions and additional operational constraints. Furthermore, a macroscopic, systemic approach is recommended, integrating timetable design and charging infrastructure placement from the outset. The goal is to formalize a "design for operational assets" methodology, analogous to the "design to cost" proven industrial approaches. A practical application of this research would be the development of a decision support tool for operational staff to monitor the fleet's status, particularly battery levels, and provide rapid recommendations to ensure efficient traffic management amid uncertainties. Finally, further investigation should also focus on integrating real-time

data, optimizing charging infrastructure, and rigorously evaluating the economic and environmental impacts of large-scale deployment.

References

1. Mwambeleko, J.J.: Battery electric multiple units to replace diesel commuter trains serving short and idle routes. J. Energy Storage. **11** (2017). https://doi.org/10.1016/j.est.2017.01.004
2. Chamaret, A., Mannevy, P., Clément, P., Ernst, J., Flerlage, H.: Analysis, trends and expectations for low carbon railway. Transp. Res. Procedia. **52** (2023). https://doi.org/10.1016/j.trpro.2023.11.808
3. Humphreys, D.: Battery-Powered Train Disruption Refunds Cost Revealed. BBC (2024)
4. Ding, D., Wu, X.: Hydrogen fuel cell electric trains: technologies, current status, and future. Appl. Energy Combust. Sci. **17** (2024). https://doi.org/10.1016/j.jaecs.2024.100255
5. Hayasaka, T., Usuki, T.: Maintenance cycle for overhead catenary systems for battery-powered electric trains. Q. Rep. RTRI. **60** (2019). https://doi.org/10.2219/rtriqr.60.1_28
6. Grzywna, M.: Evaluation of the reliability of a heavy diesel locomotive. Combust. Engines. **202** (2025). https://doi.org/10.19206/CE-205974
7. Mayoyo, A.: Factors that Cause Engine Failures on Diesel Locomotives, Thesis. University of Johannesburg (2015)
8. Brown, M.: DECARB: Battery Powered Trains: Route to Enter into Service Hazard Analysis Phase. RSSB Research Catalogue (2021)
9. ERJU: D1.1 Energy Management & Pre-Standardisation for Alternative drive trains and related railway system Intermediate Report No, ERJU Deliverable. ERJU (2024)
10. Alonso, L., Chamaret, Ap.: SNCF VOYAGEURS energy digital twin for energy saving and CO2 reduction, Innotrans Speaker Corner Conference (2024).
11. Ghaviha, N., Bohlin, M., Holmberg, C., Dahlquist, E.: Speed profile optimization of catenary-free electric trains with lithium-ion batteries. J. Mod. Transport. **27**, 153–168 (2019). https://doi.org/10.1007/s40534-018-0181-y

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A Comprehensive Evaluation Framework for Electric Bus Rapid Transit (eBRT) Systems

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Abstract. Bus Rapid Transit (BRT) systems involve scaled and high-speed transportation of passengers at affordable rates through high-frequency high-capacity buses along dedicated lines or corridors. Due to their ability to offer high quality mass transit at scale at lower total cost of system than light and heavy rail, they have become increasingly popular among cities globally. Electrification of the buses and the inclusion of charging infrastructure in BRT planning and operation has been a major recent development. This development retains high quality of service while reducing urban air pollution and greenhouse gas emissions. In this study, we present a comprehensive framework based on Key Performance Indicators (KPIs) to evaluate electric Bus Rapid Transit (eBRT) systems. This framework was developed and applied in the European project eBRT2030 to evaluate eBRT systems in the European cities of Amsterdam, Barcelona, Prague, Athens and Rimini. The study also describes the selective and contextual application of the framework in each of these cities, which vary considerably in urban landscape, requirements of passengers, technology providers and experience with electrification.

Keywords: BRT · bus evaluation · bus rapid transit · electric bus · Zero emission bus

1 Introduction

Bus Rapid Transit (BRT) systems involve scaled and high-speed transportation of passengers at affordable rates through high-frequency high-capacity buses along dedicated lines or corridors. In the last few decades, BRTs have increased in popularity with around 191 cities around the world having BRTs to date, of which 47 are in Europe [1].

Since the 1990s, European cities adopted the concept of Buses with High Level of Service or BHLS [2]. BHLS was seen as an intermediate solution between regular bus service and tram service in terms of cost, performance and capacity. Full BRT systems in contrast, achieve metro-level performance, demonstrated in flagship examples like Transmilenio in Bogotá, Colombia and Metrobüs in Istanbul, Türkiye [3].

European BRTs have not played the disruptive roles played by BRTs in Latin America, Asia and Africa [4]. With around 20 to 35 thousand daily passengers on average, the daily ridership is about a 100 times lower than the daily ridership of the largest global BRTs. The smaller sizes of European cities and the prior existence of light rail and

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metro services for high capacity corridors have played a role. In several cases, such as in Nantes, Amsterdam and Lund, BRTs were constructed according to tram specifications, in order to facilitate later conversion [4], contingent on increased demand or available funding.

In recent years, there has been a drive to electrify all buses in Europe. 18.4% of all buses and coaches and 40% of all urban buses newly registered in 2024 were battery electric vehicles [5]. Electrified BRT systems or eBRT systems involve the operation of electric buses in BRT corridors. eBRT systems involve several aspects like the choice of battery technology, choice of charging infrastructure, integration of charging infrastructure in the city, new requirements in tenders and procurement and involvement of new stakeholders like Distribution System Operators (DSOs) in the bus planning process, which are not considered in non-electrified BRTs [6].

The eBRT2030 project is a Europe-wide project involving electrified BRT systems in several European cities – Amsterdam, Athens, Barcelona, Nantes, Prague and Rimini. The evaluation of BRTs globally have often used different editions of *The BRT Standard* [7, 8] or variations of it [9]. In parallel, there is emerging literature on electric bus evaluation [10–18]. These frameworks are unsuitable for eBRT evaluation since they do not cover aspects like dedicated corridor infrastructure, urban planning, land use and traffic management aspects which are associated with BRT operations.

There is a noticeable lack of an evaluation framework suited for eBRT systems that comprehensively considers all the additional infrastructure, technology and stakeholders involved due to electrification as well as the high levels of service, high commercial speed and high capacity required of a BRT.

This study presents a dedicated framework for the evaluation of eBRT systems that was developed during the eBRT project. It is intended for use initially in the eBRT systems in the project and later, more globally. It was collaboratively created with a wide range of stakeholders from public authorities, bus operators, technology providers and academics with various disciplinary backgrounds. It aims to provide a comprehensive evaluation framework for eBRT systems, be widely applicable across a range of bus network configurations and be understandable and easy to apply in practice.

2 Methods

The framework consists of a list of Key Performance Indicators (KPIs) for quantitative evaluation. A literature review was initially conducted to formulate a preliminary KPI list. In parallel, a series of expert workshops were organised with eBRT2030 project participants. These stakeholders (from >30 organisations) included public transport authorities (PTAs), public transport operators (PTOs) or bus operators, technical consultants, technology providers and academics with backgrounds in public transport, electrification, transport economics and the social sciences.

Over these workshops, the evaluation was categorised into categories or clusters:

1) Economic
2) Performance
3) Quality of Service
4) Environmental

5) Social
6) Urban integration

KPIs fitting within each of these categories were then merged with the initial list from literature to create a final KPI list, as shown in Fig. 1. For application in the project, the list was shared with the stakeholders of each city's eBRT for review. The stakeholders typically included the PTA, PTO and technology providers as a minimum.

During this review process, these stakeholders provided feedback on the feasibility of measurement in terms of data collection, quality and format of data, timeliness of measurement and measurement techniques. This reviewing process was a critical step in ensuring active collaboration of the eBRT stakeholders in the process of evaluation, which was to be conducted several years after the formulation of the framework.

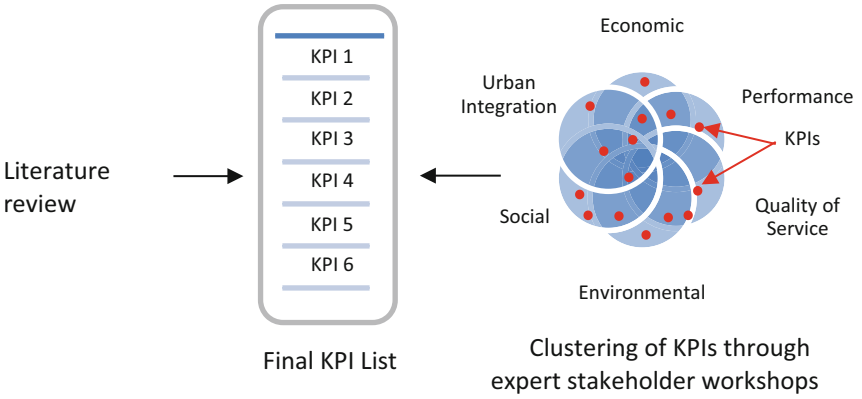


Fig. 1. Process of formulating the final KPI list for evaluation of eBRT systems

3 KPIs and KPI Clusters for eBRT Systems

The final list of KPIs grouped by clusters is shown in Table 1. Each KPI is numbered according to the cluster to which it belongs. An extended version including definitions and data requirements are not provided for the sake of conciseness, but will be published in a future work.

The framework draws extensively upon previous literature on public transit evaluation, BRT evaluation and electric bus evaluation. The sections on Capex, Opex, maintenance and efficiency are very generally applied in public transit. For electric buses however, the Total Cost of Ownership (TCO) plays an increasingly important role in decision-making, including in bus tendering and procurement [19, 20].

BRTs generally aim for high level performance, particularly in commercial speed and passenger capacity – key differentiators from regular bus networks. The annual kilometres driven and energy consumption tend to be critical for electric buses, since these are linked with the sizing of the bus battery, matching bus to specific routes and selection of charging technology as well as the TCO [21]. Investigation into energy consumption

Table 1. KPIs and Clusters for eBRT evaluation.

No	KPI cluster	Sub-cluster	KPI No.	KPI
1	Economics	Capital cost (Capex)	1.1	Capex
			1.2	Capex/year
		Operational cost (Opex)	1.3	Opex/year
		Extraordinary maintenance	1.4	Extraordinary maintenance cost
		Total operational cost per passenger-km	1.5	Opex/passenger-km
		Total cost of ownership (TCO)	1.6	TCO
			1.7	TCO/year
			1.8	TCO/km
			1.9	TCO/vehicle
			1.10	TCO/charge point
		Efficiency	1.11	Transit system efficiency (ratio of passenger kilometres to seat kilometres)
2	Performance	Commercial speed	2.1	Commercial speed at peak hours
			2.2	Commercial speed at off-peak hours
		Passenger capacity	2.3	Passenger capacity
		Ridership	2.4	Ridership
		Average distance per year	2.5	Average distance per year travelled by the fleet
			2.6	Average distance per year per vehicle
		Energy consumption	2.7	Average energy use per year
			2.8	Average energy use per day
			2.9	Average energy use per km
			2.10	Average energy use per vehicle

(*continued*)

Table 1. (*continued*)

No	KPI cluster	Sub-cluster	KPI No.	KPI
			2.11	Average energy use per charge point
3	Quality of service	Span of service	3.1	Hours of operation - weekdays
			3.2	Hours of operation - Saturday
			3.3	Hours of operation - Sundays/public holidays
		Service frequency	3.4	Service frequency - weekday peak
			3.5	Service frequency - weekday off-peak
			3.6	Service frequency - Saturday
			3.7	Service frequency - Sundays/public holidays
		Network coverage	3.8	Network coverage (geographical area covered by service)
		Reliability	3.9	Average downtime per year
		Safety	3.10	Number of fatalities and serious injuries
		Amenities at bus stops	3.11	Amenities at bus stops
4	Environment	Air pollution	4.1	Particulate matter emissions
			4.2	NO_x emissions
		Traffic congestion	4.3	Congestion and delay index
		Emission reduction in operation	4.4	Well-to-Wheel emissions/year
			4.5	Well-to-Wheel emissions/day
			4.6	Well-to-Wheel emissions/km
			4.7	Well-to-Wheel emissions/vehicle

(*continued*)

Table 1. (*continued*)

No	KPI cluster	Sub-cluster	KPI No.	KPI
		Noise pollution	4.8	Day-night sound level index
5	Social	Physical accessibility	5.1	Physical accessibility indicator
		Information accessibility	5.2	Information accessibility indicator
		Access to mobility services	5.3	Access to mobility services indicator
		Satisfaction	5.4	Overall passenger perception/ experience (survey result)
			5.5	User satisfaction (factor clustered)
		Ease of use for drivers and operators	5.6	Ease of use for drivers indicator
			5.7	Ease of use for operators indicator
6	Urban integration	Infrastructure integration	6.1	Busway separation
			6.2	Busway alignment
			6.3	Busway exclusivity
			6.4	Bus priority at intersections
			6.5	Stop/station spacing
			6.6	Boarding and alighting ease
			6.7	Vertical alignment of boarding levels
			6.8	Branding
			6.9	Intelligent Transport System passenger information
		Electricity grid integration	6.10	Peak to average power ratio
			6.11	Battery uptime
			6.12	Change in ratio of successful charging sessions

is commonly seen as a key step for electricity demand and cost estimation, future procurement and future infrastructure planning and is the focus of many evaluations [13, 15, 22].

The KPIs considered in Quality of Service are also quite general to public transport, though recent literature shows an increased focus on amenities at bus stops. For example, the 2024 edition of *The BRT Standard* places an additional emphasis on lighting, cameras and mechanisms for reporting incidents from bus stations [8], which were not included in the previous editions. Other recent research suggests that higher quality of amenities is found to increase transit ridership [23].

On the environmental aspects, a key objective of BRTs is to offer a high quality and speedy alternative to private vehicles, thereby reducing urban congestion. On the other hand, electrification of buses typically focuses on the benefits related to urban air quality, greenhouse gas emissions and noise [11, 17, 22].

Social consequences and risks tend to be understudied in recent literature on the transition to electric buses [24]. A plausible explanation for overlooking passenger acceptance is the prevalent perception that the changes due to electrification that are perceived by passengers are minimal. In contrast, in the broader literature on BRTs as well as in methods of evaluation of public transit such as Sustainable Urban Mobility Indicators (SUMI), there is a strong focus on social factors like affordability, accessibility, satisfaction with the passenger experience and so on [25]. Additionally, the social impacts related to manufacturing and procurement of electric vehicles and batteries are also increasingly receiving attention [26].

As with all BRT systems, integration with the urban environment and existing infrastructure is critical. Here, a Europeanised version of the BRT Standard has been adopted [4]. For eBRTs, a particular focus is on grid integration, including reliability of stationary batteries at bus depots whose primary purpose is to enable or ease grid integration.The framework remains in development with modifications expected based on the lessons learnt upon its application for the evaluation of eBRTs in Amsterdam, Athens, Barcelona, Nantes, Prague, Rimini and elsewhere.

4 Conclusions

This study presents an overview of a framework developed for evaluation of electric Bus Rapid Transit (eBRT) systems. While there are existing frameworks in development for the evaluation of BRT systems and of electric buses, this study presents a comprehensive evaluation framework for their combination – electrified BRT systems. The framework was developed in collaboration with key stakeholders from the public sector, private sector and academia during the pan-European eBRT2030 Horizon project. It was developed for application within the project to evaluate operational eBRT systems in 6 European cities: Amsterdam, Athens, Barcelona, Nantes, Prague, Rimini. The framework is expected to assist and guide future developments of eBRT systems, and to enable their effective, comprehensive and timely evaluation.

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References

1. brtdata.org: Global BRT Data (2025). https://brtdata.org/.
2. Heddebaut, O., Finn, B., Rabuel, S., Rambaud, F.: The European bus with a high level of service (BHLS): concept and practice. Built Environ. **36**(3), 307–316 (2010)
3. Hidalgo, D., Muñoz, J.C.: A review of technological improvements in bus rapid transit (BRT) and buses with high level of service (BHLS). Public Transp. **6**(3), 185–213 (2014)
4. Bennassar, M.R., Grazian, F.: eBRT2030 Task 2.1: BRT State of Art. UITP (2023)
5. European Commission: Communication from the Commission to the European Parliament and the Council on the Technological and Market Readiness of Heavy Duty Road Transport Vehicles. European Commission, Brussels, Belgium (2025)
6. Aldenius, M., Mullen, C., Pettersson-Löfstedt, F.: Electric buses in England and Sweden – overcoming barriers to introduction. Transp. Res. Part D: Transp. Environ. **104**, 103204 (2022)
7. ITDP: The BRT Standard. Institute for Transport and Development Policy (ITDP), New York, USA (2016)
8. ITDP: The BRT Standard: Institute for Transport and Development Policy (ITDP). Institute for Transport and Development Policy (ITDP), New York, USA (2024)
9. Allansson, J., Hansson, J., Pettersson-Löfstedt, F.: In: Outreach, K2. (ed.) Planeringsverktyg för bus rapid transit i Sverige, vol. 2, p. 22. K2, Nationellt Kunskapscentrum För Kollektivtrafik, Lund (2024)
10. Aamodt, A., Cory, K., Coney, K.: Electrifying Transit: A Guidebook for Implementing Battery Electric Buses. NREL (National Renewable Energy Laboratory (NREL) (2021). NREL/TP-7A40–76932, 1779056, MainId:24895
11. Al-Ogaili, A.S. et al.: Electric buses in malaysia: policies, innovations, technologies and life cycle evaluations. Sustainability. **13**(21), 11577 (2021)
12. Basma, H., Haddad, M., Mansour, C., Nemer, M., Stabat, P.: Evaluation of the techno-economic performance of battery electric buses: case study of a bus line in Paris. Res. Transp. Econ. **95**, 101207 (2022)
13. Eudy, L., Prohaska, R., Kelly, K., Post, M.: Foothill Transit Battery Electric Bus Demonstration Results. NREL/TP—5400-65274, 1237304 (2016)
14. Eudy, L., Jeffers, M.: Long Beach Transit Battery Electric Bus Evaluation (Final Report). NREL/TP—5400-75582, 1665840, MainId:6400 (2020)
15. Eudy, L., Jeffers, M.A.: Zero-Emission Bus Evaluation Results: County Connection Battery Electric Buses. NREL/TP—5400-72864, 1488509 (2018)
16. Jeffers, M., Eudy, L., Bigelow, E., Olberding, G., Posner, A.: Duluth Transit Authority Battery-Electric Bus Evaluation. NREL/TP-5400-83038, 1887443, MainId:83811 (2022)
17. RINA Consulting: ASSURED: Final requirement compilation and KPIs. RINA Consulting, Genoa, Italy (2018)
18. Sistig, H.M., Sinhuber, P., Rogge, M., Sauer, D.U.: Evaluating costs and operations of public bus fleet electrification. Npj Sustain. Mobil. Transp. **2**(1), 15 (2025)
19. Ghotge, R., van Rooij, D., van Breukelen, S.: Total cost of ownership of electric buses in Europe. World Electr. Veh. J. **16**, 464 (2025)
20. Jagiełło, A., Wołek, M., Bizon, W.: Comparison of tender criteria for electric and diesel buses in poland—has the ongoing revolution in urban transport been overlooked? Energies. **16**(11), 4280 (2023)
21. Ashkezari, L.S., Kaleybar, H.J., Brenna, M.: Electric bus charging infrastructures: technologies, standards, and configurations. IEEE Access. **12**, 80505–80528 (2024)
22. Cheriyan, C.A., Gadepalli, R., Nandy, R.: Performance Evaluation Framework for Electric Buses in India. UITP, New Delhi, India (2020)

23. Shi, X., Moudon, A.V., Hurvitz, P.M., Mooney, S.J., Zhou, C., Saelens, B.E.: Does improving stop amenities help increase Bus Rapid Transit ridership? Findings based on a quasi-experiment. Transp. Res. Interdiscip. Perspect. **10**, 100323 (2021)
24. Åslund, V.: The Transition to Electric Buses in Public Transport: Lessons Learned from Sweden, Norway, and the Netherlands, vol. 30. K2, Nationellt Kunskapscentrum För Kollektivtrafik, Lund (2025)
25. World Business Council for Sustainable and Development: Methodology and Indicator Calculation Method for Sustainable Urban Mobility. World Business Council for Sustainable and Development, Geneva, Switzerland (2015)
26. Skallefell, P., Fivel, J.B., Malmgren, K.: Conflicting Objectives in the Green Transition: An Impact Analysis of a Scenario Excluding the Import of Electric Buses and Batteries to the European Market. Ernst and Young (2025)

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The Climate Effects of Transport Emissions: Models and Data to Support the Development of Mitigation Strategies

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Abstract. Emissions from land-based transport, aviation and shipping significantly contribute to climate change. In addition to CO_2, the emissions include short-lived species, such as nitrogen oxides and particulate matter. These short-lived emission components not only affect air quality but also have important effects on the climate. This conference contribution highlights results of comprehensive global chemistry-climate model simulations that account for the transport-induced climate effects of all short-lived emission components, complemented by calculations of the corresponding CO_2 effect. For the first time, all transport-induced climate effects have been quantified in a self-consistent manner, not only for present-day conditions but also for multiple future scenarios. Following the Shared Socioeconomic Pathways (SSPs) developed for the sixth IPCC assessment report, these global scenarios span a wide range of emission strengths and compositions. The results confirm the important contribution of the non-CO_2 climate effects for all transport sectors at present and reveal a large significance of these effects in all considered future cases, which is of high relevance for climate protection and environmental policy. For further application of these results, we present concepts to consider both CO_2 and non-CO_2 effects when assessing the climate benefits of emission mitigation strategies in the transport sectors.

Keywords: Transport · Emissions · Non-CO_2 Effects · Climate · Mitigation

1 Introduction

Emissions from transport, including land-based transport, aviation, and shipping, contribute significantly to climate change [1, 2]. According to Gidden et al. [2], annual CO_2 emissions from global transport in 2015, the reference year for several current assessments, totaled 7.9 Gt, accounting for approximately one fifth of the total anthropogenic CO_2 emissions. Land-based transport, aviation and international shipping contributed

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77.5%, 9.7% and 12.8% to these emissions, respectively. In addition to CO_2, emissions from transport also contain a number of short-lived components, such as nitrogen oxides or aerosol particles. These not only impair air quality but also have important effects on the climate. The emissions of short-lived trace gases, in particular nitrogen oxides (NO_x, i.e. NO and NO_2), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC), chemically induce climate-relevant disturbances of the greenhouse gases ozone (O_3) and methane (CH_4), the latter via enhanced chemical loss of methane due to the reaction with the OH radical [3]. In addition, emitted aerosol particles (e.g. consisting of sulfuric acid or black and organic carbon) and aerosol precursor gases (e.g., SO_2, NO_x and NMVOC) contribute to climate change by modifying clouds and radiation fluxes [4]. Some of the short-lived emission components cause a negative global climate forcing, i.e. a cooling effect that counteracts global warming to a certain extent.

Given these effects, there is an urgent need for a consistent quantification of the climate impacts of both CO_2 and non-CO_2 emissions from the different transport sectors that describes the relative importance of the various effects not only for current conditions but also under different future pathways. Our study closes this gap, for the first time, by using up-to-date transport emission inventories for different scenarios up to 2050 in a fully coupled global chemistry-climate model. Using this approach, we describe and compare the climate impact of the various emission components and identify pathways under which effective climate protection can be achieved. We also show how the results can be utilised in an efficient response model for the development of mitigation strategies for the transport sectors.

2 Methodology

The effects of short-lived emission components resulting from transport emissions, in particular the aerosol effects, the production of ozone and the transport-induced chemical methane loss rate, are calculated with the global chemistry-climate modelling system EMAC (ECHAM/MESSy Atmospheric Chemistry model [5]). EMAC comprises several submodels for describing atmospheric processes and their interaction with oceans and land as well as for evaluating human influences. The model is applied here to describe i) the effects of transport emissions on the distribution of short-lived components in the atmosphere and ii) the resulting climate effects in terms of radiative forcing (see below). An EMAC version containing the detailed aerosol submodel MADE3 is used to simulate the aerosol effects. The specific setup and results of these simulations are described in a recent article by Righi et al. [4]. Simulations of the gas-phase chemical effects are carried out using an EMAC version equipped with a very detailed chemistry mechanism and with an algorithm to quantify the specific contributions of transport emissions to the respective atmospheric and climate effects. An extensive description of this model version and its application is provided in a companion paper by Mertens et al. [3].

The metric used here for evaluating the climate effects is the radiative forcing (RF). It describes the globally averaged change in the Earth's radiation budget caused by atmospheric disturbances, such as changes in the concentrations of greenhouse gases, as a result of emissions. A positive RF results in an increase in the global mean atmospheric surface temperature, i.e. a warming, a negative RF induces a temperature decrease, i.e.

a cooling. Here we use a slightly more advanced form of the RF, the so-called effective radiative forcing (ERF), which also describes subsequent short-term adjustments of the climate system, e.g. the change in clouds due to the initial forcing, and thus is an even better proxy of the expected climate effect.

While the spatial distributions of short-lived components show a strong variability, CO_2 and CH_4 are distributed almost homogeneously in the atmosphere due to their much longer lifetimes. Therefore, the transport effects, in this case, can be well approximated by considering global mean values with the help of simplified climate models. We use the climate response model AirClim [6, 7] for this purpose and determine the effect of CO_2 in analogy to Hendricks et al. [8]. The CH_4 effect is described by using the explicit calculation of transport contributions to the CH_4 loss rate in EMAC [9, 10] and an advanced function for the radiative forcing calculation [11]. The methodology to describe the CH_4 effect is adopted and finally applied in the recently developed climate response model TransClim (see below). Since CO_2 can reside in the atmosphere for centuries or even millennia and also CH_4 has a comparatively long atmospheric lifetime (about 9 years), we consider temporal accumulation effects of these species by time integration from preindustrial times until the analyzed year.

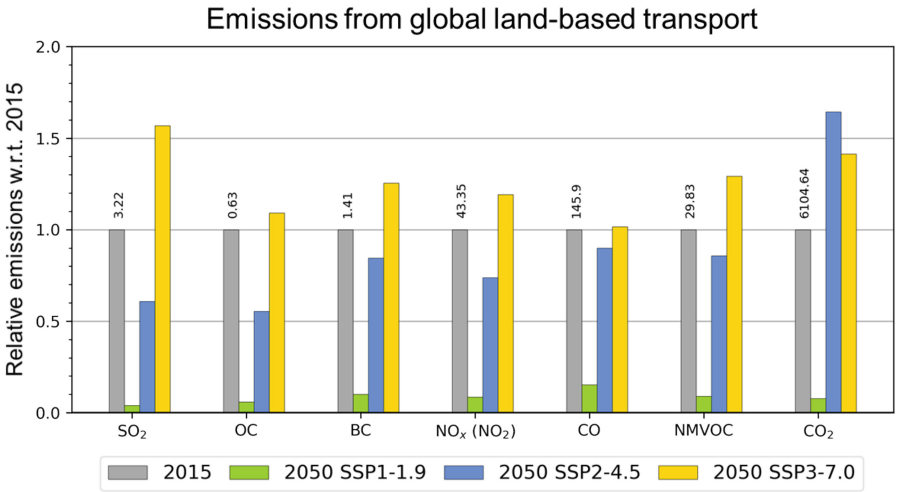


Fig. 1. Annual global emissions of land-based transport in 2050 in SSP1-1.9 (green), SSP2-4.5 (blue), and SSP3-7.0 (yellow) relative to the 2015 emissions. The total amount of emissions in 2015 taken from the SSP2-4.5 data base is indicated for each species on top of the grey bars (given in Tg, with NO_x expressed as NO_2). The abbreviations OC and BC denote particulate organic and black carbon.

As a basis for the simulations, we use the emission dataset generated as part of the CMIP6 project (Coupled Model Intercomparison Project Phase 6) for the preparation of the recent Assessment Report by the IPCC (Intergovernmental Panel on Climate Change) [1, 2, 12]. It describes the historic development of global anthropogenic emissions from 1750 to 2014 and projections up to the year 2100 for various different future developments within the framework of the SSP scenarios (Shared Socioeconomic Pathways).

According to the focus of our analyses of non-CO_2 components, we apply spatially resolved emission data for 2015 and 2050. Three different future scenarios are considered, which cover a wide range of developments: i) SSP1-1.9, as an ecological scenario with very effective emission reductions (corresponding to the 1.5 °C goal), ii) SSP2-4.5 as a "middle-of-the-road" scenario, and iii) SSP3-7.0, in which comparatively high emissions of non-CO_2 components occur due to less stringent emission regulations, despite low future growth rates. Figure 1 shows the globally aggregated emission amounts of the various components in 2015 and in the different future scenarios, exemplarily for global land-based transport. The development of the emissions reflects the basic ideas of the scenarios. Similar future developments also occur in the global aviation and shipping sectors (not shown), although future aviation emissions are characterized by higher growth rates compared to the other sectors.

3 Results and Implications

3.1 Climate Effects

Figure 2 shows our ERF results for the various effects in 2015 and 2050 caused by emissions from global land-based transport. The CO_2 effect has the largest contribution. It increases from 315 mW/m^2 in 2015 to up to 606 mW/m^2 in 2050 in SSP2-4.5 (best estimates indicated by the thick horizontal lines in each bar). A comparison with the corresponding total anthropogenic radiative forcing of about 2.4 W/m^2 and 3.7 W/m^2 [2] shows that land-based transport accounts for a significant fraction of global warming. In contrast to the emissions (Fig. 1), the ERF of CO_2 in 2050 shows no decrease in SSP1-1.9, which is due to the very long atmospheric residence time and the associated accumulation of CO_2. The decrease in emissions from 2015 to 2050 therefore only leads to an attenuated increase in its concentration.

The transport-induced aerosol particles cause a negative ERF (-164 mW/m^2 in 2015) and thus a cooling. Its future development closely follows the development of the emissions of the aerosol components BC and OC and the aerosol precursors SO_2 and NO_x. The contribution of land-based transport emissions to ozone formation leads to a positive ERF, i.e. a warming, with a slightly lower value than that of the corresponding absolute aerosol effect. Again, the future development of the effect in the different scenarios follows the relevant emissions, in this case, the ozone precursor gases NO_x, CO and NMVOC. The corresponding loss of methane leads to a negative ERF, which tends to slightly overcompensate for the warming effect of ozone formation caused by the same emission components. A striking result is the methane ERF in SSP1-1.9, which is still large despite the strong reduction of the responsible emissions, e.g. of NO_x. This results from the non-linearity in the dependence of the atmospheric oxidation capacity on NO_x. In a clean atmosphere, as in SSP1-1.9, it increases very strongly as a response to NO_x emissions. This means that in very clean environments, even low transport-related emissions can lead to significant climate perturbations.

It is important to note that the overall non-CO_2 effect of land-based transport is a cooling. This cooling offsets a substantial part of the CO_2-induced warming. For the year 2015, this results in a total ERF of land-based transport that is 56% lower than the ERF of CO_2 alone. In 2050, the reduction in total ERF due to the non-CO_2 cooling is

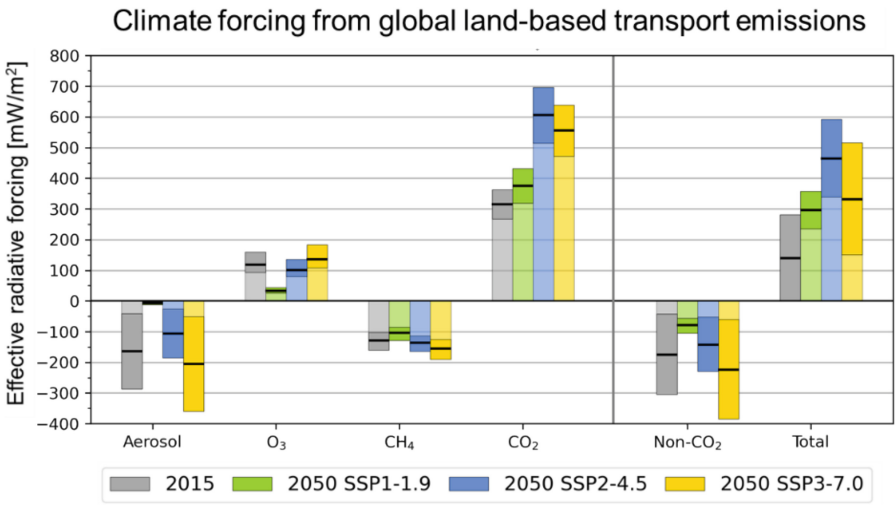


Fig. 2. Effective radiative forcing (ERF in milliwatts per square meter) caused by the emissions from global land-based transport from pre-industrial times to 2015 and 2050 for three SSP scenarios. Shown are the effects of changes in atmospheric aerosol particles, ozone (O_3), methane (CH_4), and CO_2, in 2015 (grey) and 2050 in SSP1-1.9 (green), SSP2-4.5 (blue), and SSP3-7.0 (yellow). In addition, the total non-CO_2 effect and the total ERF (sum of all contributing ERFs) are highlighted. The calculated multi-year averages are indicated by the thick horizontal lines within the bars. The darker colored areas show the uncertainties.

still 21%, 23% and 40% in SSPs 1-1.9, 2-4.5 and 3-7.0, respectively. Hence, the non-CO_2 effects retain their large relevance, despite the continuous accumulation of CO_2. This result emphasizes the particular importance of non-CO_2 compounds for the climate impact of emissions from transport also in future projections.

The specifics of the corresponding climate effects of global aviation and shipping (not shown) differ in part from those of land-based transport. While the signs of the various effects are the same as for land-based transport, with cooling aerosol and methane effects and warming induced by ozone and CO_2, the total ERFs of aviation and shipping are significantly lower. Furthermore, the ERF of CO_2 is not the dominant driver. In many cases, the non-CO_2 effects are of the same magnitude or even larger. In the case of shipping, for example, our results show a particularly large cooling effect through aerosol particles. While air traffic causes a warming in total, emissions from global maritime transport even result in an overall cooling effect in some cases.

For global transport as a whole, i.e. when summing the ERF of land-based transport, aviation, and shipping, we find that the total ERF of the non-CO_2 species is also negative and strikingly offsets the positive ERF from transport-induced CO_2 by around 80% under present-day conditions. This compensation effect is distinctively larger than indicated by earlier studies due to the application of updated methods and emissions data. In the different scenarios for 2050, the compensation still ranges between 25 and 60%. For more details on the effects of the non-CO_2 emissions in the simulations presented above we refer to Mertens et al. [3] and Righi et al. [4].

3.2 Implications for the Development of Mitigation Strategies

The findings highlighted above imply that not only CO_2 but also non-CO_2 emissions must be taken into account when assessing climate protection measures in the transport sectors. A mere consideration of CO_2 can lead to incorrect conclusions. In the aviation sector, the interplay of CO_2 and non-CO_2 effects is already part of the public and scientific debate, but in the case of land-based and maritime transport the primary focus, in many cases, is either CO_2 or non-CO_2 in isolation, depending on whether the focus is on climate or air quality. In land-based transport and shipping, cooling effects of non-CO_2 emission components can counteract the warming CO_2 effect. Mitigation of these components, e.g. to protect air quality, therefore requires a further strengthening of measures to reduce CO_2 in order to achieve a net benefit for climate. With regard to the methodical approaches for describing the effects of the emissions, it should be noted that detailed chemistry-climate models require very high computing resources and long run times. They therefore do not allow an efficient assessment of numerous mitigation measures.

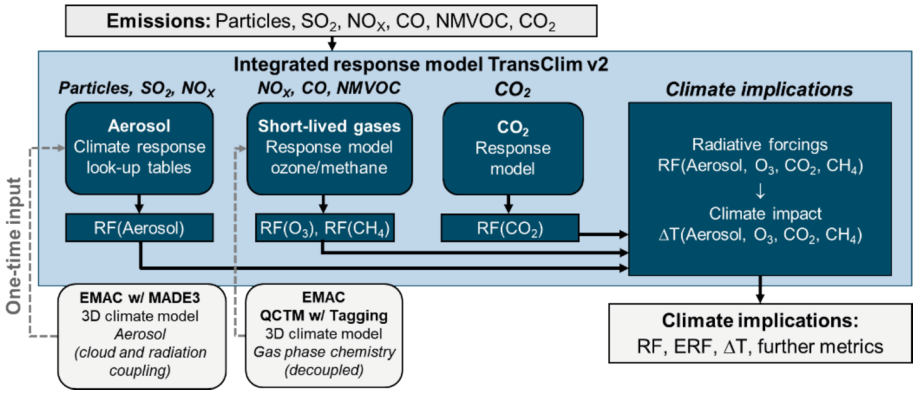


Fig. 3. Schematic representation of the rapid assessment model TransClim. Based on emission data for the various substances from transport, TransClim calculates the corresponding effects on climate. In addition to the CO_2 effect, the effects of particles and emission-induced changes in ozone and methane are also considered. The model is based on results of the detailed three-dimensional chemistry-climate model EMAC to describe aerosol [4] and gas phase [3] effects.

For this reason, we developed the rapid climate assessment model TransClim (Modelling the effect of surface Transportation on Climate [9, 13]) which is based on lookup-tables and climate response functions precalculated with the help of EMAC simulations. TransClim thus allows for a numerically very efficient determination of the climate impact of emissions from land-based transport. Global emissions or emissions in specific regions can be assessed. The model generates various metrics for climate effects, in particular the radiative forcing and the resulting change in global mean surface temperature. TransClim is currently being extended to cover also the impact of emissions from shipping and to provide metrics for estimating effects on air quality. In addition,

descriptions of the effects of aerosol particles are implemented. Figure 3 provides a schematic overview of the TransClim version that is currently being developed.

Current applications of TransClim include, for instance, the project MoDa [14], where mitigation strategies are assessed for global and European transport as well as for urban transport systems in Germany. Further TransClim applications in MoDa focus on assessing decarbonisation pathways in international shipping.

4 Conclusions

Our results clearly indicate that non-CO_2 emissions from the transport sectors have an important impact on climate. The exemplary analysis of the effects of emissions from global land-based transport presented here shows that non-CO_2 emissions of this sector have an overall cooling effect that counteracts the CO_2-induced warming. This effect occurs not only under present-day conditions. It persists in all three future scenarios analyzed, which cover a wide range of possible future developments up to 2050. The results reveal a large relevance of non-CO_2 effects also for shipping and aviation. Non-CO_2 climate effects have long been considered in the development of mitigation strategies for aviation. In contrast, in the public debate on land-based transport and shipping, non-CO_2 emissions are mainly discussed in the context of air pollution, but aspects of climate change are often neglected. Strategies to mitigate climate change in land-based and maritime transport often focus merely on CO_2. Our results, however, imply that non-CO_2 climate effects also have to be taken into account in these cases, while it is vital at the same time to avoid possible trade-offs between climate protection and air quality. Recognizing and quantifying non-CO_2 climate effects is essential if the current wave of regulation and transformation in the transport sectors is to deliver the intended benefits for climate, air quality and human health.

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References

1. Hoesly, R.M., et al.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the community emissions data system (CEDS). Geosci. Model Dev. **11**, 369–408 (2018). https://doi.org/10.5194/gmd-11-369-2018
2. Gidden, M.J., et al.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geosci. Model Dev. **12**, 1443–1475 (2019). https://doi.org/10.5194/gmd-12-1443-2019
3. Mertens, M., et al.: The contribution of transport emissions to ozone mixing ratios and methane lifetime in 2015 and 2050 in the shared socioeconomic pathways (SSPs). Atmos. Chem. Phys. **24**, 12079–12106 (2024). https://doi.org/10.5194/acp-24-12079-2024

4. Righi, M., Hendricks, J., Brinkop, S.: The global impact of the transport sectors on the atmospheric aerosol and the resulting climate effects under the shared socioeconomic pathways (SSPs). Earth Syst. Dynam. **14**, 835–859 (2023). https://doi.org/10.5194/esd-14-835-2023
5. Jöckel, P., et al.: Earth system chemistry integrated modelling (ESCiMo) with the modular earth submodel system (MESSy) version 2.51. Geosci. Model Dev. **9**, 1153–1200 (2016). https://doi.org/10.5194/gmd-9-1153-2016
6. Grewe, V., Stenke, A.: AirClim: an efficient tool for climate evaluation of aircraft technology. Atmos. Chem. Phys. **8**, 4621–4639 (2008). https://doi.org/10.5194/acp-8-4621-2008
7. Dahlmann, K., Grewe, V., Frömming, C., Burkhardt, U.: Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? Transp. Res. Part D: Transp. Environ. **46**, 40–55 (2016). https://doi.org/10.1016/j.trd.2016.03.006
8. Hendricks, J., et al.: Quantifying the climate impact of emissions from land-based transport in Germany. Transp. Res. Part D: Transp. Environ. **65**, 825–845 (2018). https://doi.org/10.1016/j.trd.2017.06.003
9. Rieger, V.S.: A New Method to Assess the Climate Effect of Mitigation Strategies in Road Traffic, PhD thesis. Delft University of Technology (2018). https://doi.org/10.4233/uuid:cc96a7c7-1ec7-449a-84b0-2f9a342a5be5
10. Rieger, V.S., Mertens, M., Grewe, V.: An advanced method of contributing emissions to short-lived chemical species (OH and HO_2): the TAGGING 1.1 submodel based on the modular earth submodel system (MESSy 2.53). Geosci. Model Dev. **11**, 2049–2066 (2018). https://doi.org/10.5194/gmd-11-2049-2018
11. Etminan, M., Myhre, G., Highwood, E.J., Shine, K.P.: Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. Geophys. Res. Lett. **43**, 12614–12623 (2016). https://doi.org/10.1002/2016GL071930
12. Feng, L., et al.: The generation of gridded emissions data for CMIP6. Geosci. Model Dev. **13**, 461–482 (2020). https://doi.org/10.5194/gmd-13-461-2020
13. Rieger, V.S., Grewe, V.: TransClim (v1.0): a chemistry–climate response model for assessing the effect of mitigation strategies for road traffic on ozone. Geosci. Model Dev. **15**, 5883–5903 (2022). https://doi.org/10.5194/gmd-15-5883-2022
14. MoDa. https://www.dlr.de/en/research-and-transfer/projects-and-missions/moda. Accessed 7 Mar 2026

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How Policy Distortions Shape EV Affordability in Africa

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Abstract. Electric vehicles (EVs) offer a cost-effective transportation alternative for Africa, particularly under favorable financing conditions and low-carbon charging scenarios. However, widespread adoption of EVs across the African continent is highly context-specific and may vary significantly between countries, depending on differences in power infrastructure, risk profiles, and policy landscapes. Using a multi-country case study approach that integrates Total Cost of Ownership (TCO) combined with environmental Life Cycle Assessment analyses, we evaluate and project, through 2040, how fuel and purchase taxes, financing mechanisms, and infrastructural barriers shape EV affordability in Egypt, Ethiopia, Ghana, and South Africa. We contrast "distortion-free" scenarios with actual policy conditions to assess impacts on TCO. Additionally, we examine the monetized external costs of the carbon footprint and particulate matter emissions, in the context of future projections for these countries' power grids. The study covers two-wheelers and four-wheelers, including minibuses, across both new and second-hand markets, and also explores a scenario involving e-fuels. Results show that EVs already offer economic and environmental advantages over fossil fuel vehicles in this decade, even under current policy conditions. Well-designed policies, such as improved access to financing and incentives for investment in renewables and charging infrastructure, could accelerate the transition to EVs.

Keywords: Electric vehicles · Africa · Fuel taxes · Financing · Sustainability

1 Introduction

Climate change has made rapid decarbonization of the transport sector a global priority. Africa accounts for only a small share of global CO_2 emissions, yet it faces disproportionate climate risks. At the same time, vehicle-related air pollution is a relevant health hazard in many cities across the continent. Tackling transport emissions by accelerating the adoption of renewables and electrification has therefore the potential to deliver both climate and health benefits.

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Electric vehicles (EVs) offer significant potential for emission reductions. However, Africa's transport decarbonization pathway is shaped by distinct structural constraints, such as the reliance on used-vehicle imports, less reliable grids and the high cost of financing [1]. Despite this, recent research has shown that electric vehicles (EVs) would – absent any government distortions like taxes and subsidies – become cost-competitive across the continent in the next 10 to 15 years [1]. EVs would, from a societal perspective, save costs while reducing the carbon footprint of mobility, both globally and locally in Africa. However, in reality, major distortions exist. Given the substantial differences among African countries regarding these distortions, but also regarding other structural factors (e.g., institutional quality resulting in different financing costs, or power sector trajectories) that shape the actual affordability and climate benefits of EV adoption, a closer look at individual countries (including the real distortions) is needed before making continental claims.

This paper addresses this gap by applying a country-level comparative approach to Egypt, Ethiopia, Ghana, and South Africa. We integrate Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA) modeling through 2040 to compare EVs and internal combustion engines (ICEs) using fossil or solar-derived e-fuels under both private consumer conditions (with distortions, including current taxes and financing) and "distortion-free" scenarios (excluding policy distortions and including externalities). Our scope covers two-wheelers (2w) and four-wheelers (4w), including minibuses, across both new and second-hand markets. This country-specific analysis aims to provide new evidence on the opportunities and barriers for low-carbon transport transitions in Africa.

2 Methodology

The prospective TCO and LCA comparing EVs and ICEs running on e-fuel and fossil fuel focuses on Egypt, Ethiopia, Ghana and South Africa, which are chosen due to their diversity in geographic distribution, population size, electricity access, total transport-related emissions, and electricity mix. For the undistorted scenario, we build on our previous work Noll et al. (2025). We highlight here the key differences from this study. The analysis uses one kilometer as the unit of comparison. The temporal scope includes both short-term (2030) and the medium-term (2040) future. The supply chains are global. We assume EVs are charged using country-specific public electricity grids. For the electricity mix, we use the Base scenario from the TEMBA model, a cost-optimization tool for long-term energy planning in Africa [2]. We neglect installation costs for home charging. E-fuel from green hydrogen is assumed to be imported from Chile, i.e., the country projected to be one of the cheapest producers of green hydrogen on earth [3]. This means we use a highly idealistic scenario, where e-fuels are produced under the most favorable conditions. Cost projections and LCA data for the production via Fischer-Tropsch synthesis, converting hydrogen from solar power-driven electrolysis and CO_2 from the atmosphere into hydrocarbons and transport of e-fuel are retrieved from [4].

We adopt the Life Cycle Inventory (LCI) database *ecoinvent 3.10.1* [5] and the tool *premise* is used to project this database into the future [6]. The prospective scenario SSP2-RCP2.6 of the Integrated Assessment Model REMIND [7] was used as inputs. PM impact on health is estimated in terms of disease incidence following the method

recommended by UNEP [8]. Conservative monetisation factors ("high") suitable for this method according to European valuation are retrieved from [9]. A cost of 230 $ per tonne of CO_2eq is assumed based on the same source [9]. We use global characterization factors for particulate matter emissions throughout the life cycle. The only exceptions are particulate matter emissions from combustion and electricity supply, for which we adjust the global characterization factors to better reflect local conditions by applying regionalized intake fractions for African regions, as recommended by Van Zelm et al. [10]. This approach captures important regional differences in exposure. Intake fractions tend to be higher in Egypt, where emissions occur near densely populated areas and where the arid climate, with little rainfall to wash pollutants out from the air, and restricted pollutant dispersion, increases exposure. In contrast, West and Eastern Africa exhibit lower values due to more dispersed populations and more effective atmospheric removal. South Africa falls in between, since coastal ventilation and favorable meteorology mitigate exposure compared to Egypt, but intake fractions remain above those of West and Eastern Africa because of more densely populated urban centers. No discounting is applied to externality costs.

We retrieved the purchase costs without taxes of the vehicles in 2030 and 2040 from [1]. We assume that most vehicles retain a residual value after their ownership period and are resold. Each year, the vehicle loses value proportionally to the depreciation rate. The depreciation rate, in turn, is influenced by the manufacturer, model, segment, and powertrain. We adopted depreciation rates of 13.9% and 10.4% for 4w EV and ICE, respectively. For 2w, we adopted depreciation rates of 20% for EV and 14.3% for ICE.

The vehicle inventories, along with their respective fuel economies, are based on Sacchi and Bauer [11]. Ghana and Ethiopia impose no age restrictions on the import of used vehicles, whereas many other African countries set limits, typically between 5 and 7 years [12]. Egypt and South Africa have a full ban on the import of used vehicles. Accordingly, no import duty was applied to used cars in these two countries, assuming domestic purchases rather than imports from abroad. For used vehicles, the impacts of vehicle and battery manufacturing were reduced in proportion to the vehicle's age at resale. We assume this age to be 5 years. Per-kilometer maintenance and repair costs for 4w are calculated using data from South Africa, with the TCO calculation tool developed by Sustainable Energy Africa [13]. Maintenance and repair costs for 2w are taken from [14]. Table 1 provides an overview of the Weighted Average Cost of Capital (WACC) per country as well as assumptions for key taxes related to the purchase of the vehicles. For the WACC, we assume third-party ownership, using financing costs faced by leasing companies, financial institutions, or fleet operators rather than those borne by private individuals.

For South Africa, the Ad Valorem Tax, and for Ethiopia, the excise tax, are also included, because they account for a significant part of the purchase-related tax burden. The ad valorem tax values in South Africa are proportionate to the vehicle's value and determined for 4w EV with a TCO comparison tool created by Sustainable Energy Africa [13]. The values for 2w ICE are from [22]. Minor taxes, such as the surtax and withholding tax in Ethiopia, are neglected.

We assume that fossil fuel prices [24] in Ethiopia, Ghana and South Africa would increase proportionally to fuel price predictions by Pappis et al. [25]. Egypt heavily

Table 1. Country-specific WACC [1] and assumed value-added tax (VAT) and import duty. Bracketed numbers indicate the value for 2w if they differ from those for 4w.*ICE with a cylinder capacity above 3000 cc are charged 20% like 2w (it does not apply to the minibus segment).

Country	WACC	EV		ICE	
		VAT	Import duty	VAT	Import duty
Egypt	16.1%	14% [15]	0% [16]	14% [15]	100% (30%) [16]
Ethiopia	13.0%	0% [17]	20% [17]	15% [15]	35% [18]
Ghana	15.5%	15% [19]	0% [20]	15% [19]	10% (20%)* [21]
South Africa	9.5%	16.5% [22]	25% [23]	16.5% [22]	18% [23]

subsidizes fuel prices. However, Egypt has been collaborating with the International Monetary Fund to phase out fuel subsidies and restore fuel prices to their cost recovery levels by December 2025 [26]. Thus, we assume that fossil fuel prices in Egypt would match basic fuel prices projected to 2030 and 2040 proportionally to fuel price predictions by Pappis et al. [25]. We apply the same tax rate to e-fuel as to conventional diesel.

3 Results

Figure 1 shows the comparison of TCO for private and undistorted scenarios for new vehicles sold in 2040 in the four countries investigated. Figure 2 presents the same analysis for South Africa in 2040, disaggregated by vehicle segment and also for used vehicles. All figures also show the 2030 total TCO values.

Across all scenarios, EVs consistently outperform ICE vehicles with fossil fuels in 2040 in terms of TCO. This advantage is evident in both distorted (including market imperfections, taxes, and subsidies) and undistorted (cost-only) perspectives. In 2030, the least competitive small 4w-EVs will be cheaper than fossil-fuel-powered ICE vehicles in Egypt and Ethiopia, will reach cost parity in Ghana, but will remain more expensive in South Africa.

From an undistorted perspective, vehicle purchase costs (excluding taxes) together with financing costs are the dominant contributors to TCO for all vehicle types. From a private consumer perspective, purchase-related taxes constitute a substantial share of total costs. Favourable taxation for EVs is present in three out of the four countries, further reinforcing their cost competitiveness. Fuel costs are prominent for ICE vehicles using e-fuels, due to the high production costs of these fuels, especially in 2030 and in South Africa, where interest rates are the lowest. In the other countries, relatively high interest rates amplify substantially the significance of capital-related costs over operating costs, making e-fuels cost overall marginal. Fuel and electricity taxes become relevant mainly for second-hand vehicles, where the lower upfront cost and shorter remaining lifetime shift the cost distribution towards operating expenditures. For 2ws, EVs will become about 50% cheaper than ICEs by 2040, under both perspectives assessed. External costs of EVs are lower than ICEs with fossil fuels in 2040 in all countries and across all applications.

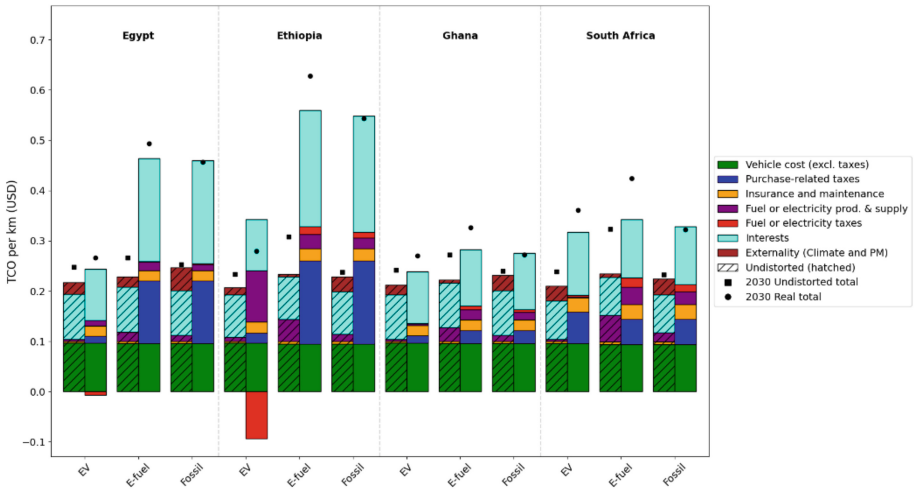


Fig. 1. 2040 TCO comparison and breakdown by country and fuel for new vehicles in the small 4 W segment.

Among the limitations of our study, we acknowledge that the regulatory environment is complex and constantly changing compared to our assumed policy distortions. Assumptions for e-fuels are highly idealised. We only consider EVs charged with grid electricity, yet 43% of the African population lacks access to electricity [27]. While the link between PM emissions and health outcomes is well established [28, 29], dispersion, transformation, and exposure processes are region-specific. We corrected for this using regionalized intake fractions for the local fraction of emissions, but a more detailed city-level analysis could improve accuracy.

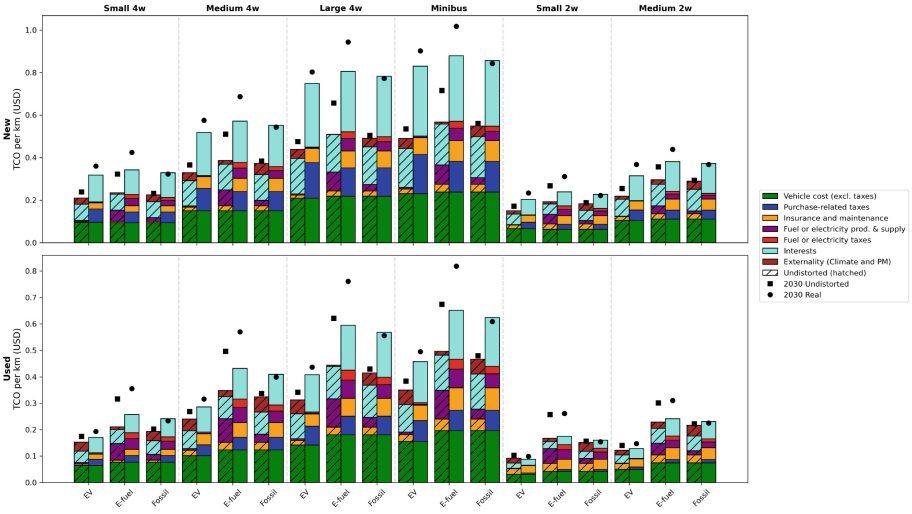


Fig. 2. 2040 TCO comparison and breakdown by vehicle type and fuel in South Africa. New vehicles at the top and used vehicles at the bottom.

4 Conclusions

This study shows that EVs will provide clear economic and environmental advantages over internal combustion engine vehicles in Egypt, Ethiopia, Ghana, and South Africa, even without major policy reforms impacting TCO competitiveness. Their competitiveness is enhanced in three out of four countries by favorable taxation for this technology and becomes even stronger once environmental and health externalities are considered. Financing is a significant barrier to the affordability of transportation. High interest rates can offset operating cost savings. This highlights the need for affordable credit to make EVs more accessible in the near term. Eliminating distortions such as fuel subsidies and uneven import duties would accelerate adoption and level the playing field. Renewables and electrification together amplify gains, as grids decarbonize.

Overall, the results indicate that African governments can unlock climate, health, and economic benefits by supporting EV adoption and infrastructure alongside renewable energy deployment. While synthetic fuels may be valuable in hard-to-abate sectors, they are not a scalable or cost-effective substitute for electrification in road transport, even under the most idealized conditions. Therefore, focusing on them for road transport could be a distraction that risks delaying the transition to e-mobility.

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References

1. Noll, B., et al.: Battery-electric passenger vehicles will be cost-effective across Africa well before 2040. Nat. Energy. (2026). https://doi.org/10.1038/s41560-025-01955-x
2. TEMBA: OSeMOSYS. http://www.osemosys.org/temba.html. Accessed 7 Jan 2025
3. Acosta, K., Salazar, I., Saldaña, M., Ramos, J., Navarra, A., Toro, N.: Chile and its potential role among the most affordable green hydrogen producers in the world. Front. Environ. Sci. **10**, 890104 (2022). https://doi.org/10.3389/fenvs.2022.890104
4. Allgoewer, L., et al.: Cost-effective locations for producing fuels and chemicals from carbon dioxide and low-carbon hydrogen in the future. Ind. Eng. Chem. Res. **63**, 13660–13676 (2024). https://doi.org/10.1021/acs.iecr.4c01287
5. ecoinvent: Data with purpose. https://ecoinvent.org/. Accessed 14 Jan 2025
6. Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., et al.: PRospective EnvironMental impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renewable Sustain. Energy Rev. **160**, 112311 (2022). https://doi.org/10.1016/j.rser.2022.112311
7. Baumstark, L., et al.: REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. Geosci. Model Dev. **14**, 6571–6603 (2021). https://doi.org/10.5194/gmd-14-6571-2021
8. UNEP: Global Guidance for Life Cycle Impact Assessment Indicators Volume 1. UNEP (2017)
9. European Commission, Trinomics: Energy Costs, Taxes and the Impact of Government Interventions on Investments – Final Report, Summary. European Commission (2020)
10. Van Zelm, R., Preiss, P., Van Goethem, T., Van Dingenen, R., Huijbregts, M.: Regionalized life cycle impact assessment of air pollution on the global scale: damage to human health and vegetation. Atmos. Environ. **134**, 129–137 (2016). https://doi.org/10.1016/j.atmosenv.2016.03.044
11. Sacchi, R., Bauer, C.: Life Cycle Inventories for on-Road Vehicles. Paul Scherrer Institut, Villigen, Switzerland (2023). https://doi.org/10.5281/ZENODO.5156043
12. FIA: Promoting Safer and Cleaner Used Vehicles for Africa. FIA (2020)
13. Sustainable Energy Africa: Total Cost of Ownership Comparison of EVs and ICE Vehicles in South Africa: Tool. Sustainable Energy Africa (2023)
14. Roam: Motorcycles. https://www.roam-electric.com/motorcycles. Accessed 14 Jan 2025
15. PwC: The World in 2050. PwC (2017) https://www.pwc.com/gx/en/research-insights/economy/the-world-in-2050.html. Accessed 23 May 2024
16. U.S. Department of Commerce: Egypt - Import Tariffs. U.S. Department of Commerce (2022) https://www.trade.gov/country-commercial-guides/egypt-import-tariffs. Accessed 13 Jan 2025
17. Capital Market Ethiopia: Ethiopia Raises Customs Duty on Electric Cars: Implications for the EV Market. Capital Market Ethiopia (2024) https://www.capitalmarketethiopia.com/ethiopian-government-increases-customs-duty-on-electric-vehicles/. Accessed 13 Jan 2025
18. AutoCango: a guide to import used cars from China to Ethiopia in 2024. https://www.autocango.com/blog-detail/import-used-cars-china-ethiopia-guide-2024. Accessed 13 Jan 2025
19. U.S. Department of Commerce: Ghana Customs Valuation for Used Vehicles. U.S. Department of Commerce (2023) https://www.trade.gov/market-intelligence/ghana-customs-valuation-used-vehicles. Accessed 13 Jan 2025
20. U.S. Department of Commerce: Ghana Electrical Vehicle Tariffs. U.S. Department of Commerce (2023) https://www.trade.gov/market-intelligence/ghana-electrical-vehicle-tariffs. Accessed 13 Jan 2025

21. Ghana Revenue Authority: Vehicle importation. https://gra.gov.gh/customs/vehicle-importation/. Accessed 13 Jan 2025
22. South African Revenue Service: Value-Added Tax Levied on the Importation of Goods into South Africa. South African Revenue Service (2022)
23. Panchia, Y.: Interpreting South Africa's EV import duties (2024). https://www.forbesafrica.com/current-affairs/2024/01/26/interpreting-south-africas-ev-import-duties/. Accessed 13 Jan 2025
24. GlobalPetrolPrices.com: Diesel prices around the world. https://www.globalpetrolprices.com/diesel_prices/. Accessed 14 Jan 2025
25. Pappis, I., Howells, M., Sridharan, V., Usher, W., Shivakumar, A., Gardumi, F., et al.: Energy Projections for African Countries. JRC Publication Repository (2019). https://doi.org/10.2760/678700
26. Singh, K., Lewis, A.: IMF Approves Release of $820 Million for Egypt, Calls for More Reforms. Reuters (2024)
27. International Energy Agency: Africa Energy Outlook 2022. International Energy Agency (2022)
28. Pope III, C.A.: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA J. Am. Med. Assoc. **287**(9), 1132 (2002). https://doi.org/10.1001/jama.287.9.1132
29. Lim, S.S., et al.: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010. Lancet. **380**(9859), 2224–2260 (2012). https://doi.org/10.1016/S0140-6736(12)61766-8

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Clustering the European Union Electric Vehicle Markets: Status in 2025

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Abstract. The European Union (EU) passenger car market has experienced rapid growth in electric vehicle (EV) adoption since 2020, with EVs representing over 20% of new registrations in 2024. Adoption remains uneven across Member States, reflecting differences in policy frameworks, infrastructure availability, and socio-economic conditions. Building on our clustering analysis using 2020 data [1], this study updates the clustering of EU countries for 2024, grouping countries according to their progress toward net zero-emission passenger car registrations. The analysis demonstrates that most clusters remain stable over time, identifies emerging markets such as Denmark and Finland, and shows that late majority and laggard countries lag in EV adoption and public charging infrastructure. It further examines the influence of regulatory mechanisms, infrastructure deployment, and market-driven factors, illustrated by non-EU countries such as Türkiye, Switzerland, and Iceland. Our findings confirm and extend the previously developed framework for analyzing EV adoption, demonstrating its continued relevance for guiding policy interventions and providing a solid foundation for future modeling of EU EV market adoption, including transportation models that benefit from reduced data requirements.

Keywords: electric vehicles · European Union · passenger car market · clustering

1 Introduction

The decarbonization of the European passenger car market is progressing rapidly, driven by the adoption of electric vehicles (EVs). The European Commission (EC) aims for net zero CO_2 emissions for all new passenger cars by 2035, gradually tightening allowed emission levels for passenger cars [2]. Non-compliance will result in substantial penalties for OEMs, hereby accelerating the phase-out of conventional internal combustion engine vehicles (ICEVs) in favor of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Alternative technologies such as FCEVs or biofuel-powered ICEVs are expected to remain marginal until 2035 [3,4].

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EV uptake in Europe has accelerated: from 10% of new registrations in 2020 (1 million vehicles) to 22% in 2024 (2.2 million vehicles) [5], despite temporary market contractions linked to policy adjustments. Early 2025 figures suggest a further rise to 25%, driven by more competitively priced EV models and evolving EU CO_2 compliance mechanisms [6].

National policies play a pivotal role in shaping EV adoption. Subsidies, infrastructure support, taxation schemes, and public awareness campaigns all affect both supply and demand for EVs [7]. The socio-economic context of each Member State further influences the effectiveness of these policies, leading to large discrepancies in EV market maturity across the EU [8].

To capture these differences, we update our 2020 analysis [1] by clustering EU Member States according to EV adoption progress. This highlights groups of countries with similar market characteristics, policy environments, and socio-economic contexts, allowing us to track cluster evolution, identify emerging leaders, and assess whether lagging countries are catching up. Using a framework that combines hierarchical clustering with Principal Component Analysis (PCA), incorporating EV market share, policy support, and infrastructure, we provide a structured view of the current European EV landscape and a foundation for scenario-based projections through 2035.

2 Literature Review

Despite growing interest in electric vehicles (EVs) in Europe, comprehensive models covering the full European territory remain limited [9,10]. This is partly due to the substantial data requirements of many transportation models, such as agent-based approaches [11]. Some studies address this challenge through simplifying assumptions; for example, [12] applies uniform vehicle survival rates across the EU, while [7] defines representative country groups based on a small set of variables. Such simplifications risk overlooking important differences in market maturity, policy frameworks, socio-economic conditions, and infrastructure across Member States.

Previous research identifies multiple factors influencing EV adoption, including economic conditions, policy interventions, infrastructure availability, and fleet characteristics [13,14]. The share of new alternative powertrain registrations therefore provides a useful indicator of a country's position in the transition toward net zero-emission vehicles [15]. Given this complexity, multi-parameter approaches are required to capture the heterogeneity of European markets more realistically than single-variable representations.

Clustering methods that combine dimensionality reduction, such as Principal Component Analysis (PCA), with hierarchical or k-means clustering have been widely applied to analyze patterns in small datasets [16,17]. Building on our previous 2020 analysis [1], this study updates the clustering of EU Member States using 2024 data, providing an up-to-date view of market progress and enabling direct comparison with earlier results. Details on the data and methodology are provided in Sect. 3.

3 Methodology

3.1 Data and Features

The dataset comprises 29 countries, including the 27 EU Member States, the UK, and Norway. Countries are characterized by 11 parameters [1] capturing economic, social, policy, and automotive sector dimensions, including EV market share, GDP per capita, charging infrastructure density, fleet age, and policy support measures (Table 1). These features were selected based on prior studies highlighting their relevance for EV adoption [13–15]. For additional analysis, Iceland, Switzerland, and Türkiye are later included.

Table 1. Parameters of the updated clustering model, unit of measure, and year.

Parameters	Unit	Year
GDP per capita	current prices US$ PPP	2024
Long term interest rate	10 year government bonds	2025
Greenhouse gas intensity reduction of road transport	% of decrease between 2010 and 2022	2022
Effort sharing regulation target for 2030	% of CO_2 emissions reduction since 2005	2024
Renewable energy consumption share	Share in %	2023
New registrations of electric passenger cars	number of passenger car vehicles	2024
Electric public charger density	number of public chargers per 100km^2	2024
Electric public charger availability	electric vehicles per public charger	2024
Average age of the passenger car fleet	years	2023
Climate change awareness indicator	share in %	2024
Employment in the automotive industry	share in %	2023

3.2 Clustering Approach

To group countries based on the maturity of their EV markets, we apply a framework combining dimensionality reduction with clustering techniques, consistent with [1]. Principal Component Analysis (PCA) reduces the dimensionality of the dataset while preserving relevant variance, allowing a more robust clustering process for a moderate number of countries [16,17].

Hierarchical clustering is chosen for its flexibility in grouping countries without predefining the number of clusters [18]. Euclidean distance is used as a similarity measure, and Ward's criterion is applied as the linkage method to optimize cluster cohesion and separation [19]. Cluster validity is assessed using the Silhouette score, an internal metric measuring how well countries fit within their assigned clusters [20].

3.3 Cluster Interpretation

To interpret the clusters, we assign labels inspired by Rogers' innovation adoption curve [21], categorizing countries as innovators, early adopters, early majority, late majority, or laggards, based on the maturity of their national EV markets. This framework allows for a meaningful understanding of the relative positions of countries and facilitates comparisons over time, particularly with the updated 2024 data.

4 Results

4.1 Principal Component Analysis (PCA)

To investigate cross-country differences in zero-emission passenger car adoption, we first apply Principal Component Analysis (PCA) to reduce dimensionality. PCA summarizes the main drivers of variation across countries and provides a compact visualization of clustering results. The first two principal components (PCs) capture the majority of variance and show structural, policy, and socio-economic differences among countries.

Figure 1 shows country positions in the PC space, with colors indicating cluster membership from subsequent hierarchical clustering analysis (cf. Sect. 4.2). (a) presents 2024 data, while (b) shows 2020 data. Comparison highlights shifts in country positions and cluster boundaries over time.

In 2024, Sweden and Norway remain distinct in the first two PCs, while Denmark diverges from the previous early majority cluster grouping, reflecting its advanced EV adoption and policy indicators. Early majority and laggard clusters remain stable, indicating limited structural shifts since 2020.

Including Switzerland, Iceland, and Türkiye underscores European market heterogeneity. Türkiye is distant from EU countries due to higher long-term interest rates and absent binding CO_2 regulations. Switzerland aligns with early majority countries, while Iceland is near innovators such as Sweden and Norway. These patterns highlight the influence of both economic and regulatory factors in shaping cross-country EV adoption differences.

4.2 Hierarchical Clustering and PCA

To group countries based on their transition toward net zero-emission passenger cars, we applied agglomerative hierarchical clustering to the PCA-reduced 2024 dataset. Four principal components are retained, accounting for 78% of the total variance, which capture the main drivers of cross-country differences. Using Ward's linkage and Euclidean distance, eight clusters are identified, representing distinct types of EV markets across Europe.

The clustering is generally robust. For eight clusters, the silhouette score is 0.39, very close to the 0.40 score obtained for the 2020 clustering. The clusters obtained in 2024 and 2020 can be found in Fig. 2. Minor differences in cluster density are observed, for example, Finland and Denmark form less compact clusters.

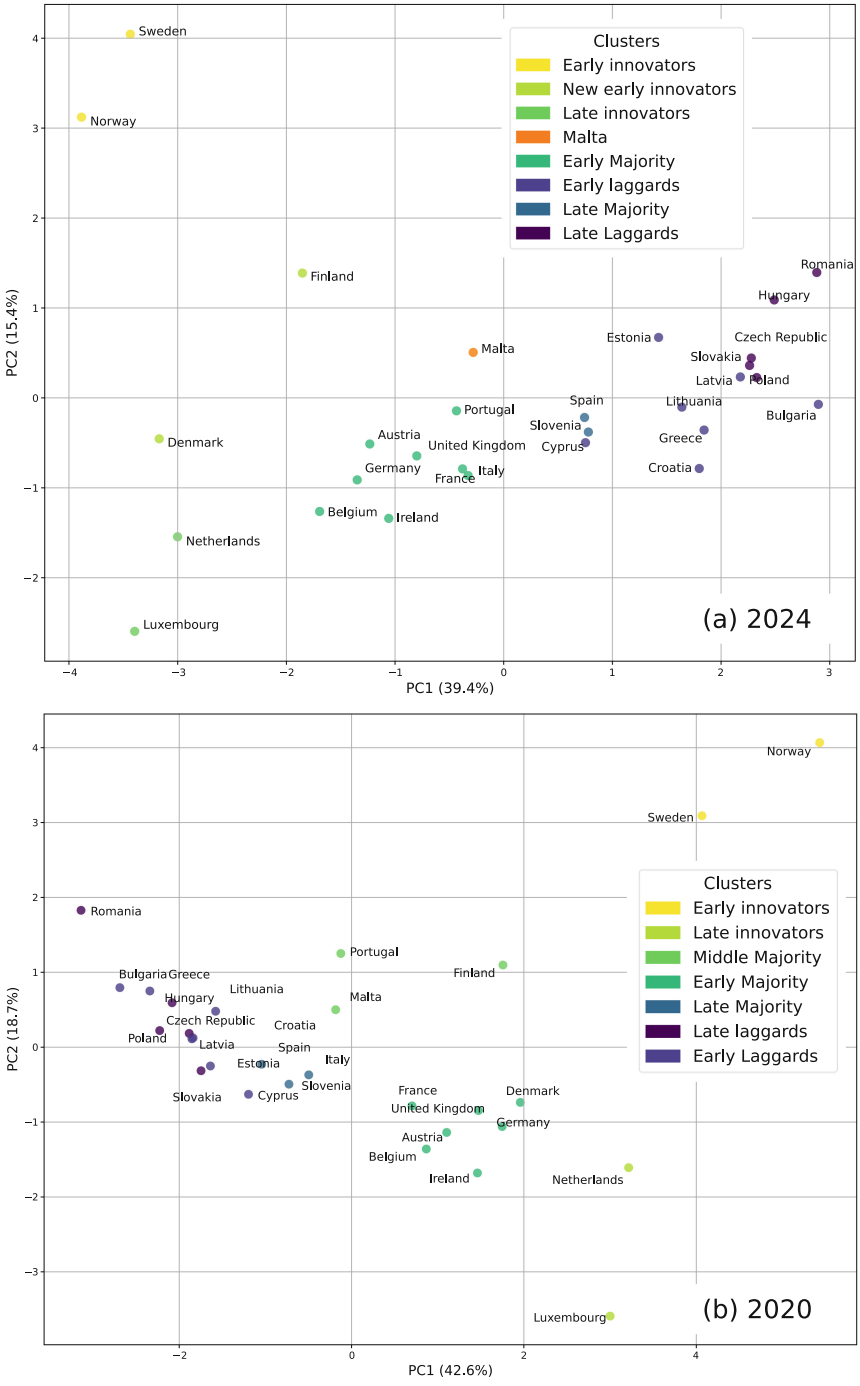


Fig. 1. Visualization of EU Member States, Norway and UK clustered in principal component space in 2024 (a) and in 2020 (b). Colors indicate cluster membership.

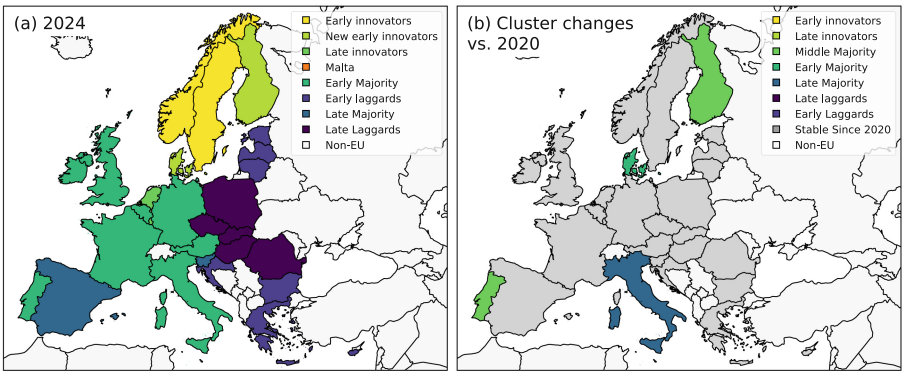


Fig. 2. Comparison of European countries' clusters in progress toward net zero-emission passenger car sales: (a) 2024 results, (b) countries that changed clusters since 2020. Colors indicate cluster membership.

4.3 Results Interpretation

Across Europe, the economic and policy environment has shifted since 2020, with gradual improvements in emissions intensity and renewable energy shares, alongside new challenges such as higher interest rates and an ageing vehicle fleet. Most notably, the EV market itself has accelerated: the share of new electric passenger cars more than doubled and public charger density quadrupled between 2020 and 2024. These developments provide the context for interpreting the cluster results below, which assess how different groups of countries are progressing in EV uptake and charging infrastructure deployment.

Norway and Sweden remain clear early innovators, combining very high EV uptake (around 75% of new sales) with dense charging infrastructure. Their trajectory illustrates the outcomes achievable when strong policy frameworks align with high consumer acceptance.

Denmark and Finland emerge as new early innovators, with Denmark showing particularly rapid growth, increasing its EV share from 18% to over 50% within four years. This highlights the effectiveness of recent taxation and incentive reforms in accelerating market transitions. Late innovators, including the Netherlands and Luxembourg, have also doubled their EV shares since 2020 and now exhibit charging infrastructure densities comparable to the new early innovators.

The early majority cluster (Austria, Belgium, France, Germany, Ireland, Italy, and Portugal) shows heterogeneous progress. While several countries display strong adoption trends, others, notably Italy, remain below the EU average, indicating persistent structural or policy barriers. In contrast, late majority and laggard countries continue to show limited advances, with EV shares near or below 10% and slow charging infrastructure deployment, raising concerns about their ability to meet the 2035 decarbonization target.

Taken together, these patterns underline that while Europe as a whole is progressing rapidly, the pace of transition is highly uneven. The challenge for the coming decade is not only to sustain momentum in the innovator markets but also to close the widening gap with laggard countries, where policy support and infrastructure investment remain insufficient.

5 Conclusion

This study provides an updated assessment of the European passenger car market's transition toward net zero-emission vehicles, using 2024 data to cluster countries based on EV adoption, policy support, and infrastructure development. The results reveal substantial disparities across Europe, while most clusters remain largely stable compared to 2020, confirming the robustness of the clustering approach previously applied to forecast EU market developments [1]. Early innovators such as Norway and Sweden continue to lead with high EV shares and dense charging infrastructure, while Denmark and Finland emerge as new early innovators driven by favorable policy frameworks.

Regulatory frameworks play a central role in shaping market dynamics. Türkiye, which lacks EU CO_2 compliance mechanisms, does not align with any EU cluster, whereas Switzerland and Iceland integrate well into European clusters, highlighting the importance of supportive policies and comparable socio-economic conditions.

Despite overall growth, countries in the late majority and laggard clusters remain below 15% EV share, highlighting the need for targeted efforts in underperforming markets. The stability of clusters over time confirms the robustness of our methodology and provides a practical framework for monitoring progress and guiding policy interventions toward a balanced transition to a zero-emission passenger car fleet across Europe.

References

1. Möring-Martínez, G., Senzeybek, M., Jochem, P.: Clustering the European union electric vehicle markets: a scenario analysis until 2035. Transp. Res. Part D: Transport Environ. **135**, 104372 (2024). https://doi.org/10.1016/j.trd.2024.104372
2. European Commission: Zero emission vehicles: first Fit for 55' deal will end the sale of new CO2 emitting cars in Europe by 2035 (2022). https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_22_6462/IP_22_6462_EN.pdf
3. Plötz, P.: Hydrogen technology is unlikely to play a major role in sustainable road transport. Nat. Electron. **5**(1), 8–10 (2022). https://doi.org/10.1038/s41928-021-00706-6
4. Yuan, X., Cai, Y.: Forecasting the development trend of low emission vehicle technologies: based on patent data. Technol. Forecasting Soc. Change **166**, 120651 (2021). https://doi.org/10.1016/j.techfore.2021.120651
5. EAFO: Road statistics (2025). https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road

6. Transport & Environment: The drive to 2025: Carmakers' progress towards their EU CO2 target in H1 2024 (2024). https://www.transportenvironment.org/articles/the-drive-to-2025-why-eus-2025-car-co2-target-is-reachable-and-feasible
7. Neshat, N., Kaya, M., Ghaboulian Zare, S.: Exploratory policy analysis for electric vehicle adoption in European countries: a multi-agent-based modelling approach. J. Cleaner Prod. **414**, 137401 (2023). https://doi.org/10.1016/j.jclepro.2023.137401
8. Martins, H., Henriques, C.O., Figueira, J.R., Silva, C.S., Costa, A.S.: Assessing policy interventions to stimulate the transition of electric vehicle technology in the European union. Socio-Econ. Plann. Sci. **87**, 101505 (2023). https://doi.org/10.1016/j.seps.2022.101505
9. Domarchi, C., Cherchi, E.: Electric vehicle forecasts: a review of models and methods including diffusion and substitution effects. Transport Rev. **43**(6), 1118–1143 (2023). https://doi.org/10.1080/01441647.2023.2195687
10. Maybury, L., Corcoran, P., Cipcigan, L.: Mathematical modelling of electric vehicle adoption: a systematic literature review. Transp. Res. Part D: Transport Environ. **107**, 103278 (2022). https://doi.org/10.1016/j.trd.2022.103278
11. Jochem, P., Gómez Vilchez, J.J., Ensslen, A., Schäuble, J., Fichtner, W.: Methods for forecasting the market penetration of electric drivetrains in the passenger car market. Transport Reviews 38(3), 322–348 (2018). https://doi.org/10.1080/01441647.2017.1326538
12. Pasaoglu, G., Harrison, G., Jones, L., Hill, A., Beaudet, A., Thiel, C.: A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the eu light duty vehicle road transport sector. Technol. Forecasting Soc. Change **104**, 133–146 (2016). https://doi.org/10.1016/j.techfore.2015.11.028
13. ACEA: 2021 progress report – making the transition to zero-emission mobility (2021). https://www.acea.auto/publication/2021-progress-report-making-the-transition-to-zero-emission-mobility/
14. Demeulenaere, X.: The use of automotive fleets to support the diffusion of alternative fuel vehicles: a rapid evidence assessment of barriers and decision mechanisms. Res. Transp. Econ. **76**, 100738 (2019). https://doi.org/10.1016/j.retrec.2019.100738
15. Peng, R., Tang, J.H.C.G., Yang, X., Meng, M., Zhang, J., Zhuge, C.: Investigating the factors influencing the electric vehicle market share: a comparative study of the European union and united states. Appl. Energy **355**, 122327 (2024). https://doi.org/10.1016/j.apenergy.2023.122327
16. Maugeri, A., Barchitta, M., Basile, G., Agodi, A.: Applying a hierarchical clustering on principal components approach to identify different patterns of the SARS-CoV-2 epidemic across Italian regions. Sci. Rep. **11**(1), 7082 (2021). https://doi.org/10.1038/s41598-021-86703-3
17. Grein, A.F., Sethi, S.P., Tatum, L.G.: A Dynamic Analysis of Country Clusters, the Role of Corruption, and Implications for Global Firms. East-West J. Econ. Bus **13**(2), 33–60 (2010)
18. Everitt, B., Landau, S., Leese, M.: Cluster analysis, 4th ed. edn. Wiley, Chichester (2011)
19. Saxena, A., et al: A review of clustering techniques and developments. Neurocomputing **267**, 664–681 (2017). https://doi.org/10.1016/j.neucom.2017.06.053

20. Dudek, A.: Silhouette Index as Clustering Evaluation Tool. Studies in Classification, Data Analysis, and Knowledge Organization. Springer (2020). https://doi.org/10.1007/978-3-030-52348-0_2,
21. Rogers, E.M.: Diffusion of Innovations, 5th ed. edn. Free Press, Riverside (2003). https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=4935198

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Impact of Low Emission Zones on Urban Mobility and the Environment

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Abstract. Paris has historically ranked among the most congested cities in the world, with heavy motorized traffic affecting quality of life. In 2024, the city introduced the Zone à Trafic Limité (ZTL), which limits access to the city center by prohibiting most through-traffic while allowing the access of public transport, residents, emergency vehicles, and deliveries. This paper provides a first assessment of the policy's impact on mobility and environmental outcomes using data from the municipality, public transport authority, and air quality observatory. Using a difference-in-differences (DiD) approach, this research compares pre- and post-policy trends between districts inside and outside the ZTL to evaluate effects on motorized traffic, metro ridership, bike usage, and air quality. The analysis finds that motorized traffic within the ZTL fell by 33.5 vehicles per hour post-implementation, a statistically significant decrease. Changes in metro ridership and bike usage were smaller and not statistically significant. Air quality worsened following implementation: PM2.5 increased by 0.529 $\mu g/m^3$ in the ZTL area relative to the control area, significant at the 99.9% level. This suggests the ZTL may have displaced congestion and emissions to surrounding areas. Overall, the findings indicate that complementary policies may be needed to achieve broader sustainability goals.

Keywords: Environment · Low emission zones · Air quality · Urban mobility · Difference-in-differences

1 Introduction

Paris consistently ranks among the most congested cities in the world, with drivers spending an average of 101 h annually in traffic jams [1]. Motorized traffic, henceforth referred to as traffic, is a major source of air pollution, accounting for 19% of the PM2.5 emissions in the Paris area [2]. These pollutants have severe public health implications, contributing to over 2,500 preventable deaths each year in the city [3]. Limiting polluting vehicles in Paris could generate an estimated cost savings of up to €2.36 billion from lowered mortality and €8.3 million from reduced asthma cases [4]. Combined, the productivity losses and health impacts of congestion and air pollution represent a major burden on the city.

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To address congestion and improve air quality, Paris has already implemented a low emission zone (2015), weekend road closures (2016) and speed limit restrictions (2021). Despite these efforts, in 2024, 12.3 million residents of the region were exposed to air pollution levels exceeding World Health Organization recommendations [5]. Congestion and air quality in the city center remain critical challenges, prompting the need for more targeted interventions.

On November 4, 2024, Paris introduced the Zone à Trafic Limité (ZTL), a restricted traffic zone covering around 131 km of roadway in the 1st, 2nd, 3rd, and 4th arrondissements [6]. The policy allows trips that start or end within the ZTL but prohibits through-traffic, with exemptions for public transport, emergency vehicles, and residents. Although the ZTL aims to reduce congestion and air pollution, it has prompted mixed reactions. Critics warn that it may turn central Paris into a tourism-oriented area, face enforcement challenges, shift traffic to neighboring districts, and harm local businesses [7]. These concerns, together with potential plans to expand the ZTL, underscore the need for a robust assessment of the policy's initial impacts.

This study assesses changes in traffic patterns by examining shifts in traffic volumes and modal shares within the ZTL compared to similar control areas. It analyzes public transport and alternative modes by investigating variations in metro ridership and cycling activity following the ZTL's introduction. It also measures environmental benefits by estimating changes in PM2.5 levels.

The analysis utilizes a difference-in-differences (DiD) approach to compare pre- and post-policy trends between the treated and control area, isolating the effects of the ZTL. By exploring the impact of the ZTL on congestion, mobility and air quality, the research seeks to provide insights for future urban mobility policies and initiatives.

2 Study Area and Data

This assessment is restricted to the treated area, defined as the ZTL, and control area, defined as the region outside the ZTL but within Paris. This spatial delineation ensures that the analysis captures the true effects of the policy change.

The study focuses on the 28 days before and after ZTL implementation on November 4, 2024. For metro ridership, bike usage, and air quality, the study period extends from October 7, 2024, to December 1, 2024. For traffic, the study period extends from October 7, 2024, to December 11, 2024 due to a post-implementation data gap. This study period was selected due to data availability and to avoid potential disruptions associated with the Paris 2024 Olympic and Paralympic Games.

The analysis draws on several key datasets. Traffic data from the City of Paris includes the date and hour of measurement, sensor latitude and longitude, and hourly traffic by sensor [8]. Metro ridership data from IDF Mobilités includes the date of measurement, day type (e.g., weekday), stop latitude and longitude, daily number of validations by stop, and percentage of total validations recorded by stop and day type [9]. Bike usage data from the City of Paris includes the date and hour of measurement, counter latitude and longitude, and hourly bike usage by counter [8]. Air quality data from Airparif includes the date and hour of measurement, air quality station latitude and longitude, and hourly PM2.5 pollution by station [10].

These datasets rely on point-based measurements distributed across Paris, ensuring full geographical coverage of the city (see Fig. 1).

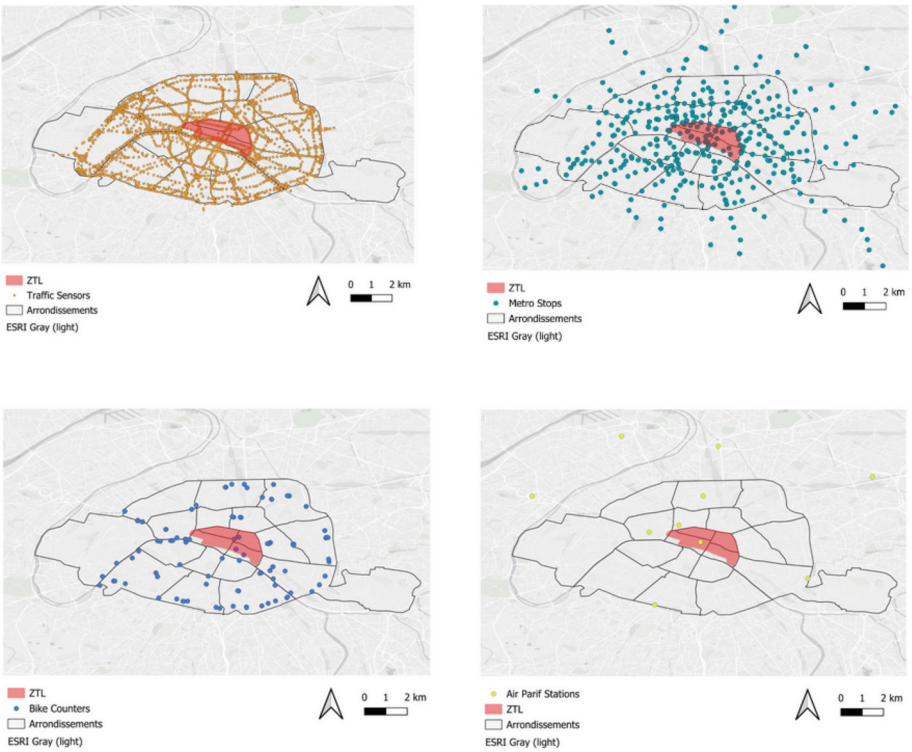


Fig. 1. Counting sites for traffic, metro ridership, bike, and air quality

Data cleaning was performed using Python and QGIS to create consistent datasets for traffic, metro ridership, bike usage, and air quality. Traffic, bike, and metro data were cleaned, geolocated, and aggregated at the arrondissement level. Metro ridership was downscaled from daily to hourly values using day type profiles [11]. Hourly PM2.5 measurements were averaged by station and date, and arrondissement level estimates were generated using inverse distance weighted interpolation from nearby stations. Each dataset was ultimately structured by date, hour, arrondissement, ZTL classification, and the relevant measurement variable.

A descriptive analysis was then conducted to explore spatial and temporal trends in traffic, metro ridership, bike usage, and air quality. The cleaned datasets were imported into RStudio, where summary statistics were computed for each indicator at the arrondissement level. Observations were categorized by treatment group and time period based on arrondissement and date. Box plots were used to compare differences in the four indicators before and after ZTL implementation (see Fig. 2), providing a foundational understanding of data patterns that informed the subsequent analysis.

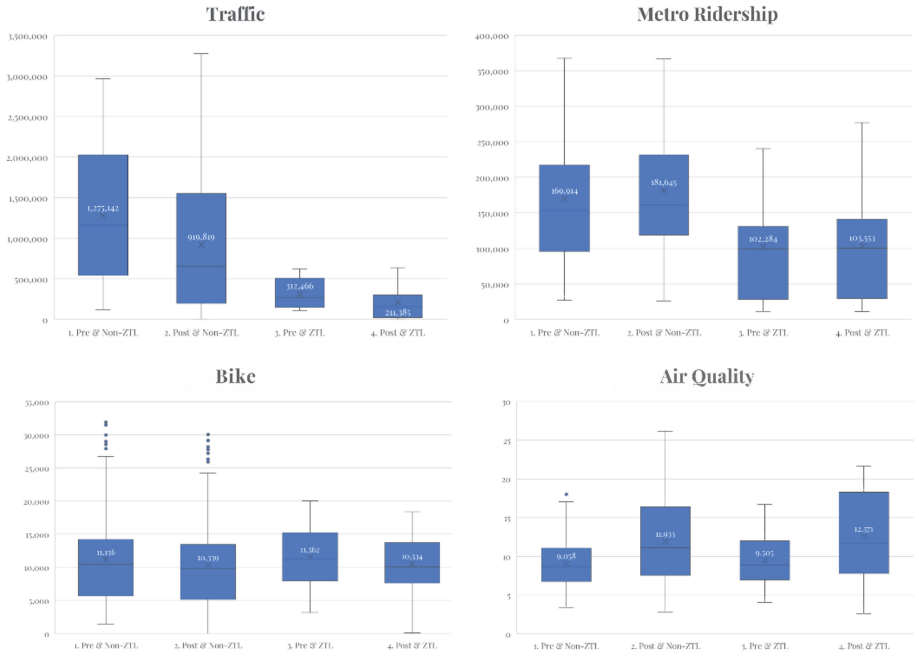


Fig. 2. Distribution of arrondissement-level average daily values for traffic, metro ridership bike, and air quality (PM2.5 concentration in $\mu g/m^3$) pre- and post-ZTL

3 Method and Results

3.1 Modeling Approach

A DiD approach is used to evaluate the impact of traffic restrictions on mobility patterns and air quality [12, 13]. This method uses a regression model to compare trends in the treated group (ZTL) with trends in the control group (non-ZTL) before and after policy implementation. The DiD approach estimates a model of the form:

$$Y_{ith} = \beta_1(ZTL_i \times Period_t) + \gamma_i + \delta_{ht} + \epsilon_{it} \quad (1)$$

The baseline DiD model is specified for each of the four outcome variables. The coefficient of interest is β_1, which captures the causal effect of the ZTL policy on the outcome variable. The parallel trend assumption was validated through visual inspection of pre-treatment patterns for ZTL and non-ZTL arrondissements. By focusing on the interaction term, the DiD model allows for an analysis of the effect of the ZTL policy, controlling for both time-invariant location characteristics and period-specific variations.

The estimators produced by the baseline DiD model could be biased if the changes in outcome variables are observed in both zones and are caused by external factors (e.g., bike counts decreasing in all arrondissements post-ZTL implementation due to winter weather). Thus, a triple DiD model is specified using data from the study period in 2023 and 2024, and including an additional dummy variable $Year_t$indicating whether

the observation occurred in 2024 [14].

$$Y_{ith} = \beta_1(ZTL_i \times Period_t \times Year_t) + \gamma_i + \delta_{ht} + \epsilon_{it} \quad (2)$$

By specifying a triple DiD model, this analysis explores whether post-implementation patterns in the key outcome variables changed in 2024 compared to 2023.

3.2 Descriptive Analysis of Mobility and Air Quality in Paris

Traffic volumes in Paris show strong spatial and temporal variation, with higher levels in peripheral arrondissements, likely reflecting traffic around the Périphérique, the main ring road for suburban commuters. Before ZTL implementation, average daily traffic in non-ZTL arrondissements was nearly four times higher than in ZTL arrondissements. After implementation, average daily traffic declined by 32% in ZTL arrondissements and by 28% in non-ZTL arrondissements, indicating a broader citywide reduction. Metro ridership is relatively evenly distributed between central and peripheral arrondissements. Prior to implementation, average daily ridership in non-ZTL arrondissements was 1.6 times higher than in ZTL arrondissements. Post implementation, ridership increased by 1.2% in ZTL arrondissements and by 4.9% in non-ZTL arrondissements, suggesting a shift from car use to public transport. Before ZTL implementation, average daily bike counts were well-distributed citywide. After implementation, bike counts fell by 11% and 9% in ZTL and non-ZTL arrondissements, respectively, pointing to a citywide decline in cycling likely driven by colder temperatures. Air quality, measured by PM2.5, shows clear spatial patterns, with the lowest concentrations in peripheral arrondissements such as the 12th (11.8 μg/m^3) and the highest in the central 8th arrondissement (18 μg/m^3). Following implementation, average daily PM2.5 increased by 13% in ZTL arrondissements and by 11% in non-ZTL arrondissements, indicating citywide deterioration in air quality. This trend is consistent with seasonal effects, as winter conditions in Paris are associated with higher pollution due to thermal inversions and increased heating emissions [15].

3.3 Difference-in-Differences Analysis

Traffic within the ZTL fell by about 55 vehicles per hour (9.1%) after implementation relative to the control area, statistically significant at the 99.9% level. To test robustness, the baseline DiD analysis is extended to a triple DiD model using 2023 as an additional pre-treatment period. The triple DiD coefficient (−33.5) is smaller than the baseline estimate, indicating that the initial result partly reflected broader traffic trends, but it remains strongly negative and significant at the 99.9% level. This supports the conclusion that the traffic reduction is largely attributable to the ZTL. Metro ridership within the ZTL declined in the baseline DiD model by around 13.4 trips per hour (2.7%) relative to the control area, significant at the 95% level. However, this effect is not statistically significant in the triple DiD analysis ($p = 0.3833$), suggesting that short-term changes in metro ridership are driven by broader temporal trends. Cycling within the ZTL decreased in the baseline DiD model by approximately 9.6 bikes per hour (12.03%) relative to the control area, significant at the 99.9% level, but the effect is not significant in the

triple DiD model ($p = 0.2979$). Given the policy's introduction in early November, this decline coincides with colder temperatures and reduced daylight, indicating that seasonal factors likely explain the observed reduction in bike usage. For air quality, the baseline DiD coefficient is positive (0.162) but not statistically significant ($p = 0.111$). In contrast, the triple DiD model yields a larger and statistically significant increase in PM2.5 levels (0.529, $p = 0.0012$), indicating that air quality within the ZTL deteriorated in 2024 relative to 2023 trends. This may reflect congestion at ZTL boundaries, traffic displacement, or seasonal pollution effects.

Overall, the results (see Tables 1 and 2) indicate that the ZTL is associated with a robust reduction in traffic volumes and a significant increase in PM2.5 concentrations, while short-term effects on metro ridership and bike usage are not statistically significant in the triple DiD specification.

Table 1. Difference-in-differences model results

Outcome variable	Coefficient	t-value	p-value
Hourly Traffic	−54.7	−9.12	<2.2e-16***
Hourly Metro Ridership	−13.4	−2.03	0.043
Hourly Bike	−9.6	−4.09	9.26e-05***
Hourly Air Quality	0.162	1.67	0.11103

Table 2. Triple difference-in-differences model results

Outcome variable	Coefficient	t-value	p-value
Hourly traffic	−33.5	−3.82	<0.001***
Hourly metro ridership	17.7	0.873	0.383
Hourly bike	−4.26	−1.05	0.29791
Hourly air quality	0.5289	3.79	0.0001223**

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4 Discussion and Conclusion

The analysis suggests that implementing the ZTL in Paris has reduced traffic in the city center, with limited evidence of short-term impacts on other mobility modes. The triple DiD approach confirms a statistically significant additional reduction in traffic within the ZTL post-implementation. Though bike and metro ridership exhibited a statistically significant decline relative to the control area post-implementation, this effect diminished in the triple DiD specification, indicating that external factors like weather may be driving the observed trends. Air quality worsened citywide, consistent with patterns of higher PM2.5 levels during colder weather [16]. However, the statistically significant

effect observed in the triple DiD model indicates that these external factors cannot fully explain the PM2.5 trend. The ZTL may have exacerbated congestion and emissions at its boundaries or along alternative routes, amplifying citywide trends linked to exogenous factors like weather.

Several limitations warrant cautious interpretation and point to avenues for further research. First, the short post-implementation period may not capture longer term adaptation effects. Second, the traffic observation period differs due to a sensor-induced data gap, potentially introducing model inconsistency. Third, although the downscaling methods used to increase the spatial and temporal resolution of air quality and metro data are consistent with prior empirical research, they may reduce precision for these variables. Fourth, the study does not assess impacts on pedestrian traffic in Paris. Finally, the analysis relies exclusively on quantitative methods. While statistical modeling provides robust empirical insights, an interdisciplinary approach could offer a more comprehensive understanding of the ZTL's effects.

Future research should therefore (1) use a full year of data before and after implementation to account for seasonal effects and behavioral adjustments, (2) incorporate more granular air pollution data and actual hourly ridership counts to improve estimates, (3) include data on pedestrian patterns within the ZTL to capture effects on other non-motorized transport modes, and (4) integrate qualitative methods such as interviews, field studies, and questionnaires to contextualize the findings. Addressing these limitations would support a more robust understanding of the ZTL's impact and inform evidence-based urban mobility policy.

In the short-term, the analysis demonstrates that the ZTL has successfully reduced traffic, but has not yet improved air quality. The limited evidence of shifts in bike usage and metro ridership is consistent with behavioral changes, which often require longer time horizons, complementary incentives, or improvements in service quality and infrastructure. In the long-term, additional measures may be needed to promote sustainable mobility and improve air quality. The ZTL is already well-served by metro stops, but enhancing service frequency to reduce overcrowding and improving safety may also incentivize greater public transport use. The city can also encourage metro use by improving affordability, which is especially relevant for low-income households impacted by metro fare increases in early 2025 in Paris.

Finally, to mitigate spillover pollution, the city can establish secondary low-emission zones (LEZs) directly outside the ZTL, restricting access for high-emission vehicles while allowing low-emission alternatives. Given that air quality within the ZTL worsened post-implementation, a targeted LEZ around the ZTL border would help limit pollution spillover from rerouted traffic. Additionally, since traffic counts were highest in peripheral arrondissements, Paris should consider expanding LEZs to these high-traffic outer areas. By simultaneously strengthening restrictions around the ZTL while addressing peripheral high-traffic zones, Paris can balance accessibility with air quality objectives. Overall, complementary investments in transportation infrastructure and policy will be essential to ensuring the ZTL supports sustainable mobility and enhances air quality in the long run.

References

1. TomTom: 2024 Traffic Index Ranking. https://www.tomtom.com/traffic-index/ranking/. Accessed 10 Aug 2025
2. Leroutier, M., Quirion, P.: Air pollution and CO_2 from daily mobility: who emits and why? Evidence from Paris. Energy Econ. **109** (2022). https://doi.org/10.1016/j.eneco.2022.105941
3. Khomenko, S., et al.: Premature mortality due to air pollution in European cities: a health impact assessment. Lancet Planet. Heath. **5**(3), 121–134 (2021). https://doi.org/10.1016/S2542-5196(20)30272-2
4. Moreno, E., Schwarz, L., Host, S., Chanel, O., Benmarhnia, T.: The environmental justice implications of the Paris low emission zone: a health and economic impact assessment. Air Qual. Atmos. Health. **15**, 2171–2184 (2022). https://doi.org/10.1007/s11869-022-01243-7
5. Airparif: Bilan de la qualité de l'air en Île-de-France. https://www.airparif.fr/etudes/2025/bilan-de-la-qualite-de-lair-ile-de-france-2024. Accessed 21 Aug 2025
6. Ville de Paris: La Zone à Trafic Limité en vigueur dans le centre de Paris: comment ça marche?. https://www.paris.fr/pages/paris-cree-une-zone-apaisee-dans-le-centre-de-la-capitale-20426#les-derogations. Accessed 10 Aug 2025
7. Raynaud, H.: Zone à trafic limité dans l'hypercentre de Paris. https://www.liberation.fr/economie/transports/zone-a-trafic-limite-dans-lhypercentre-de-paris-a-terme-les-gens-vont-utiliser-dautres-modes-de-deplacement-20241104_FR2XKV7EXZCKFP3CIHB6CFMGSM/. Accessed 10 Aug 2025
8. City of Paris: Paris Open Data. https://opendata.paris.fr/pages/home/. Accessed 19 Feb 2025
9. Île-de-France Mobilités: Open Data Portal. https://data.iledefrance-mobilites.fr/pages/home/. Accessed 19 Feb 2025
10. Airparif: Airparif Portal. https://data-airparif-asso.opendata.arcgis.com/. Accessed 19 Feb 2025
11. Denby, B.R., et al.: Description of the uEMEP_v5 downscaling approach for the EMEP MSC-W chemistry transport model. Geosci. Model Dev. **13**(12), 6303–6323 (2020). https://doi.org/10.5194/gmd-13-6303-2020
12. Sarmiento, L., Wägner, N., Zaklan, A.: The air quality and well-being effects of low emission zones. SSRN Electron. J. (2023). https://doi.org/10.2139/ssrn.4142070
13. Zhai, M., Wolff, H.: Air pollution and urban road transport: evidence from the world's largest low-emission zone in London. Environ. Econ. Policy Stud. **23**(4), 721–748 (2021). https://doi.org/10.1007/s10018-021-00307-9
14. Liang, Y., et al.: Panacea or placebo? Exploring the causal effects of nonlocal vehicle driving restriction policies on traffic congestion using a difference-in-differences approach. Transportation. **51**(6), 2253–2275 (2024). https://doi.org/10.1007/s11116-023-10404-1
15. Bessagnet, B., et al.: Origin of particulate matter pollution episodes in wintertime over the Paris Basin. Atmos. Environ. **39**(33), 6159–6174 (2005). https://doi.org/10.1016/j.atmosenv.2005.06.053
16. Rowland, O.E.: Comparative analysis of meteorological parameters and their relationship with NO_2, PM_{10}, $PM_{2.5}$ and O_3 concentrations at selected urban air quality monitoring stations in Krakow, Paris, and Milan. Discover Environ. **2**(1) (2024). https://doi.org/10.1007/s44274-024-00060-2

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From Feasibility to Profitability: Economic Evaluation of On-Board H_2 Production for Rail Operators

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Abstract. Building on TRA2024 publication "Technico-economic Feasibility Study of On-board H2 Production in a Passenger Hydrogen Train for Railway Operators" [1], which demonstrated the feasibility of on-board hydrogen production for regional trains, this work compares three decarbonization solutions: a bi-mode hydrogen train (Régiolis H_2), a newly sized all-battery train, and a reversible hydrogen train. These alternatives were evaluated across 13 challenging French routes, selected for their length and limited electrification. For each solution, we assessed CAPEX (electrification, depot upgrades, hydro gen infrastructure) and OPEX (maintenance and energy costs over the rolling stock's mid-life). Results reveal distinct trade-offs: the Régiolis H_2 is optimal for shorter unelectrified sections due to lower rolling stock costs but requires hydrogen infrastructure; the all-battery train offers extended range with minimal infra-structure, though at higher individual costs; and the reversible hydrogen train emerges as a versatile compromise, eliminating hydrogen infrastructure needs while providing greater range—though dependent on on-board electrolysis R&D. This analysis provides actionable insights for railway operators investing in decarbonization technologies.

Keywords: hydrogen & batteries trains · technico-economic feasibility · railway operations decarbonization

1 Introduction

1.1 Introduction

Rail is already a low-carbon emission means of transport. However, about 45% of the network is not electrified (around 15% of rail traffic) and still relies on diesel trains.

By 2030, SNCF Group will have to reduce its greenhouse gas emissions from transport by 30% vs. 2015, in line with the 2015 Paris Agreement objective of carbon neutrality by 2050. While full network electrification would be the most effective solution for reducing CO_2 emissions, the required investment makes it economically unrealistic.

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Several alternatives are currently being tested, including biofuels, battery trains with partial electrification, hybrid systems, and hydrogen trains such as the *Régiolis* H_2. As no single solution fits all operational contexts, a case-by-case analysis is required. For use cases requiring high autonomy, hydrogen trains are foreseen as more suitable. However, infrastructure cost (ie. Refueling station) is an economic lock to its deployment. This study therefore investigates the potential of onboard hydrogen production using existing infrastructure (ie. Catenary) to reduce infrastructure investments and increase operational autonomy.

This paper presents the range of applications of the so-called reversible hydrogen train compared to Régiolis H_2 and battery trains with a power car.

1.2 State-of-the-Art

While the Alstom Coradia iLint represents the first commercially operated hydrogen train in Germany, numerous hydrogen train prototypes are being tested worldwide, particularly bi-mode systems (catenary-hydrogen) such as the Régiolis H_2 in France, or FCH2Rail in Spain [2], as well as prototypes across Europe, Japan, and China [3]. None incorporate on-board electrolysers.

Current studies on hydrogen supply strategies for railways focus solely on infrastructure, examining either on-site production [4] or distribution chains [5]. In contrast, this study, building on Villaume et al. [1], uniquely investigates on-board hydrogen production to eliminate dependency on costly, immature hydrogen infrastructure that currently hinders railway hydrogen implementation [5].

2 Hypotheses and Methodology

2.1 Preliminary Sizing of the H2 Reversible and all-Battery Trains

H2 Reversible Design. The first step finalizes the reversible hydrogen train concept proposed by Villaume et al. [1]. All hydrogen equipment—electrolyser, fuel cells, compressors, and tanks—is integrated into a dedicated power car, freeing space in the end cars previously occupied by hydrogen components in the *Régiolis* H_2 and allowing the installation of additional battery packs. To meet the *Régiolis* H_2's axle load and power requirements, the same energy-dense battery packs as those used in the all- battery design are adopted (detailed in the following section). The final configuration is summarized in Table 1.

All-Battery Design. The second alternative to the Régiolis H_2 explored in this study mirrors the reversible train's configuration and replaces all hydrogen system with energy-dense batteries, with identical total mass.

While current battery-electric trains mainly use LTO batteries for their high-power density, their limited energy density restricts range to typically below 100 km [6]. With the addition of a power car, allowing for higher permissible mass and volume, NMC batteries —known in automotive applications for their high energy density and low power density—emerge as a viable alternative for increasing the train's range.

Among several automotive-grade options, a modular truck battery pack [7] was selected for its scalability and integration potential. Each pack delivers 93 kW of power, with a usable capacity of 84 kWh (93 kWh nominal) and a mass of 617 kg. Simulations accounted for end-of-life degradation, assuming an industry-standard 20% capacity loss, reducing usable capacity to 67.2 kWh per pack.

Due to stricter railway safety regulations, protective layers account for 50% of train battery pack weight, compared to 40% in road applications, per SNCF experts. Thus, the mass of the automotive battery packs was adjusted by a 6/5 factor to account for their railway adaptation. Additionally, thermal management systems and converters, also specified by SNCF experts, are included in the total weight.

Table 1. Comparison of the three model configurations

Component	Régiolis H_2	H2 Reversible	All-battery
Fuel cell	**660 kW**	**660 kW**	N/A
Hydrogen tanks	32 tanks, **160 kg usable**	24 tanks, **120 kg useable**	N/A
Electrolysers	N/A	2 x 500 kW = **1 MW**	N/A
Battery type and capacity	LTO, **200kWh**	20 NMC packs, **1344kWh usable** (end-of-life)	56 NMC packs (inc. 36 in power car) **3763kWh usable** (end-of-life)
Total weight	183 t	183 t + 44 t (P.C) = 227 t	183 t + 44 t = 227 t

2.2 Infrastructure Requirement Assessment

The second step of the study involved simulating train operations on 13 existing daily routes to evaluate the additional infrastructure requirements for replacing diesel trains with the *Régiolis* H_2, H2 Reversible and all-battery trains. These routes were intentionally selected as long and poorly electrified, making them particularly challenging to decarbonize. On average, they cover 748 km over 13.6 h, with less than one-third of their length electrified.

Simulations used the algorithm developed by Villaume et al. [1] with operational data of regular bi-mode electro-diesel *Régiolis* trains, provided by SNCF, including train status, position, power demand, and catenary use. Power demand was adjusted to account for the additional weight of the power car and to maximize the use of existing and planned electrified sections. The simulations maintained identical operational conditions to electro-diesel *Régiolis* trains to avoid introducing delays affecting operations (Fig. 1).

Since train configurations are fixed, feasibility relies on adding infrastructure. The process identifies power and energy shortages and, when necessary, upgrades depots with fast-charging equipment, electrifies depots, extends existing electrified sections, or installs isolated catenary segments, with one substation installed approximately

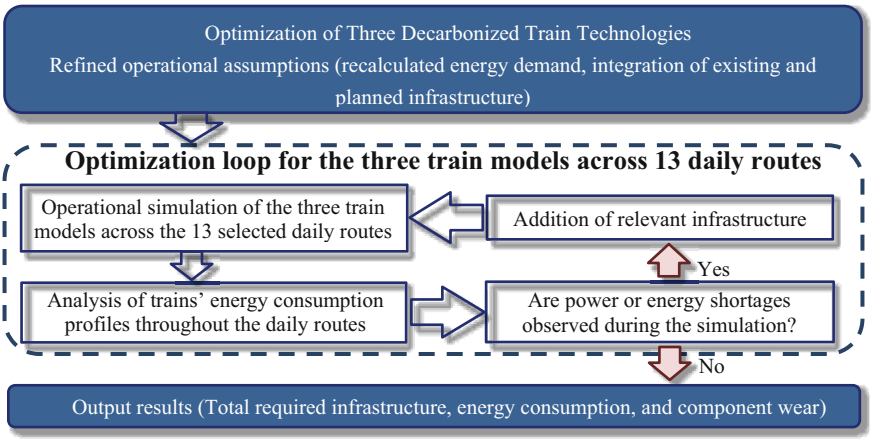


Fig. 1. Process diagram of the infrastructure addition assessment method

every 35 km of catenary according to SNCF Réseau experts. A scenario is considered successful if no power shortages occur and the train can fully recharge within 24 h.

For the *Régiolis* H_2, this required systematically adding a fueling station at the train overnight parking area, also usable during stops longer than 30 min – the standard hydrogen fueling time. For reversible and all-battery trains, this constraint sometimes necessitated installing fast-charging docks at depots. These docks enable static power draw of up to 1.5 MW from the catenary – compared to the standard 480 kW – by mitigating overheating at the contact point.

2.3 Total Cost Assessment

The previous step was aimed at determining the required infrastructure addition for each train to operate in place of electro-diesel *Régiolis*. This step evaluates the cost impact of operating each train model over the half-life of a train, 20 years, including CAPEX and OPEX, but excluding development costs.

CAPEX includes the additional cost of rolling stock relative to the *Régiolis* H_2 (e.g., power car and batteries), as well as the cost of added infrastructure. OPEX includes maintenance of additional components, end-of-life replacements, and energy consumption. Both CAPEX and OPEX are therefore assessed on a comparative basis, accounting only for items that differ between train models.

Based on SNCF public data [8], normal operation of a line requires 6 to 9 trains. Each daily route was therefore modeled with 7 trains, assuming 310 operating days per year over a 20-year horizon, based on SNCF Voyageurs data. For each train, the simulation computed energy demand for hydrogen and electricity, as well as NMC battery and fuel cell wear. Battery lifetime was set at 4,000 charge–discharge cycles to 20% capacity loss, while fuel cells were assumed to last 15,000 operating hours, according to e-mobiTech datasheets and SNCF expertise.

Table 2. List of components and consumable individual costs, industry-standard estimates

	Component	Individual cost	Yearly maintenance cost factor
Rolling-stock	Fuel cell	1,200 €/kW	6% of CAPEX
	Hydrogen circuit	15,000 €	6% of CAPEX
	Hydrogen tanks	400 €/kg capacity	6% of CAPEX
	Electrolyser	1,000,000 €/MW	6% of CAPEX
	Hydrogen compressor	38,657 €/unit	6% of CAPEX
	Energy dense battery	1,500 €/nominal kWh	5% of CAPEX
	Power dense battery	1,000 €/kW	5% of CAPEX
	BTMS	30,000 €/kW	5% of CAPEX
	Converter	100,000 €/unit	5% of CAPEX
	Car chassis	2,000,000 €/unit	5% of CAPEX
Infrastructure	Catenary installation	1,000,000 €/km	3,300€/km/year
	Hydrogen fueling station	8,000,000 € for 3 full tanks daily	6% of CAPEX
	Substation	5,500,000 €/unit	300,000€/unit/year
	Fast charge depot installation	5,000,000 €/depot	5% of CAPEX
Energy	Hydrogen	10€/kg	N/A
	Electricity	105.3 €/MWh	N/A

The base cost of a hydrogen fueling station is 8 million euros for a station capable of fully fueling 3 trains a day (480 kg hydrogen output). This cost was assumed to be proportional to the station's hydrogen capacity.

Electricity costs are based on SNCF forecasts for 2027. Hydrogen cost was taken as an average estimate from a study by Caponi et al. [9], comparing different fueling station types such as on-site production and trailer delivery.

Battery costs are based on NMC battery cost projections from Lukas Mauler et al. [10], adjusted upward by a factor of 5 to 10 according to SNCF experts to account for the complexity of railway integration and small production volumes.

This assessment is comparative and only includes costs that vary between solutions. It excludes shared costs, such as the base cost of the 4-car *Régiolis* train and regular commercial operating expenses.

3 Results and Analyses

Following the configurations and reference costs detailed in Tables 1 and 2, the comparative cost of each configuration was assessed on all 13 daily routes for a fleet of 7 trains over 20 years (Table 3).

Table 3. Total comparative cost and electrification addition for *Régiolis H*$_2$, H2 Reversible and All-battery trains on each daily route, over 20 years. (7 trains per route, 1500€/kWh battery packs, 10€/kg H2, 105.3€/MWh electricity)

Route No.	Length (km)	*Régiolis H*$_2$	H2 Reversible	All-battery
1	303	131.9 M€ / 11 km	141.6 M€	152.5 M€
2	423	146.0 M€	162.0 M€	163.5 M€
3	587	155.6 M€	156.9 M€	169.2 M€
4	593	237.4 M€	211.0 M€ / 7 km	178.7 M€
5	679	134.6 M€	151.0 M€	195.3 M€
6	682	225.8 M€ / 48 km	169.8 M€	193.0 M€
7	716	240.1 M€ / 49 km	190.1 M€ / 1 depot	211.8 M€ / 1 depot
8	742	147.3 M€	161.1 M€	168.2 M€
9	895	185.5 M€ / 11 km	174.5 M€	209.7 M€
10	942	204.8 M€ / 11 km	186.7 M€	216.1 M€
11	977	288.4 M€ / 68 km	244.5 M€ / 1 depot	258.5 M€ / 1 depot
12	989	170.0 M€ / 50 km	152.4 M€	215.2 M€
13	1193	278.5 M€ / 58 km	219.7 M€	276.1 M€
	TOTAL	2542.4 M€ / 312 km	2321.3 M€ / 7 km	2607.9 M€ / 0 km

Overall, only the *Régiolis H*$_2$ requires substantial infrastructure – 39 km on average– on eight of the routes, and systematic fueling stations. However, its rolling stock costs 1.9 M€, compared to 7.2 M€ and 10.1 M€ for the reversible and all-battery trains, respectively. Thus, the *Régiolis H*$_2$ is competitive on the five least demanding routes, while the H2 Reversible has the advantage on all but one of the other challenging routes. With a more expensive rolling stock, CAPEX and part replacement included, heavily affected by battery costs, the all-battery train is only competitive on Route 4, where the other trains require a large fueling station and a fast-charging dock (Fig. 2).

Sensitivity Analysis. To capture the uncertainty and variability in future operational conditions, a sensitivity analysis was conducted on 3 critical cost drivers by varying hydrogen and electricity prices independently by ±50% (hydrogen: €5–15/kg; electricity: €52.65–158.0/MWh), NMC battery costs between €1000 and €2000/kWh, and fleet size from 1 to 9 trains, corresponding to a full fleet replacement scenario (Fig. 3).

Electricity costs only marginally affect the relative cost of the 3 trains, while hydrogen costs are decisive for the *Régiolis H*$_2$, which is only competitive below €12/kg.

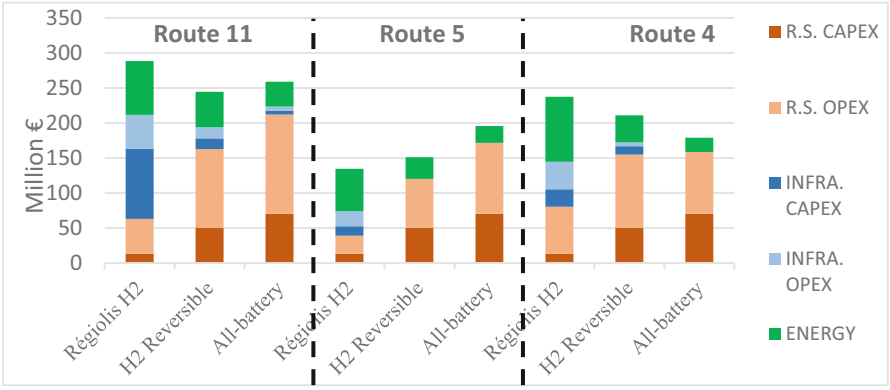


Fig. 2. Detailed cost distribution over 20 years of the three train models on Granville – Paris, La Rochelle – Bordeaux and Rodez – Toulouse – Auch 7 trains, 1500€/kWh battery packs, 10€/kg H2, 105.3€/MWh electricity

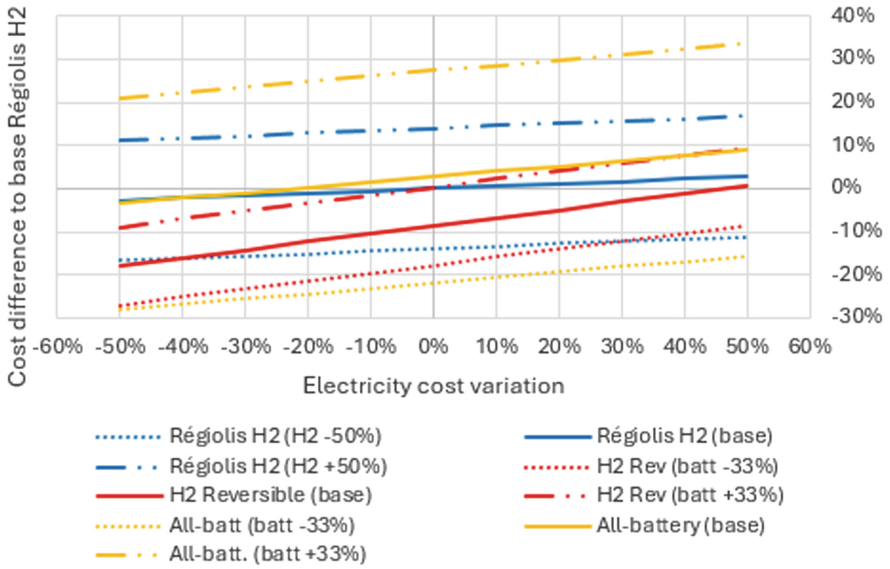


Fig. 3. Total cost of H2 Reversible, all-battery and *Régiolis* H_2 trains, relative to reference case, as a function of battery and energy costs. - Hypotheses: 7 trains, 20 years operation - Reference case: *Régiolis* H_2, 10€/kg_H2, 105.3€/MWh electricity

A 33% battery cost reduction would lower total costs by 20–25% for the all-battery trains making it competitive for the first time and about 10% for H2 Reversible trains.

The Régiolis H2 becomes always more cost-effective from 5 trains a day.

4 Limitations and Conclusion

This study should be regarded as a preliminary investigation based on assumptions whose validity will need to be tested against future technical, economic, and operational developments. In particular, energy prices—which strongly influence the total cost of ownership (TCO) of rail vehicles—remain highly volatile and depend on multiple external factors, including geopolitics, technological progress, and the logistics of energy production and distribution. Moreover, the present economic assessment excludes research and development costs, notably those associated with the onboard electrolysers, the integration of NMC batteries, and the safety requirements inherent to railway applications. These omitted factors could significantly affect the actual cost of the proposed prototypes.

Moreover, the operational analysis must also be interpreted with caution, as the 13 routes examined here are especially demanding and are not representative of the French rail network. In practice, hydrogen-powered rolling stock was conceived to operate on most of French regional services. From an environmental perspective, although these prototypes are aligned with decarbonization and carbon-neutrality objectives, no life cycle assessment has yet been carried out.

According to Alstom's criterion, catenary installation is justified when traffic exceeds one train per hour on a given section. Below this threshold, the three alternatives examined in this paper may constitute relevant solutions, depending on the service profile. From an operational standpoint, the results support a differentiated technological strategy as the best solution changes regarding the number of trains a day as well as the profile of the route and its existing infrastructure. The result also depends on the levels of electricity, batteries and hydrogen prices.

The *Régiolis* H_2 appears well suited to partially electrified routes, and rather competitive for more than 5 trains a day, but its dependence on hydrogen refueling infrastructure, complex logistics, and limited capability under demanding mountainous conditions may constrain its deployment. The NMC battery train offers high autonomy and power, making it attractive for long, weakly electrified, and steep routes, although a high rolling-stock cost makes it uncompetitive except for optimistic batteries cost scenarios. The hydrogen reversible train emerges as the most versatile option, combining long range, high power, regenerative braking potential, and flexibility in refueling strategy. Nevertheless, this concept remains at conceptual stage and will require substantial further research and development before practical deployment becomes feasible.

References

1. Villaume, S., Foncin, C., Dalbavie, J.-M.: Technico-economic feasibility study of on-board H_2 production in a passenger hydrogen train for railway operators. In: Transport Research Arena Conference, pp. 308–315. Springer, Dublin (2024)
2. Preston, R.: FCH2Rail completes hydrogen fuel cell trials. Int. Railw. J. **65**(2), 24–30 (2025)
3. Nqodi, A., Mosetlhe, T.C., Yusuff, A.A.: Advances in hydrogen-powered trains: a brief report. Energies. **16**(18), 6715 (2023)
4. Funez Guerra, C., Reyes-Bozo, L.: Sustainability of hydrogen refueling stations for trains using electrolysers. Int. J. Hydrog. Energy. **46**(26), 13748–13759 (2021)

5. Xu, Z. et al.: Hydrogen supply chain for future hydrogen-fuelled railway in the UK: transport sector focused. Int. J. Hydrog. Energy. **86**, 1–13 (2024)
6. SNCF Voyageurs et Alstom présentent le premier des cinq trains à batteries commandés. https://www.alstom.com/fr/press-releases-news/2023/10/. Accessed 10 Sep 2025
7. NMC930. https://e-mobitech.com/nmc-930-battery-93kwh-622v/. Accessed 26 Sep 2025
8. SNCF Data. https://ressources.data.sncf.com/pages/accueil/. Accessed 12 Sep 2026
9. Caponi, R., Monforti Ferrario, A., Del Zotto, L., Bocci, E.: Hydrogen refueling station cost model applied to five real case studies for fuel cell buses. In: E3S Web Conference on 76th Italian National Congress ATI, vol. 312, (2021)
10. Mauler, L., Duffner, F., Zeier, W.G., Leker, J.: Battery cost forecasting: a review of methods and results with an outlook to 2050. Energy Environ. Sci. **14**, 4712–4739 (2021)

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Decarbonizing Portugal's Taxi Fleet via Public Incentives: An Empirical Policy Evaluation

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Abstract. Urban taxi fleets represent a high-impact segment for transport decarbonisation due to their intensive urban operation and high annual mileage. In Portugal, the Public Transport Fund (PTF), managed by the Institute for Mobility and Transport (IMT, I.P.), has provided targeted incentives for taxi electrification since 2018, combining subsidies for electric vehicle (EV) acquisition, scrappage of fossil-fuel vehicles, and co-financing of charging infrastructure. Between 2018 and 2025, 378 applications were approved, supporting 378 electric taxis, 96 vehicle scrappages, and 227 charging systems, with total public disbursements of approximately €2.54 million.

Using a conservative baseline of 6.0 tCO_2 per conventional taxi per year, cumulative avoided tailpipe emissions for 2018–2025 are estimated at approximately 2,000 tCO_2eq, with accelerated adoption scenarios projecting cumulative savings exceeding 8,000 tCO_2eq by 2030.

The article evaluates programme uptake, environmental effectiveness, financial efficiency, and international positioning. Results indicate accelerating uptake since 2023 but still limited fleet penetration relative to Portugal's ~12,000 licensed taxis. While infrastructure deployment has progressed significantly, cost-effectiveness remains above international benchmarks, reflecting the early-stage scale of the programme. Policy implications highlight the importance of scaling incentives, integrating regulatory measures such as ZE-only licensing, and aligning national support schemes with EU climate and transport frameworks.

Keywords: Taxi · Electrification · Incentives · Portugal · Decarbonisation

1 Introduction

Urban mobility decarbonisation is a central climate policy challenge, particularly in high-intensity urban services such as taxis [1, 2]. Owing to their high annual mileage and continuous operation, taxi fleets represent a strategic segment for early electrification, as emission reductions per vehicle are significantly higher than in private passenger cars [3, 4].

Across Europe, financial incentives and regulatory measures have been used to accelerate taxi and fleet electrification. Empirical evidence suggests that uptake is stronger where direct financial support is combined with regulatory certainty, such as low-emission zones or zero-emission licensing requirements [5, 6].

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International experience indicates that the most effective transitions combine financial incentives with binding regulatory frameworks, creating stable investment signals and reducing long-term public abatement costs [7, 8]. However, empirical evaluations of sector-specific electrification incentives for professional urban fleets remain limited, particularly in medium-sized European markets.

In Portugal, the Public Transport Fund (PTF), managed by the Institute for Mobility and Transport (IMT, I.P.), has provided targeted incentives for taxi fleet renewal since 2018. The programme supports electric vehicle (EV) acquisition, fossil-fuel vehicle scrappage and charging infrastructure deployment. Between 2018 and 2025, 378 applications were approved, supporting 378 electric taxis, 96 scrappages and 227 charging systems, with total public expenditure of approximately €2.54 million. Although uptake has accelerated since 2023, the scale remains modest relative to Portugal's approximately 12,000 licensed taxis (Table 1) [9].

Table 1. Financial incentives for taxi fleet electrification under the PTF (2018–2025).

Year	Electric vehicle (€)	Scrappage (€)	Charging (€)
2018	€ 5,000	€2,500 (vehicles ≥10 years) €5,000 (vehicles ≥15 years) €7,500 (vehicles ≥20 years)	100% of eligible costs, up to €5,000
2019			100% of eligible costs, up to €2,000
2020–2024		€2,500 (vehicles ≥10 years) €5,000 (vehicles ≥12 years)	100% of eligible costs, up to €1,000
2025	€5,000 or €6,000 (low-density municipalities)	€6,000 (vehicles ≥10 years)	75% of eligible costs, up to €750

This paper evaluates programme uptake, environmental effectiveness and financial efficiency, complemented by forward-looking emissions scenarios for 2026–2030. By combining data analysis, emission estimation and international benchmarking, the study provides an empirical policy evaluation of taxi fleet electrification in Portugal. The study contributes to the emerging literature on electrification of high-mileage professional fleets by providing one of the first empirical assessments of a national taxi electrification incentive programme.

2 Methodology

Recent modelling studies confirm that electrifying high-mileage taxi fleets delivers substantially larger emission reductions than private vehicle electrification [3].

This study adopts a mixed-methods approach, combining quantitative analysis of official Public Transport Fund (PTF) data with qualitative contextualisation. Administrative records for the period 2018–2025 report 378 approved applications, 96 scrapped taxis, 227 charging systems and total disbursements of €2.54 million. Complementary emission parameters are drawn from the European Environment Agency, International Energy Agency and International Transport Forum [2, 10, 11].

Avoided emissions are estimated based on the replacement of conventional diesel taxis by battery electric vehicles (EVs), reflecting the operational intensity of professional taxi services. The analysis focuses on Tank-to-Wheel (TTW) emissions, consistent with EU regulatory accounting frameworks for road transport decarbonisation and commonly applied in transport policy impact assessment.

A conservative Tank-to-Wheel (TTW) emission factor of 6.0 tCO_2 per taxi per year is adopted, derived from average fleet-weighted diesel emissions (≈120 gCO_2/km) and annual taxi mileage (≈50,000 km): 50,000 km × 120 gCO_2/km ≈ 6.0 tCO_2/year.

The 6.0 tCO_2 value reflects a conservative baseline assumption derived from average diesel emission factors and observed taxi mileage [10, 12], used for programme impact calculation. By contrast, the 9.7 tCO_2 figure presented later reflects the fleet-wide weighted average derived from national fleet activity and emission statistics [9, 10].

Considering the phased introduction of 378 electric taxis between 2018 and 2025, cumulative avoided emissions are estimated at approximately 2,000 tCO_2eq, accounting for progressive annual stock growth rather than assuming full-year impact from 2018. Forward projections indicate that 200 additional electric taxis by 2030 would increase cumulative savings beyond 8,000 tCO_2eq. Future refinements will apply COPERT (2025) emission factors once disaggregated fleet composition and mileage data become available.

Financial efficiency is assessed by dividing cumulative programme expenditure by avoided TTW emissions, yielding an average abatement cost of approximately €1,270/tCO_2eq. This follows a marginal abatement cost (MAC) framework widely applied in transport decarbonisation assessment [8], enabling comparison across technologies and policy instruments.

This value exceeds cost-effectiveness ranges typically reported in European regulatory and independent assessments of large-scale passenger vehicle electrification (€100–€250/tCO_2) [1, 7]. However, the higher figure observed in the Portuguese taxi programme reflects early-stage implementation, limited scale and gradual stock accumulation rather than structural inefficiency of electrification as a mitigation strategy. Economic modelling of fleet electrification pathways highlights the importance of scale effects and regulatory certainty in reducing marginal abatement costs over time [3, 4].

The analysis relies on average mileage and emission factors and does not differentiate between urban and rural taxi operation. Sensitivity analysis varying annual mileage between 50,000 and 65,000 km does not alter the relative ranking of scenarios, affecting only proportional emission magnitudes. This analytical framework enables reproducible estimation of emission impacts and policy cost-effectiveness using publicly available programme data.

3 Results

Uptake remained modest between 2018 and 2022, with 63 electric taxis supported in total. A marked expansion occurred from 2023 onwards. In 2023, 81 electric taxis were supported, followed by 87 in 2024 and 147 in 2025 (+67% year-on-year). Despite this acceleration, electric taxis still represent less than 2% of Portugal's approximately 12,000 licensed taxis [9].

As shown in Table 2, programme strengthening after 2023 is evident in all components.

Table 2. Support given by PTF along the years by component (EV, scrappage and charging).

Year	Electric taxis		Scrappage		Charging systems		Total support r/o
	No	€	No	€	No	€	
2018	10	40 000.00 €	2	12 500.00 €	5	11 090.71 €	63 590.71 €
2019	18	90 000.00 €	11	67 500.00 €	12	11 984.15 €	169 484.15 €
2020	9	35 000.00 €	5	25 000.00 €	5	2 502.67 €	62 502.67 €
2021	12	60 000.00 €	1	5 000.00 €	9	5 669.68 €	70 669.68 €
2022	14	70 000.00 €	4	20 000.00 €	11	5 939.65 €	95 939.65 €
2023	81	405 000.00 €	16	77 500.00 €	44	22 844.09 €	505 344.09 €
2024	87	435 000.00 €	16	77 500.00 €	50	25 616.56 €	538 116.56 €
2025	147	754 000.00 €	41	246 000.00 €	91	38 810.60 €	1 035 810.60 €
Total	**378**	**1 889 000,00 €**	**96**	**531 000,00 €**	**227**	**121 458,11 €**	**2 541 458,11 €**

In 2025, the scrappage incentive increased from €5,000 to €6,000 per vehicle, raising its share of total programme expenditure to approximately 20%, while the share allocated to EV acquisition declined to 76%, as illustrated in Fig. 1.

During the programme's early phase, charging infrastructure support accounted for 17% of total expenditure in 2018. Scrappage incentives also represented a significant share in 2019–2020, when higher payments were available for older vehicles [1, 7].

Taxi services operate at substantially higher intensity than private vehicles, a pattern also observed in other high-mileage urban commercial fleets such as delivery vehicles [13]. Empirical evidence for Portugal indicates annual taxi mileage between 54,000 and 65,000 km [12], consistent with international estimates of 50,000–70,000 km/year in dense urban areas [14]. Assuming an average annual mileage of approximately 60,000 km and a fleet of roughly 12,000 taxis [9], total annual taxi activity amounts to approximately 0.72 billion vehicle-kilometres.

Applying indicative tank-to-wheel (TTW) emission factors [2, 10, 11] yields annual emissions of approximately 116 ktCO_2, corresponding to a fleet-weighted intensity of around 161 gCO_2/km and 9.7 tCO_2 per taxi per year. Diesel vehicles account for approximately 98% of these emissions, highlighting the substantial mitigation potential of electrification in this segment.

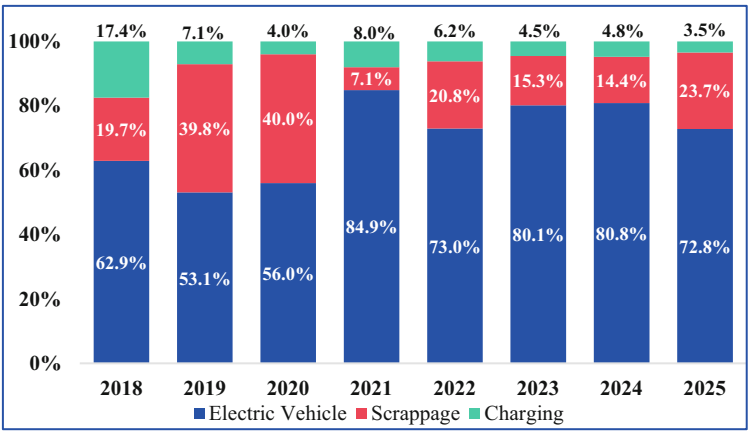


Fig. 1. Weights of different components of support.

Figure 2 presents projected taxi TTW emissions in Portugal for 2026–2030 under three policy scenarios, using final 2025 programme outcomes as the empirical baseline. The 2026 starting level reflects the additional electric taxis introduced in 2025.

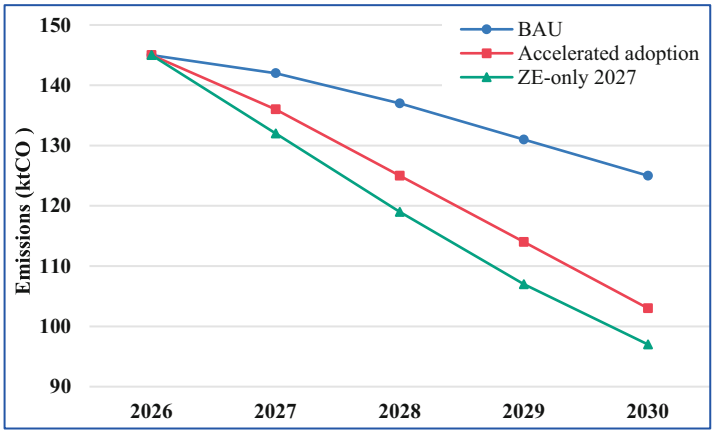


Fig. 2. Taxi TTW emissions scenarios, 2026–2030 ($ktCO_2$).

The accelerated adoption scenario assumes sustained incentive-driven uptake consistent with post-2023 trends, calibrated conservatively to avoid overestimation. Relative to business-as-usual (BAU), this pathway achieves cumulative reductions of approximately 25–30 $ktCO_2$ by 2030.

The Zero-Emission-only (ZE-only) licensing scenario builds on Portaria n.° 451/2023, assuming mandatory registration of only zero-emission taxis from 2027 onwards. This pathway delivers the largest reduction, reaching around 30 $ktCO_2$ below BAU by 2030 due to stronger post-2027 fleet renewal dynamics.

The difference between the accelerated and ZE-only pathways remains modest (around 2–3 $ktCO_2$ per year after 2028), indicating that fleet renewal—supported by infrastructure and regulatory certainty—drives emissions reduction.

Dividing cumulative programme expenditure by estimated TTW emission reductions (≈2,000 tCO_2eq) achieved between 2018 and 2025 yields an average abatement cost of about €1,270/tCO_2eq, exceeding international benchmarks for cost-effective transport decarbonisation (typically €100–€250/tCO_2eq) reported in EU regulatory assessments and independent analyses of large-scale vehicle electrification [1, 7]. This result is consistent with economic modelling of fleet electrification pathways highlighting strong scale effects and declining marginal abatement costs over time [4, 8].

The higher cost in the Portuguese case reflects three structural factors: limited early uptake (2018–2022), front-loaded charging infrastructure investment, and the voluntary nature of the scheme relative to mandate-driven transitions. Although early infrastructure deployment aligns with international best-practice recommendations for enabling electrification [8, 14], the temporal mismatch between infrastructure expansion and vehicle uptake temporarily inflated the observed cost per tonne of CO_2 avoided.

Portugal's performance remains modest compared with leading cases such as Shenzhen and Oslo, where binding mandates enabled rapid electrification of taxi fleets [15, 16]. London and Amsterdam illustrate intermediate pathways combining financial incentives with regulatory measures—particularly low-emission zones—resulting in sustained uptake over time [17, 18], while Paris represents a structured long-term transition strategy supported by both access regulation and infrastructure funding [19].

Evidence from Ireland highlights the substantial emissions abatement potential associated with full electrification in high-mileage taxi operations [3] consistent with European analyses of ride-hailing electrification costs and benefits. In contrast, studies from Germany show that fragmented and non-sector-specific policies are less effective when not accompanied by binding regulatory instruments [6].

Portugal demonstrates positive momentum following the acceleration observed in 2023–2025. However, the transition remains slower than in contexts where electrification has been established as a binding requirement rather than a voluntary option supported primarily by subsidies.

As summarised in Table 3, the international comparison therefore suggests that aligning financial support with stronger regulatory certainty could substantially enhance both environmental effectiveness and financial efficiency. These findings are consistent with the broader literature showing that combining financial incentives with regulatory instruments tends to accelerate fleet electrification and improve policy effectiveness.

Table 3. International taxi electrification programs.

City/country	Programme	Key incentive	Results
Portugal	PTF	€5 k–6 k + scrappage + charging system	378 taxis financed by 2025
London (UK)	Plug-in Taxi Grant	£7,500/taxi + infra	~45% taxi fleet EV (2023)
Oslo (Norway)	Low-emission Zone (LEZ) + national policy	VAT/tax exemptions; mandate for ZEV taxis (2024)	~88% of new taxi registrations EV (2023); 100% mandate Oslo 2024
Shenzhen (China)	EV mandate	Fleet-wide requirement; subsidies	100% (~21,000 taxis) EV since 2019
Paris (France)	LEZ + Advenir	LEZ + charging subsidies	Target 100% by 2030
Amsterdam (Netherlands)	Municipal incentives + LEZ	Local subsidies + LEZ	Strong uptake since 2015
Academic and policy studies			
Dublin (Ireland)		Scenario modelling	Up to 77% reduction under full uptake
Germany		Policy evaluation	EU/national measures insufficient

4 Conclusion

Between 2018 and 2025, the Portuguese Public Transport Fund supported 378 electric taxi acquisitions, alongside 96 vehicle scrappages and 227 charging systems, with cumulative public expenditure of €2.54 million. These measures are estimated to have avoided around 2,000 tCO_2eq of tailpipe emissions over the programme period.

Although uptake accelerated markedly after 2023, electric taxis still represent a small fraction of Portugal's approximately 12,000 licensed vehicles. Scenario analysis indicates that sustained incentive-based acceleration or ZE-only licensing could reduce sectoral emissions by more than 20% by 2030 relative to business-as-usual trajectories.

The observed average abatement cost of approximately €1,270/tCO_2eq reflects early-stage deployment dynamics, limited cumulative fleet penetration and front-loaded infrastructure investment, rather than structural inefficiency of electrification. As fleet penetration increases and infrastructure utilisation improves, average abatement costs are expected to decline, consistent with international evidence on high-mileage fleet transitions.

International comparison shows that jurisdictions combining financial incentives with regulation—such as zero-emission licensing or strict low-emission zones—achieve faster electrification and lower long-term public cost per tonne of CO_2 avoided. The

Portuguese case illustrates positive momentum but also highlights the limits of subsidy-driven transitions when not accompanied by binding regulatory signals.

From a policy perspective, the results reinforce the importance of an integrated policy mix. Aligning stable financial support with regulatory instruments, infrastructure planning and national decarbonisation strategies (PNEC 2030, Climate Law, European Green Deal, Fit for 55, AFIR) will be critical to transform incremental progress into structural decarbonisation of urban taxi mobility.

Beyond the Portuguese case, the results contribute to the broader discussion on policy design for high-mileage fleet electrification, highlighting the importance of combining financial incentives, infrastructure readiness and regulatory certainty. These findings reinforce evidence that integrated policy mixes are more effective than isolated subsidy schemes in accelerating transport decarbonisation. These insights are particularly relevant for medium-sized European markets where fleet electrification is constrained by limited fiscal capacity and fragmented regulatory frameworks.

The Portuguese experience therefore provides a policy-relevant empirical case for other mid-sized European markets seeking to decarbonise professional urban fleets under constrained fiscal conditions.

References

1. European Commission: Fit for 55′: Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality. European Commission, Brussels (2021)
2. International Transport Forum: ITF Transport Outlook 2023. OECD Publishing, Paris (2023)
3. Kinsella, L., Stefaniec, A., Foley, A., Caulfield, B.: Pathways to decarbonising the transport sector: the impacts of electrifying taxi fleets. Renew. Sust. Energ. Rev. **174** (2023). https://doi.org/10.1016/j.rser.2023.113160
4. Kelly, J.A., Guo, Y., Clinch, J.P.: Who benefits from fleet electrification? Quantifying the costs and benefits of transportation electrification strategies from different perspectives. Transp. Res. Interdiscip. Perspect. **32** (2025). https://doi.org/10.1016/j.trip.2025.101492
5. Santos, G., Davies, H.: Incentives for quick penetration of electric vehicles in five European countries: perceptions from experts and stakeholders. Transp. Res. Part A Policy Pract. **137**, 326–342 (2020). https://doi.org/10.1016/j.tra.2018.10.034
6. Peiseler, L., Cabrera Serrenho, A.: How can current German and EU policies be improved to enhance the reduction of CO_2 emissions of road transport? Revising policies on electric vehicles informed by stakeholder and technical assessments. Energy Policy. **168** (2022). https://doi.org/10.1016/j.enpol.2022.113124
7. International Council on Clean Transportation (ICCT): Annual Update on the Global Transition to Electric Vehicles: 2022. ICCT, Washington DC (2023)
8. Ricci, L.M., Gonçalves, D.N.S., de D'Agosto, M.A.: Transport sector GHG mitigation measures: abatement costs application review. Future Transp. **5**(4), 195 (2025). https://doi.org/10.3390/futuretransp5040195
9. Instituto da Mobilidade e dos Transportes, IP (IMT, IP): Anuário Estatístico da Mobilidade e dos Transportes 2024. IMT, IP, Lisboa (2024)
10. European Environment Agency (EEA): Greenhouse gas emission intensity of electricity generation in Europe. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1
11. International Energy Agency (IEA): Global EV Outlook 2024: Moving towards Increased Affordability. IEA, Paris (2024)

12. Castel-Branco, A.P., Ribau, J.P., Silva, C.M.: Taxi fleet renewal in cities with improved hybrid powertrains: life cycle and sensitivity analysis in Lisbon case study. Energies. **8**, 9509–9540 (2015). https://doi.org/10.3390/en8099509
13. International Transport Forum (ITF): how Urban Delivery Vehicles Can Boost Electric Mobility: Decarbonising Transport. OECD Publishing, Paris (2020)
14. Hall, D., Lutsey, N.: Emerging Best Practices for Electric Vehicle Charging Infrastructure. International Council on Clean Transportation (2017)
15. C40 Cities: Case Study: Shenzhen – Low-Emission Vehicle Promotion. C40 Cities (2022)
16. Oslo Kommune: Zero-emission taxis regulation. https://www.oslo.kommune.no/gate-transport-og-parkering/drosjeloyver/drosjeregelverk
17. Tamis, M., Van Den Hoed, R.: Moving a taxi sector to become electric: An innovative incentive programme in Amsterdam. In: Proceedings of the 32nd Electric Vehicle Symposium (EVS32), Lyon, France (2019)
18. Transport for London: More than half of London's black taxis are zero emission capable. https://tfl.gov.uk/info-for/media/press-releases/2023/december/more-than-half-of-london-s-black-taxis-are-zero-emission-capable
19. Ministère de la Transition Écologique: Zones à faibles émissions (ZFE). https://www.ecologie.gouv.fr/politiques-publiques/zones-faibles-emissions-zfe

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An Evaluation Framework for Aviation Decarbonization Strategies and Policies

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Abstract. Achieving net-zero emissions in aviation requires a coherent mix of policy instruments that are environmentally effective, economically efficient, politically durable, and socially equitable. This paper develops a sector-specific evaluation framework grounded in multi-criteria decision analysis and environmental policy evaluation, designed to enable systematic, transparent, and replicable assessment of aviation decarbonization policies. The framework identifies six evaluation dimensions—mitigation potential, economic efficiency, feasibility and scalability, implementation speed, policy credibility, and equity and just transition—and provides measurement guidance. Applying the framework to two European instruments, the EU Emissions Trading System (EU ETS) and the Sustainable Aviation Fuel (SAF) mandate (ReFuelEU), demonstrates comparative assessment without collapsing complex trade-offs into a single score. The analysis highlights complementarities between pricing and mandates, the need for temporal sequencing of instruments, and the integration of non-CO_2 effects and equity safeguards. The framework offers a practical tool for policymakers, regulators, and researchers to design, evaluate, and adapt aviation decarbonization strategies.

Keywords: aviation decarbonization · Sustainable aviation · policy evaluation · EU ETS · sustainable aviation fuel · multi-criteria analysis · net zero

1 Introduction

The decarbonization of the global aviation sector constitutes one of the most intractable challenges in climate policy. Aviation contributes approximately 2–3% of anthropogenic CO_2 emissions, yet its total radiative forcing is significantly higher when non-CO_2 effects such as contrail-induced cloudiness are included. While the International Civil Aviation Organization (ICAO) has adopted a Long-Term Aspirational Goal (LTAG) of net-zero carbon emissions by 2050, and the European Union (EU) has embedded aviation within its "Fit for 55" and ReFuelEU Aviation packages, the pathway to net zero remains contested in both technical and political terms [1].

Aviation's structural dependence on high energy-density liquid fuels, the slow turnover of fleets, and the projected post-pandemic rebound in demand exacerbate the difficulty of achieving deep and rapid decarbonization. Policy instruments have proliferated, ranging from market-based measures (e.g., the EU Emissions Trading System,

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CORSIA) to blending mandates, R&D subsidies, and demand management tools. Yet systematic, comparative evaluation of these policies remains underdeveloped.

Existing scholarship tends to assess individual instruments in isolation, often privileging either techno-economic modelling or qualitative policy analysis. This fragmentation hampers the ability to compare policy effectiveness across jurisdictions and to synthesize insights for integrated decarbonization strategies. The absence of a coherent, transparent, and reproducible evaluation methodology risks policy lock-in to suboptimal measures and undermines international coordination.

This paper responds to that gap by proposing a structured evaluation framework tailored to aviation decarbonization. The framework draws on multi-criteria decision analysis (MCDA) methodologies developed in transport appraisal [2], integrates principles from environmental policy evaluation [3], and incorporates insights from political economy analyses of climate policy durability [4]. The framework is designed to enable rigorous, cross-contextual comparison of decarbonization policies, to enhance policy design, and to provide a replicable tool for future empirical studies.

2 Literature Review

Multi-criteria decision analysis (MCDA) provides a formalised approach to evaluating alternatives against a set of heterogeneous criteria, both quantitative and qualitative. In transport policy, MCDA has been employed to reconcile trade-offs between environmental objectives, economic efficiency, and social acceptability [2, 5]. Unlike purely cost-benefit approaches, MCDA accommodates dimensions that resist monetisation, such as political feasibility or distributional equity. Yet it remains critical to the viability of decarbonisation measures.

While MCDA frameworks are widely used in infrastructure planning (e.g., the UK's WebTAG, the EU's TEN-T evaluation guidelines), their application to policy instruments—as opposed to physical projects—is comparatively limited. Aviation decarbonisation presents a particularly complex domain for MCDA because of (a) multiple interacting emissions sources (CO_2, NO_x, contrails), (b) heterogeneous stakeholder interests across borders, and (c) high uncertainty in technology cost and performance trajectories.

A small but growing body of scholarship evaluates aviation decarbonisation policies. Studies of the EU ETS [6, 7] often focus on marginal abatement costs and leakage effects but do not systematically compare the ETS to alternative instruments. Research on the ReFuelEU Aviation Regulation [8] examines supply chain readiness and lifecycle emissions of sustainable aviation fuels (SAF) but rarely integrates these findings into a multi-instrument comparative framework. Analyses of CORSIA [9] highlight issues of offset quality and additionality but treat these in isolation from broader policy portfolios.

Given aviation's unique characteristics, such as slow technological turnover, stringent energy density requirements, governance under a global regime, and substantial non-CO_2 climate impacts, policy evaluation in this sector must adopt a tailored approach [10]. This requires technological specificity to capture sectoral constraints and opportunities; sensitivity to policy design that considers enforceability, adaptability, and long-term political durability; global applicability that aligns with ICAO-led frameworks while remaining responsive to diverse regional contexts; and explicit integration of uncertainty

to account for contested cost and performance trajectories of decarbonisation options, including SAF, hydrogen, and demand elasticity.

3 Evaluation Framework

The framework follows four principles (see Table 1): transparency (explicit definitions, indicators, sources), comparability (like-for-like assessment across instruments), adaptability (criteria updated as science and costs evolve, including non-CO_2), and policy-design sensitivity (enforceability, durability, fairness).

Table 1. Core design principles

Principle	Description	Example in aviation policy context
Transparency	All criteria definitions, indicators, and data sources are explicit and documented for replication.	Publishing the exact MRV methodology used to assess ETS aviation emissions reductions.
Comparability	Enables side-by-side assessment across diverse policy types.	Evaluating SAF mandates and ticket taxes on common dimensions such as cost-effectiveness and mitigation potential.
Adaptability	Criteria and weightings can evolve with new evidence and technologies.	Updating framework to include contrail mitigation metrics once operational protocols mature.
Policy-design sensitivity	Captures enforceability, political durability, and fairness beyond technical metrics.	Analysing how legislative embedding of SAF mandates affects long-term compliance.

The policy taxonomy (Table 2) groups aviation decarbonisation instruments into four categories: market-based measures, which create price signals to internalise environmental costs (e.g., emissions trading schemes, carbon or ticket taxes); mandate or regulatory measures, which set binding standards or quotas to drive specific outcomes (e.g., SAF blending mandates, aircraft performance standards); enabling or support measures, which reduce barriers and accelerate innovation through funding, infrastructure, or procurement; and demand-management measures, which aim to moderate or shift air travel demand through pricing reforms, behavioural interventions, or targeted restrictions. This classification helps ensure that different policy types—each with distinct mechanisms, strengths, and risks—are compared on a consistent basis within the evaluation framework.

The framework operationalises "what good looks like" for aviation decarbonisation policy through six evaluation dimensions (Table 3): mitigation potential, assessing the

Table 2. Policy Taxonomy

Category	Definition	Typical instruments	Primary mechanism	Key benefits	Principal risks/bottlenecks	Typical evidence needed
Market-based	Puts a price on emissions or flying.	EU ETS, CORSIA, carbon/ticket taxes.	Price signal; internalises external costs.	Cost-effective abatement; revenue for recycling	Volatile/low prices; partial coverage; leakage.	MRV flight-level data; ex-post econometrics; revenue/incidence analysis.
Regulatory/mandate	Sets a standard or quota.	SAF blending mandates; aircraft performance standards; NOx limits.	Quantity/standard – forces fuel/tech switch.	High certainty on volumes; investment signal.	Supply capacity; high near-term costs; certification lags.	LCA/TEA of fuels; supply chain projections; compliance data.
Enabling/support	Lowers barriers to adoption	R&D grants, PtL infrastructure finance, green public procurement.	Cost de-risking; network effects.	Accelerates innovation and scale-up.	Picking winners; lock-in; fiscal cost.	Programme evaluations; CGE/IO modelling; cost-learning evidence.
Demand-management	Moderates demand or shifts behaviour.	Frequent-flyer levies; VAT/ticket tax reforms; advertising limits.	Price/choice architecture	Immediate impact; complements supply-side.	Equity concerns; substitution/leakage.	Elasticity estimates; distributional incidence; cross-border effects.

scale of emissions reduction (including non-CO_2 impacts) relative to a defined baseline; economic efficiency, evaluating the cost-effectiveness and wider welfare effects of the policy; feasibility and scalability, examining the capacity to deploy and expand the intervention at sectoral level; implementation speed, measuring how quickly meaningful impacts can be realised; policy credibility, considering enforceability, stability, and adaptability over time; and equity and just transition, analysing how costs and benefits are distributed across stakeholders and regions. Together, these dimensions provide a balanced lens that integrates environmental, economic, technical, political, and social performance.

In practical terms, equity in aviation decarbonisation policy can be assessed by combining distributional incidence analysis with qualitative stakeholder perspectives. Quantitatively, this can include:

- Income decile analysis. Use national or EU household expenditure surveys to estimate air travel demand by income group, apply estimated ticket price changes from the policy, and calculate the relative burden (as % of disposable income) for each decile.
- Geographic incidence. Map effects by region using input–output tables or regional accounts to capture employment gains/losses (e.g., in SAF production hubs vs. non-production regions) and changes in connectivity for remote areas.
- Employment transition metrics. Track job creation in low-carbon aviation supply chains and job losses in fossil-fuel-dependent sectors; adjust for skill-matching potential.

Table 3. Evaluation Dimensions and Indicators

Dimension	Definition	Preferred indicators (units)	Minimum acceptable methods	Reporting notes
Mitigation potential	Expected CO_2e reduction vs. baseline by 2050.	% sector reduction; $MtCO_2e$; CO_2e per RPK.	Robust LCA or ex-post econometrics; IAM/sector models with documented assumptions.	State baseline, horizon, and whether non-CO_2 included.
Economic efficiency	Cost per tonne avoided and welfare effects.	€/tCO_2e; ΔGDP; consumer surplus; airline cost pass-through.	MACCs; CGE/PE models; audited cost data.	Report ranges and price assumptions; show sensitivity to fuel and EUA prices.
Feasibility & scalability	Ability to deploy at sector scale.	TRL; certified fuel capacity (Mt/y); infrastructure readiness milestones.	Supply-chain analysis; certification status; programme audits.	Flag critical inputs (renewable electricity, CO_2, feedstocks).
Implementation speed	Time from adoption to measurable reductions.	Years to first impact; abatement profile (early vs. late).	Documented regulatory/industry timelines; ex-post case histories.	Separate legislative lead time from physical ramp-up.
Policy credibility	Likelihood the instrument endures and bites.	Compliance rates; penalty stringency; mandated ratchets.	Legal analysis; governance audits; historical stability.	Note derogations, free allocations, or carve-outs.
Equity & just transition	Distribution of costs/benefits.	Incidence by income/region; employment effects; revenue recycling share.	Microsimulation or incidence analysis; regional IO studies.	Report design of compensations and who gains/losses.

- Revenue recycling impacts. Model how hypothecating ETS or other policy revenues to targeted rebates, public transport subsidies, or green skills training changes the net distributional outcome.
- Accessibility indicators. Monitor changes in affordability of essential air services for low-income or peripheral communities.

The evaluation process begins with (1) defining the scope of the analysis, specifying the jurisdiction, baseline year, time horizon, and coverage of the policy under review; this stage produces a scope note, a baseline dataset, and, where relevant, a policy logic model. (2) The evaluator then collects evidence for each of the six framework dimensions, ensuring that all data sources are fully documented and quality-checked; outputs at this stage include an evidence matrix, a data dictionary, and quality assurance records. (3) Next, the evaluation criteria are applied, either qualitatively or in a semi-quantitative form, with explicit justifications for each assessment and sensitivity tests to account for uncertainty; this typically results in dimension-by-dimension assessments and a sensitivity analysis appendix. (4) Finally, the evaluator synthesises and reports the findings, comparing the performance of different policy instruments, identifying synergies and trade-offs, and highlighting evidence gaps; the deliverables include a comparative results table, a narrative synthesis, and an uncertainty register to inform policy refinement.

Key uncertainties in aviation decarbonization policy include variability in lifecycle assessment (LCA) results by feedstock, process inputs, and co-product crediting; these should be tested using parameter ranges, Monte Carlo simulations, and sensitivity checks for ILUC, grid carbon intensity, and refinery efficiency. Price volatility for EUAs, fossil jet fuel, and SAF/PtL fuels warrants scenario analysis with ±1–2 standard deviation shocks. Demand elasticity varies by market and income, requiring meta-analytic or market-specific estimates with ±25–50% sensitivity tests. Non-CO_2 impacts, such as contrail radiative forcing, NO_x chemistry, and CO_2-equivalence choices, should be assessed using alternative metrics and time horizons. Compliance risks from enforcement limits, exemptions, or free allocations can be modelled using historical rates and partial-compliance scenarios.

4 Discussion and Conclusion

The evaluation framework developed in this paper addresses a persistent methodological gap in assessing aviation decarbonization policies. While most studies examine individual instruments in isolation, such as the EU ETS [6] or SAF mandates [8, 11], this framework enables structured cross-instrument comparison, incorporating both quantitative performance indicators and qualitative policy design features. By operationalizing six dimensions—mitigation potential, economic efficiency, feasibility and scalability, implementation speed, policy credibility, and equity—it moves beyond conventional evaluations to reflect aviation-specific dynamics.

Application of the framework shows that the central policy risk in aviation decarbonization is not selecting the "wrong" instrument but relying on any single instrument in isolation. Market-based measures such as the ETS perform strongly in economic efficiency, scalability, and implementation speed, but at plausible carbon price levels are insufficient to induce large-scale structural fuel switching. Regulatory mandates such as ReFuelEU provide greater mitigation certainty and long-term investment signals, including potential non-CO_2 benefits, yet are constrained by near-term supply chain limits, high costs, and distributional impacts. The main policy-relevant result is therefore that complementarity and sequencing of instruments are more decisive for mitigation outcomes than the relative performance of individual policies.

The framework consequently supports a sequenced portfolio approach to aviation decarbonization. First, strengthened pricing instruments can deliver immediate operational efficiencies, modest demand responses, and revenue generation. Second, supply-building measures, including SAF mandates and enabling infrastructure and innovation support, should be deployed in parallel to create the conditions for deeper long-term emissions reductions. Third, revenue recycling and explicit distributional safeguards are required to maintain political durability and social legitimacy, particularly where policies increase ticket prices. This shifts policy design from optimizing single instruments to stress-testing portfolios across mitigation, feasibility, credibility, and equity dimensions.

Equity considerations are therefore critical. Both instruments can increase ticket prices and disproportionately affect lower-income travelers. ETS revenues, however, create opportunities for socially progressive investment, unlike mandates. Including equity as a core dimension ensures these distributional effects are addressed at the design stage. Non-CO_2 effects also remain poorly integrated despite their significant warming impact [12]. The framework's focus on CO_2e rather than CO_2 alone enables future evaluations to incorporate contrail avoidance and operational measures as methodologies develop.

Decarbonising aviation in line with net-zero targets requires policies that combine environmental effectiveness, economic efficiency, political durability, and social equity [13–16]. This paper proposes a sector-specific framework that operationalises these aims through six measurable dimensions. Grounded in multi-criteria decision analysis and environmental policy evaluation theory, it provides a transparent, replicable method for comparing policy types, from carbon pricing to fuel mandates and demand management. The framework is intended as both an assessment tool for existing policies and a design guide for future measures.

The framework therefore supports a sequenced portfolio approach: (1) immediate strengthening of pricing instruments to drive operational and demand-side efficiencies; (2) parallel deployment of supply-building measures (SAF mandates, infrastructure support) with clear scale-up pathways; and (3) mandatory integration of revenue recycling and distributional safeguards to maintain political durability. Policymakers should use the framework ex-ante to stress-test instrument portfolios across all six dimensions, rather than optimising policies on mitigation or cost alone.

Nevertheless, the framework has some limitations. Its use depends on data availability and quality, which vary across jurisdictions and instruments. Semi-quantitative scoring can introduce subjectivity without transparent justification and sensitivity testing. Cross-jurisdictional application may also require adapting weightings and indicators to different governance and market contexts.

References

1. Martín-Domingo, L., Efthymiou, M., Mújica-Mota, M.: Airline sustainability reportingin Europe: progress, compliance and challenges. Environ. Sustain. Indic. **28**, 101008 (2025)
2. Yannis, G., Kopsacheili, A., Dragomanovits, A., Petraki, V.: State-of-the-art review on multi-criteria decision-making in the transport sector. J. Traffic Transp. Eng. (English edition). **7**(4), 413–431 (2020)
3. Huang, I.B., Keisler, J., Linkov, I.: Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Sci. Total Environ. **409**(19), 3578–3594 (2011)
4. Greening, L.A., Bernow, S.: Design of coordinated energy and environmental policies: use of multi-criteria decision-making. Energy Policy. **32**(6), 721–735 (2004)
5. Macharis, C., Bernardini, A.: Reviewing the use of multi-criteria decision analysis for the evaluation of transport projects: time for a multi-actor approach. Transp. Policy. **37**, 177–186 (2015)
6. Efthymiou, M., Papatheodorou, A.: EU emissions trading scheme in aviation: policy analysis and suggestions. J. Clean. Prod. **237**, 117734 (2019)
7. Dominioni, G., Efthymiou, M.: Market-based measures for international aviation and shipping: lessons learned from a cross-sectoral analysis of EU ETS. In: Transport Research Arena Conference, pp. 117–124. Springer Nature Switzerland, Cham (2025)
8. Breen, M., Carton, J.G., Efthymiou, M.: Sustainable aviation fuel (SAF) supply. In: Transport Research Arena Conference, pp. 646–651. Springer Nature Switzerland, Cham (2025)
9. Prussi, M. et al.: CORSIA: the first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renew. Sust. Energ. Rev. **150**, 111398 (2021)
10. Efthymiou, M., Papatheodorou, A.: Environmental policies in European aviation: a stakeholder management perspective. In: Sustainable Aviation: Greening the Flight Path, pp. 101–125. Springer International Publishing, Cham (2019)
11. Efthymiou, M., Ryley, T.: Governance and policy developments for sustainable aviation fuels. In: Sustainable Alternatives for Aviation Fuels, pp. 201–214. Elsevier (2022)
12. Scheelhaase, J., Maertens, S., Grimme, W.: Options for improving the EU emissions trading scheme (EU ETS) for aviation. Transp. Res. Procedia. **59**, 193–202 (2021)
13. Sun, X. et al.: From hero to zero: barriers to achieving IATA's 2050 sustainability targets. Transp. Policy. **174**, 103830 (2025)
14. Efthymiou, M., Martín-Domingo, L., Mújica-Mota, M.: Aviation decarbonisation: a bibliometric analysis of productivity, research trends, and gaps. Transp. Res. Procedia. **94**, 26–35 (2026)
15. Agarwal, S., Efthymiou, M.: Market reactions to ESG sanctions in the European airline industry. J. Air Transp. Res. Soc. **5**, 100087 (2025)
16. Efthymiou, M., Papatheodorou, A.: Environmental considerations in the single European sky: a Delphi approach. Transp. Res. A Policy Pract. **118**, 556–566 (2018)

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Underpinning Factors Influencing the Adoption of Battery Electric Buses: Enablers, Barriers, and Global Learnings

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Abstract. The deployment of battery electric buses (BEBs) is influenced by a set of enabling and constraining factors that vary across local contexts and stages of adoption. This paper presents a structured framework for assessing the significance of 21 key factors identified. The study examines several MENA cities, alongside global frontrunners. Public transport authorities and operators were asked to evaluate these factors as enablers or barriers. The analysis, visualised through radar charts, reveals how the relative importance of these factors evolves with deployment maturity. Findings provide actionable guidance for MENA cities navigating early-stage transitions and offer transferable insights for advancing BEBs adoption globally.

Keywords: Electrification · Public Transport · Factor Analysis

1 Introduction

Cities worldwide are working towards greenhouse gas (GHG) reduction targets, with transport both driving economic activity and contributing nearly one-fifth of global carbon emissions [1, 2]. Public transport serves as a backbone of sustainable mobility, and within it, bus transport plays a central role in this [2, 3].

BEBs represent one of the most advanced alternatives, offering reliable technologies supported by well-established charging solutions and strategies [4, 5]. BEBs operate solely on rechargeable battery packs, eliminating the need for internal combustion engines and reducing emissions at the tailpipe [5].

Beyond environmental benefits, BEBs can reduce operational costs and enhance air quality and public health [6, 7]. Nevertheless, the transition remains challenging, requiring high capital investment, technological adaptation, and operational restructuring [8]. The life-cycle impact of BEBs is also influenced by electricity generation sources, with renewable-rich grids enhancing environmental performance and fossil-dependent grids reducing benefits [9, 10].

In the MENA region, the electrification of bus fleets is accelerating. Governments are setting ambitious targets and integrating electric mobility into policy frameworks

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[2]. The bus market in the MENA region currently exceeds 32,000 vehicles [11]. These developments reflect both regional commitments to sustainable mobility and the recognition of public transport's role in advancing broader socio-economic goals such as the UN Sustainable Development Goals [2].

Adoption dynamics differ across markets: emerging adopters (e.g., MENA) face distinct enablers and barriers compared to mid-level or advanced cities. Supportive policies, renewable energy integration, and technological innovation act as enablers, while high costs, infrastructure gaps, and policy ambiguity function as barriers [3, 8]. Recent empirical analyses also emphasise the importance of targeted institutional and policy enablers in accelerating e-bus uptake [12]. In addition, some factors can play dual roles depending on local conditions. For instance, subsidies and clear regulatory frameworks accelerate adoption, whereas ambiguous or fossil-fuel-supportive policies hinder progress [9, 10]. Recognising these context-dependent dynamics enables policymakers and operators to allocate resources strategically, anticipate risks, and build consensus among stakeholders. A flexible analytical framework that distinguishes enablers from barriers, while acknowledging their shifting roles provides cities with a robust tool for adapting BEB strategies to local conditions [3]. This paper examines the deployment of BEBs through a framework designed to assess the significance of enabling and constraining factors.

The remainder of this paper is structured as follows. Section 2 presents the research methodology while Sect. 3 provides the identified framework and Sect. 4 highlights the findings and discussions. Finally, the conclusion and future research recommendations are given in Sect. 5.

2 Methodology

2.1 Factors Collection

Data was gathered by reviewing the literature to compile a list of factors influencing the adoption of BEBs. This covers a content literature review, which involves several resources such as UITP literature, UITP expertise academic literature, and publicly available reports. The identification of the factors is conducted through an input from key stakeholders, including public transport authorities (PTAs) and public transport operators (PTOs). In this phase, the focus is on gathering relevant information and setting the foundation for subsequent analysis.

In addition to the literature review and stakeholder input, this study builds on the methodological foundation of the Assured project [13], which provided guidelines for fleet upscale of electric buses across Europe. The methodology focused on the technological aspects including interoperability of charging solutions, integration of electrification strategies within Sustainable Urban Mobility Plans, and system-level planning that considers vehicles, infrastructure, and operations as an integrated whole. Our study extends and improves upon this framework by applying a structured factor-based approach to assess the relative significance of enablers and barriers. Unlike the ASSURED project, which concentrated on demonstrating technological feasibility and standardisation in mature European markets, this research adapts the methodology to emerging contexts

by comparing early-adopter MENA cities with advanced global benchmarks. This extension allows for the generation of region-specific insights while situating the findings as part of a broader continuum of global e-bus deployment studies.

2.2 Validation and Categorisation

The list was then validated by subject matter experts (UITP experts from the Knowledge and Innovation Department) to ensure comprehensiveness. This step involves the refinement of the collected factors, which may include adding, removing, or combining the factors. The collected factors are then categorized into groups for enhancing their representation.

2.3 Construction of Open-Ended Questionnaire, Selection of Respondents, and Data Analysis

The evaluation is conducted through an open-ended questionnaire, which is divided into two elements.

The assessment consists of two main components. First, the collected factors are evaluated through a dual assessment that examines the extent to which each factor functions as an enabler or a barrier within its specific context. This evaluation follows a qualitative scoring scheme in which stakeholders rate the influence of each factor on a Likert scale from 1 (very low influence) to 5 (very high influence). Second, open-ended questions capture insights on the most critical factors, key barriers, and the strategies adopted by entities to strengthen enablers and address constraints. Finally, each factor is assessed by the identified list of entities (either PTAs or PTOs) presented below.

- **MENA region:** Dubai (Roads and Transport Authority), Abu Dhabi (Abu Dhabi Mobility), Ras Al Khaimah (Ras Al Khaimah Transport Authority), Taif (Transport General Authority), Muscat (Mwasalat Oman), Cairo (Mwasalat Misr), and Amman (Greater Amman Municipality).
- **Other regions:** Toronto (Toronto Transit Commission), Shenzhen (Shenzhen Bus Group), London (Arriva), and Kayseri (Kyaseri Ulasim).

From each entity, either a PTA or a PTO, the targeted sample involves experts working in different departments that are directly or indirectly involved in buses electrification. Besides identifying the significance of enablers and barriers, it is important to examine the relationship between the level of deployment of BEB technology and how these attributes are perceived.

By studying the above cities, which are at different stages of BEB adoption, we can gain valuable insights into how the relative importance of these factors changes over time and adapt strategies to accelerate transitions in diverse contexts.

The factors are then weighed up based on their relative importance, as determined by stakeholders. The results of the assessment are then visualised using radar charts, which provide a clear graphical representation of the strengths and weaknesses of each factor as an enabler or barrier. This allows stakeholders to easily compare the relative influence of various factors and identify areas needing attention. For each city, multiple responses were collected, depending on availability, and then aggregated using the average. For the

MENA, the city-level averages were then combined, and the median value was selected to represent the regional results.

3 Identified Framework

After several refinements and mapping the factors, the framework, in Fig. 1, ends up with 21 factors that are mapped into four main clusters, namely, technological dimension, economic dimension, environmental dimension, and socio-institutional and policy dimension.

The Technological dimension encompasses various factors that directly impact the operational efficiency, sustainability, and long-term viability of BEB fleets. The economic dimension is a critical consideration in the adoption of BEBs, as it directly affects financial viability, and long-term sustainability of BEB deployment. The environmental dimension is critical for ensuring that the adoption of electric buses aligns with broader sustainability objectives. The identified factors ensure that BEB deployment not only reduces tailpipe emissions but also addresses environmental trade-offs throughout their lifecycle. The socio-institutional and policy dimension is crucial for the successful implementation of bus electrification as it provides the foundational framework needed to drive systemic change. This dimension addresses technical, operational, and societal barriers comprehensively, ensuring a holistic transition.

4 Findings and Results

4.1 Key Insights – Technological Dimension

Supporting infrastructure remains the key enabler across all cities, while operational and technical efficiency pose major barriers, particularly in early adoption regions. Shenzhen demonstrates how sustained investment ensures success, showing strong technological enablers and minimal barriers. London and Toronto perform moderately, benefiting from established frameworks but facing challenges in renewable energy integration and cost structures. MENA shows strong infrastructure potential but continues to struggle with operational efficiency and maintenance due to its early development stage.

Figure 2 shows the significance of each factor as an enabler and barrier. Supporting infrastructure functions as both an enabler and a constraint, as expanding fleets require continuous charging upgrades. Battery technology continues to improve but remains sensitive to harsh climates, particularly in cities such as Toronto. Renewable energy integration remains limited, reflecting weak alignment with clean energy systems. Even advanced adopters like Shenzhen continue optimising operations; MENA must strengthen efficiency, operator readiness, and driving practices to scale effectively [14]. Maintenance and capacity-building remain essential for reliable deployment. It is worth noting that radar charts were also generated for the other dimensions, however, due to number of figures limitations, only the results for the first dimension are only demonstrated in figures.

Key learning lessons include accelerating zero-emission bus deployment requires structured PPP to expand charging infrastructure and collaboration with global suppliers to develop regional battery ecosystems. Strengthening technical training will enhance

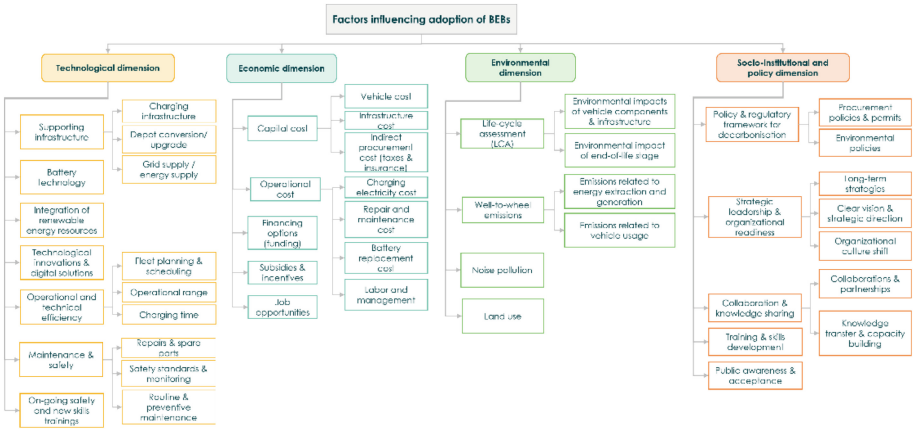


Fig. 1. Framework of underpinning factors influencing adoption of BEBs.

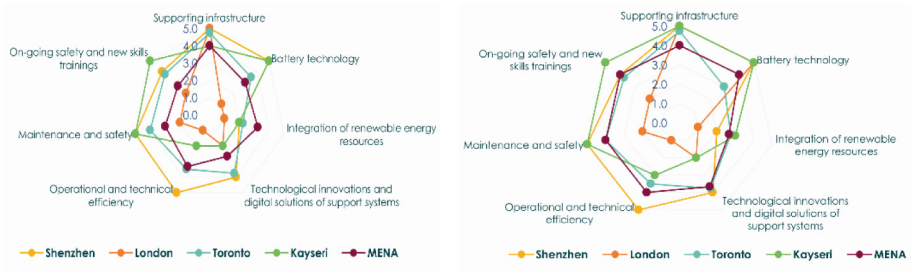


Fig. 2. Significance of technological factors (a: enablers, b: barriers).

maintenance and operational readiness, while engagement with international frontrunners can support the adoption of best practices and innovation. Coordination with utility providers is essential to ensure grid reliability and optimise charging schedules, and aligning infrastructure with clean energy sources remains critical to achieving genuine decarbonisation outcomes.

4.2 Key Insights – Economic Dimension

Capital and operational costs remain the dominant global barriers. Shenzhen's strong economic base and sustained investment make it a leader in cost-efficient BEB deployment, though financial management remains crucial. London faces high costs and funding shortages, requiring policy and operational reforms. MENA views financing as an enabler but struggles with capital costs, underlining the need for structured funding mechanisms.

High capital costs remain a common constraint across cities, placing pressure on public budgets. Operational costs, however, can be managed through smart energy management and route optimisation systems, and quantitative total cost of ownership models

indicate that cost parity is achievable under supportive policy and energy pricing conditions [15]. Access to diversified financing mechanisms is essential to sustain progress. Most cities depend on subsidies or private investments such as in Toronto, while MENA requires stronger regional financial backing. Maintenance and safety remain critical, demanding continuous training and capacity-building.

Key lessons from more advanced cities include scaling e-bus deployment requires Public–Private Partnerships and innovative business models beyond direct procurement, supported by expanded green and long-term financing. Incentives should extend beyond electricity subsidies toward broader capital and risk-sharing mechanisms. Optimised charging infrastructure and data-driven route planning are equally critical to lowering operational costs and improving overall system efficiency.

4.3 Key Insights – Environmental Dimension

Life-cycle assessment is a key enabler but requires strong sustainability monitoring. Although well-to-wheel (WTW) emissions reductions are significant, full life-cycle evaluation and renewable energy integration are essential to secure real environmental benefits. Land-use impacts vary, limited in Kayseri but more constrained in parts of MENA, requiring improved spatial planning, while noise reduction remains an operational advantage of BEBs. Governments should adopt LCA-based procurement supported by carbon tracking and circular economy policies and integrate e-buses within multimodal strategies while complementing them with renewable energy–powered fleets to enhance WTW emissions performance.

4.4 Key Insights – Socio-Institutional and Policy Dimension

This dimension is a strong enabler of BEB deployment in MENA, supported by clear regulatory frameworks and decarbonisation mandates. Strategic leadership drives progress, though stronger institutional coordination is still needed. Sustained momentum depends on enhanced inter-agency collaboration, regional knowledge sharing, and expanded workforce training. Lessons from advanced cities emphasise the importance of coherent BEB policies, Public–Private Partnerships to mobilise investment and share risk, and structured knowledge-sharing platforms linking policymakers, PTAs, PTOs, and industry stakeholders to enable coordinated deployment.

4.5 Overall Summary and Key Takeaways

The comparative assessment underscores distinct pathways to BEB deployment across leading and emerging cities.

Shenzhen demonstrates how strong government support, subsidies, and investment in batteries and charging infrastructure can overcome financial barriers and enable large-scale electrification. London highlights the importance of consistent policies and phased transition strategies aligned with emissions targets. Toronto underscores the role of political commitment and legislative mandates, supported by workforce training and operational readiness. Kayseri illustrates a pragmatic approach focused on operational

range optimisation and workforce preparedness, reinforced by strong public support for environmental benefits.

In contrast, the MENA region reflects a balanced approach that integrates cost efficiency, infrastructure development, and strategic planning, adapting solutions to local institutional and market conditions. Table 1 consolidates the key findings and suggests the following for MENA cities: enhancing financial accessibility through PPP structures, targeted subsidies, and green financing instruments; scaling charging infrastructure and grid readiness; strengthening regulatory clarity and enforcement; and investing in structured workforce development programs to support long-term reliability and system expansion.

Table 1. A summary of the key barriers and enablers.

City/Region	Deployment status	Key enabler(s)	Key barrier(s)
Shenzhen	Complete deployment	Strong government support, low costs, high efficiency	Stringent regulatory compliance
London	Phased transition	Leadership, public support	High costs, land-use restrictions, policy gaps
Toronto	Growing adoption	Leadership, public backing	Financial barriers, infrastructure challenges
Kayseri	Early adoption	Environmental support, public awareness	Technological and economic limitations
MENA	Early adoption / emerging market	Infrastructure ongoing development, emissions reductions, growing policy support	Financial hurdles

5 Conclusion

This paper examined the deployment of BEBs through a structured framework assessing 21 enablers and barriers across seven MENA cities and global frontrunners. The analysis showed how the significance of these factors shifts with the stage of adoption, ranging from investment support and pilot projects in early phases, to operational challenges in intermediate phases, and system-level concerns such as supply chain resilience and battery recycling in advanced phases.

By contrasting MENA cities with mature markets, the study highlighted transferable lessons while emphasising regional specificities. The framework provides policymakers, operators, and industry stakeholders with a comparative tool to guide decision-making and resource allocation for accelerating zero-emission bus adoption.

Future research could extend this framework to other regions beyond MENA, enabling cross-continental comparisons of enablers and barriers. Moreover, expanding the framework to include other zero-emission technologies, such as fuel cell electric

buses, would enrich the understanding of how different propulsion systems interact with policy, market, and operational conditions.

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References

1. Ritchie, H.: Cars, Planes, Trains: Where Do CO_2 Emissions from Transport come from? Our World in Data (2020). https://ourworldindata.org/co2-emissions-from-transport
2. UITP: Why Public Transport is Key to Achieve the SDGs. UITP (2023). https://mylibrary.uitp.org/PermaLinkRecord.htm?archive=291818001909
3. UITP: Going Electric: A Pathway to Zero-Emission Buses. UITP (2021). https://www.uitp.org/publications/policy-paper-going-electric-a-pathway-to-zero-emission-buses/
4. Bartłomiejczyk, M.: Driving performance indicators of electric bus driving technique: naturalistic driving data multicriterial analysis. IEEE Trans. Intell. Transp. Syst. **20**(4), 1452–1463 (2018)
5. ASSURED.: Clean bus report (2022). https://cms.uitp.org/wp/wp-content/uploads/2022/05/ASSURED-Clean-Bus-report_final2.pdf.
6. Avenali, A., Catalano, G., Giagnorio, M., Matteucci, G.: Factors influencing the adoption of zero-emission buses: a review-based framework. Renew. Sust. Energ. Rev. **196**, 114388 (2024). https://doi.org/10.1016/j.rser.2024.114388
7. Sadrani, M., Najafi, A., Mirqasemi, R., Antoniou, C.: Charging strategy selection for electric bus systems: a multi-criteria decision-making approach. Appl. Energy. **349**, 121415 (2023). https://doi.org/10.1016/j.apenergy.2023.121415
8. Bakker, S., Konings, R.: The transition to zero-emission buses in public transport – the need for institutional innovation. Transp. Res. Part D: Transp. Environ. **64**, 204–215 (2018). https://doi.org/10.1016/j.trd.2017.08.023
9. Rupp, M., Handschuh, N., Rieke, S., Kuperjans, I.: Country-specific electricity mix and charging time can swing LCA results for e-buses: when high-carbon grids erode advantages. Appl. Energy. **237**, 862–872 (2019)
10. Gustafsson, M., Svensson, N., Anderberg, S.: Energy performance indicators as policy support for public bus transport – the case of Sweden. Transp. Res. Part D: Transp. Environ. **65**, 396–407 (2018). https://doi.org/10.1016/j.trd.2018.10.008
11. UITP MENA CTE.: MENA transport report (2025). https://mylibrary.uitp.org/PermaLinkRecord.htm?archive=296031301421.
12. Ghosh, A.M., Sekhar, S., Chakraborty, D., Sinha, S.: Identifying enablers for accelerated uptake of electric bus deployment. Int. J. Sustain. Transp. **18**(7), 552–568 (2024). https://doi.org/10.1080/29941849.2024.2374398
13. ASSURED.: Guidelines on fleet upscale with electric buses. (2022). https://mylibrary.uitp.org/GED_V14/298301301658/D11-12_2022.pdf.
14. Orji, I.J., Oloruntoba, R., Chowdhury, M.: Adopting electric bus for improving efficiency in the local public transport sector. Transp. Res. Part A: Policy Pract. **184**, 103832 (2024). https://doi.org/10.1016/j.tra.2024.103967
15. Ramingwong, S., Sampattagul, S., Jintana, J.: Economic viability of electric bus adoption for public transportation in Thailand: a Monte Carlo simulation approach. Logistics. **9**(2), 60 (2025). https://doi.org/10.3390/logistics9020060

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Towards Harmonized Air Quality Assessment and Management in Underground Railway Stations: The Rail4Earth Initiative

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Abstract. Air quality in underground railway stations (URS) is a growing public health and operational concern, with particulate matter (PM) levels often exceeding outdoor concentrations. The Rail4Earth project, under Europe's Rail Joint Undertaking, addresses this issue through a dedicated work package on URS air quality. This paper presents intermediate results from five components: (A) harmonized measurement specifications, (B) evaluation of low-cost sensors (LCS), (C) predictive modelling, (D) mitigation strategies, and (E) emission factor development for non-exhaust sources. Reference instruments remain essential, but calibrated LCS networks can extend monitoring coverage. Predictive models using statistical and machine-learning approaches (Random Forests, CNNs) show promising forecasting capability but require local calibration. Mitigation strategies include source reduction, air treatment and operational measures, with combined approaches proving most effective. These results provide the basis for a harmonized framework supporting improved air-quality management in URS.

Keywords: Underground railway stations · Low-cost sensors · Predictive modelling · Non-exhaust emissions · Mitigation strategies

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1 Introduction

Air quality in underground railway stations (URS) is a growing concern for public health and occupational safety. Particulate matter (PM) concentrations often exceed outdoor levels and mainly originate from mechanical wear processes such as braking, wheel–rail contact and pantograph–catenary interaction. Addressing this issue is challenging because emission sources are diverse, measurements are complex and mitigation measures must balance technical feasibility, operational constraints and cost. Within the Europe's Rail Joint Undertaking, the Rail4Earth project addresses these challenges through a dedicated work package on URS air quality. The project gathers railway operators and research institutes to develop harmonized monitoring methods, predictive models, emission factors and mitigation strategies. This paper presents progress across five tasks covering monitoring specifications, sensor networks, predictive modelling, mitigation solutions and emission factor development.

2 Task 1. Measurement Specifications

Background and Objective: Regulatory approaches to air quality in URS remain heterogeneous. Only a few jurisdictions, notably South Korea and Taiwan, have established specific PM limits, while most countries rely on adapted ambient air standards or time-weighted exposure approaches. These differences partly reflect remaining uncertainties regarding the health impacts of the iron-rich particulate mixture typical of underground environments. This situation highlights the need for harmonized monitoring methodologies enabling reliable comparison between systems and supporting the development of evidence-based regulatory frameworks.

Methods: A literature review combined with partner expertise identified best practices for URS monitoring. Particulate matter (PM) was confirmed as the main pollutant of concern, typically exceeding outdoor urban levels. Monitoring therefore focuses on PM_{10} and $PM_{2.5}$ mass concentrations, complemented by metallic composition analysis (Fe, Cu, Mn). CO_2 is measured as an indicator of ventilation and passenger density, while temperature and humidity provide contextual information. The INERIS guideline served as a methodological basis [1]. Because PM is a complex mixture, assessment combines three metrics: mass concentration, particle number concentration and chemical composition. Three instrument types are used: reference continuous analysers (e.g. FIDAS or TEOM) for high-resolution PM data, gravimetric samplers for filter analysis by ICP-MS or XRF, and calibrated low-cost sensors (LCS) deployed in dense networks to capture spatial and temporal variability.

Results and Discussion: A pre-normative monitoring framework for URS was developed, structured into three complementary specifications. Short-term characterization consists of 14-day intensive campaigns to ensure cross-station comparability. Instruments installed at mid-platform measure PM_{10}/$PM_{2.5}$ mass, calibrated LCS networks, CO_2 and comfort parameters. Long-term monitoring relies on continuous measurements at sentinel stations (typically one per line) over 12 months to capture seasonal and operational variability. Reference instruments are complemented by contextual [2] data such

as train frequency, ventilation operation, outdoor PM and meteorology. Treatment efficiency assessment uses before/during/after campaigns to quantify the impact of mitigation technologies (e.g. filtration systems or platform screen doors). These campaigns combine reference monitors and LCS networks to evaluate concentration reductions and spatial variability. This framework supports harmonized URS air-quality monitoring by translating heterogeneous practices into scalable protocols for regulatory and operational use. The focus on PM mass, metallic composition and confinement indicators targets key pollutants, while calibrated LCS networks enable dense monitoring. The three level structure establishes baselines, tracks trends and verifies mitigation effectiveness.

3 Task 2. Low-Cost Sensors and Calibration

Introduction and Background: Air-quality monitoring in underground railway stations (URS) traditionally relies on reference instruments that provide accurate measurements but are expensive and bulky, limiting spatial coverage. Low-cost sensors (LCS) offer a complementary solution: compact and affordable, they can be deployed in dense networks to capture spatial gradients and short-term fluctuations such as train-induced peaks. However, their performance in URS remains uncertain. Potential limitations include reduced precision, sensor drift and sensitivity to temperature and humidity. Moreover, most LCS are calibrated for outdoor aerosols, whereas URS particles are typically metal-rich, which may introduce systematic biases. Task 2 therefore aims to develop a methodology to evaluate and calibrate LCS for URS applications and assess whether they can reliably complement reference instruments.

Methods: Several optical LCS were deployed on two metro platforms in Stockholm and co-located with a reference instrument (Fidas 200S), gravimetrically calibrated using a Dekati PM10 Impactor. Measurement campaigns were conducted across seasons to capture variations in particle characteristics and environmental conditions. Sensor performance was evaluated in terms of detection limits, linearity, inter-sensor variability, drift and responsiveness to rapid concentration changes. Particular attention was given to humidity effects, as hygroscopic particles can absorb water and bias optical measurements. Monthly recalibration was implemented to account for drift and dust deposition.

Results: LCS successfully captured temporal fluctuations and spatial variability in PM concentrations, including short peaks associated with braking or ventilation events. Spatial gradients along platforms were also observed, with higher concentrations near tunnel entrances. Some sensors showed good agreement with reference measurements, with calibration coefficients (R^2) exceeding 0.9 for $PM_{2.5}$ and PM_{10} (Fig. 1). However, significant variability between individual sensors was observed, indicating the need for sensor-specific calibration. Differences between platforms were also detected, reflecting variations in particle size distribution, density, concentration and environmental conditions. Humidity had a strong influence on measurements, artificially increasing $PM_{2.5}$ readings. After humidity correction, one sensor achieved $R^2 = 0.98$ for PM_1. Parallel measurements at three locations at Arlanda C station further illustrated strong spatial variability of PM concentrations along the platform (Fig. 2).

Discussion and Conclusion: The results highlight both the potential and limitations of LCS for URS monitoring. These sensors capture temporal trends and spatial variability in particulate matter, improving spatial coverage and enabling near-real-time observations. However, variability between sensors and sensitivity to environmental conditions require calibration and periodic validation against reference instruments. LCS therefore represent a valuable complement to conventional monitoring but cannot yet replace reference-grade instruments for regulatory assessments. Further improvements in sensor stability, calibration procedures and data processing are needed to fully integrate LCS networks into URS air-quality management. This study has several limitations. The evaluation covered a limited number of platforms and sensor models and may not represent the full diversity of URS environments. In addition, the metal-rich composition of underground particles and humidity effects introduce systematic biases in optical sensors, highlighting the need for site-specific calibration.

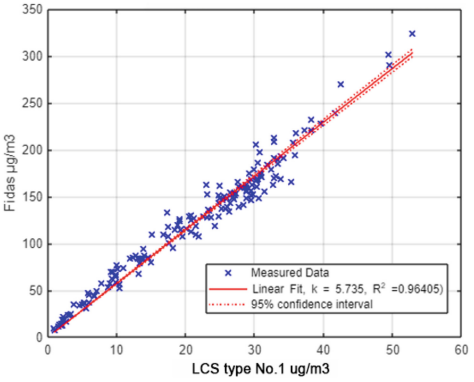


Fig. 1. LCS vs. reference no-intercept linear regression at Metro Platform (PM10)

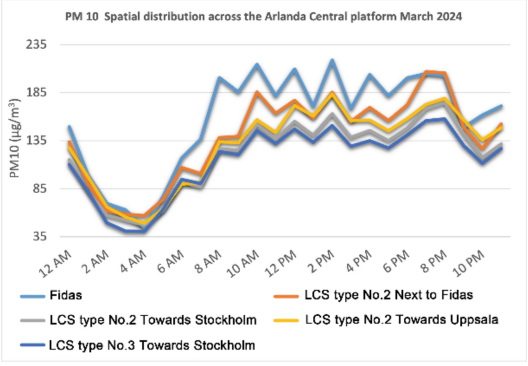


Fig. 2. Spatial distribution (PM10) across Arlanda C platform (Stockholm)

4 Task 3. Predictive Models

Introduction and Background: Accurate and continuous measurements are essential for developing predictive models of air quality in underground railway stations (URS). Such models can forecast pollution peaks and support preventive actions such as ventilation control. URS air quality is influenced by multiple sources [3], including mechanical wear, brake dust, diesel exhaust (where relevant), resuspension driven by the piston effect, passenger activity and outdoor pollution infiltration. Key drivers of platform PM levels include train frequency and type, passenger density, ventilation operation and outdoor PM. Previous work in Stockholm [4] showed that simple statistical models could explain much of PM_{10} variability. Advances in machine learning now allow modelling of non-linear interactions and short-term dynamics. Task 3 therefore develops and compares predictive models across cities to assess accuracy, interpretability and transferability.

Methods: A multi-model strategy was applied. Statistical regression models (linear and mixed effects) provided interpretable baselines linking PM concentrations to predictors such as train frequency, passenger density, ventilation operation and outdoor PM. For example, a Stockholm regression including train frequency and ventilation explained daily PM_{10} variability with $R^2 = 0.8$. Two machine-learning approaches were also tested. A Random Forest (RF) model captured non-linear interactions while ranking predictor importance. A Convolutional Neural Network (CNN) was adapted for time-series forecasting, predicting $PM_{2.5}$ concentrations four hours ahead based on the previous 20 h of operational data, outdoor pollution and meteorology. Models were trained on long-term Stockholm data and shorter Paris datasets to assess transferability. Performance was evaluated using R^2 and RMSE.

Results: Both statistical and machine-learning models performed well but with different strengths. Regression analyses confirmed train frequency, rolling stock type, passenger flow and ventilation as key predictors of PM concentrations. In Stockholm, higher train frequency and older trains using friction braking were associated with increased PM_{10} levels ($R^2 = 0.8$). However, regression models struggled to represent interactions, such as the dependence of train-frequency effects on ventilation conditions. Random Forest models better captured non-linear relationships, achieving $R^2 = 0.82$ in Stockholm, although performance was lower in Paris ($R^2 = 0.62$). Feature-importance analysis identified equivalent train frequency (combining train number and length) and fleet composition as dominant drivers, followed by passenger flow and outdoor PM. Meteorological variables had a smaller but consistent contribution. The CNN provided the highest predictive performance for short-term dynamics, reaching $R^2 = 0.75$ for four-hour-ahead $PM_{2.5}$ predictions in Paris. It reproduced recurrent temporal patterns such as rush-hour peaks and nighttime minimum as well as lagged effects. However, interpretability remained limited compared with statistical models.

Discussion and Conclusion: The modelling results highlight a trade-off between interpretability and predictive performance. Linear models are transparent and confirm intuitive mechanisms linking train operations and PM emissions, but they capture interactions only partially. Machine-learning approaches improve predictive accuracy and integrate multiple variables and lagged effects, although their interpretability remains

limited. Transferability tests showed that local calibration is necessary. Models trained on long-term Stockholm data performed robustly there but lost accuracy when applied to Paris due to differences in infrastructure and rolling stock. However, adding only one week of local data significantly improved performance (R^2 increasing from 0.43 to 0.71), indicating that cross-network application is feasible with limited calibration effort. Operationally, predictive modelling of URS air quality appears feasible and valuable. Identifying drivers such as train frequency, fleet composition, passenger flow and ventilation provides actionable levers for management. Integrating such models into forecasting tools could support ventilation optimisation while balancing energy consumption and air-quality objectives. The approach nevertheless remains constrained by data availability. Some influential variables, such as detailed passenger flows, maintenance train operations or infrastructure characteristics (track curvature, gradients and ventilation configurations), were not consistently available. Incorporating richer operational and infrastructure datasets could further improve model robustness and transferability (Fig. 3).

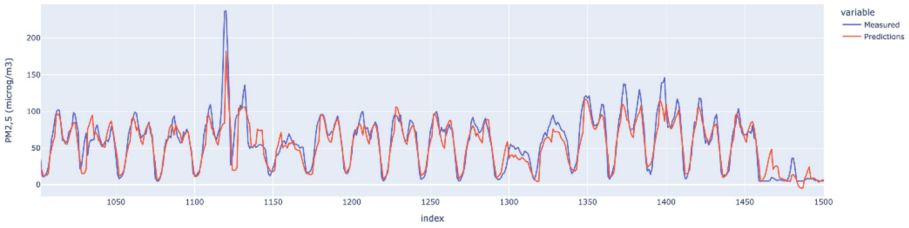


Fig. 3. Comparison of measured and CNN-estimated $PM_{2.5}$ levels in Paris Magenta station

5 Task 4. Improvement Solutions

Given the high pollution levels observed in many subway systems, improving air quality in underground railway stations (URS) has become a strategic priority. Numerous mitigation solutions have been tested worldwide [5], but their effectiveness varies and many involve significant cost or engineering constraints. Decision making therefore requires comparing measures not only by pollutant reduction but also by feasibility, maintenance requirements, energy use and potential side effects. Task 4 addresses this need by developing a practical toolkit for operators. A literature and industry survey was conducted to classify mitigation options and compile available case studies from pilot projects, operator feedback and academic research. Measures were grouped into three categories: (i) at-source control, including regenerative braking, low-wear materials, lubricants, eco-driving and on-board particle capture; (ii) reduction of airborne concentrations through tunnel cleaning, platform screen doors, filtration units and optimized ventilation; and (iii) emerging technologies such as photocatalytic coatings [6], magnetic collectors and ionization, which remain experimental. The review confirms that no single solution is sufficient. Source-reduction strategies can reduce emissions by 20–50%,

while air-cleaning measures provide immediate but sometimes short-lived improvements (e.g. 30–40% PM_{10} reduction after tunnel cleaning and 10–30% near filtration units). Platform screen doors can halve platform PM concentrations but require major investment. Overall, effective strategies require a phased approach: short-term operational actions (cleaning and ventilation optimization), medium term upgrades such as filtration or improved braking systems, and long-term investments including fleet renewal and platform screen doors. In practice, implementation must also consider operational constraints, ensuring that air-quality benefits are balanced with energy use, maintenance and lifecycle cost.

6 Task 5. Non-exhaust Emission Factors

With the electrification of rolling stock fleets, the relative importance of non-exhaust particulate matter has increased. Most particles originate from mechanical wear (brakes, wheel/rail contact, pantograph/catenary) and dust resuspension. These emissions remain poorly quantified compared with exhaust emissions, although the EU and OECD now recognize them as an emerging environmental issue. Reliable emission factors (EFs), defined as the mass of pollutants emitted per activity unit, are needed to estimate inventories, guide mitigation and support policy development. Task 5 therefore aims to develop a transparent methodology for deriving EFs for key rail processes. A review of two decades of studies identified three complementary approaches: (i) material-loss methods estimating wear from component mass reduction and converting it to airborne PM [1]; (ii) tunnel measurements inferring emissions from concentration increases during train passages [7]; and (iii) laboratory bench tests using dynamometers or tribometers to quantify emissions under controlled conditions [8]. Our approach combines these methods: maintenance based wear data provide baseline estimates, tunnel measurements constrain real world values, and bench tests refine source specific contributions and particle size distributions. Preliminary results indicate that braking dominates non-exhaust PM emissions (up to 50%), followed by wheel-rail wear, while pantograph emissions remain minor. Early EF equations, for example relating brake emissions to train mass, frequency and pad material, are consistent with literature values. Work is ongoing, with remaining uncertainties regarding airborne fractions and ultrafine particles generated during high-temperature braking. The objective is to develop a reproducible methodology that could serve as a pre-standard, allowing rail wear emissions to be routinely included in emission inventories and supporting predictive modelling (Task 3) and mitigation assessment (Task 4).

7 Conclusion

Across Tasks 1 to 5, a clear conclusion emerges: improving air quality in underground railway stations requires an integrated strategy combining monitoring, modelling, mitigation and emission quantification. Tasks 1–5 addressed harmonized monitoring, dense sensor networks, predictive modelling, mitigation options and non-exhaust emission factors. Initial results demonstrate the feasibility of this integrated approach, although

challenges remain regarding standardization, long-term validation and health-based regulations. Together, these tools provide metro operators with a framework to reduce particulate levels and make underground transport not only low carbon but also healthier for passengers and staff. Future work should focus on integrating advanced monitoring technologies and predictive models. Hybrid approaches combining physics-based understanding with machine learning appear particularly promising for improving accuracy while maintaining interpretability. Emerging solutions such as smart ventilation control, real-time sensor networks and particle capture technologies may further improve underground air quality. Additional research is also needed to better understand the toxicity and health impacts of iron-rich railway particles.

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References

1. INERIS: Recommandations pour la réalisation de mesures harmonisées de la qualité de l'air dans les enceintes ferroviaires souterraines. INERIS, Verneuil-en-Halatte (2023)
2. Zheng, T., Bergin, M.H., Johnson, K.K., Shirodkar, S., Landis, M.S., Carlson, D.E.: Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments. Atmospheric Measurement Techniques. **11**(8), 4823–4846 (2018). https://doi.org/10.5194/amt-11-4823-2018
3. Cha, Y., Olofsson, U., Gustafsson, M., Johansson, C.: On particulate emissions from moving trains in a tunnel environment. Transport and Environment. **59**, 35–45 (2018). https://doi.org/10.1016/j.trd.2017.12.016
4. Tu, M., Cha, Y., Wahlström, J., Olofsson, U.: Towards a two-part train traffic emissions factor model for airborne wear particles. Transport and Environment. **67**, 67–76 (2019). https://doi.org/10.1016/j.trd.2018.11.006
5. Health Canada: Guidance for Improving Subway Air Quality. Government of Canada, Ottawa (2022)
6. Institute of Materials, Minerals and Mining (IOM3): Photocatalytic concrete to reduce traffic pollution in tunnels. https://www.iom3.org/resource/photocatalytic-concrete-to-reduce-traffic-pollution-in-tunnels.html. Accessed 9 Mar 2026
7. Fruhwirt, D., Sturm, H., Steiner, H.: Partikelemissionen des Schienenverkehrs-Ergebnisse aus in-situ Messungen in Tunnelanlagen. Gefahrstoffe Reinhaltung der Luft. **81**(5–6), 71–76 (2021). https://doi.org/10.37544/0949-8036-2021-05-06-71
8. Fruhwirt, D., Sturm, P., Bucca, G., Bode, G., Michael, S., Rodler, J.: Emissions from railways: Results of tests on a pantograph–catenary test bench. Transport and Environment. **115**, 103667 (2023). https://doi.org/10.1016/j.trd.2023.103667

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Preparing for the Future in the Automotive Sector Education

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Abstract. The automotive industry is undergoing rapid transformation driven by advances in vehicle technology, transport systems, and changing mobility preferences. These developments are reshaping the knowledge and skills required for vehicle maintenance, repair, and sales, with significant implications for vocational education. The transition from petrol and diesel vehicles to electric powertrains demands substantial changes in energy infrastructure, while increasing vehicle automation alters driver roles and introduces new requirements for automotive services. Within the AutoCove 2.0 project, key trends in the automotive sector, including powertrain diversification, advanced driver assistance systems, and automation, were analysed alongside differences in national vehicle fleets. A Europe-wide survey of automotive educators and industry representatives revealed the most pronounced knowledge gaps in emerging technologies such as hydrogen systems and vehicle automation, as well as in generic IT, language, and information-seeking skills. To address these gaps, industry, educational institutions, and research organisations are collaboratively developing future-oriented training courses delivered via an online learning platform. The courses are aligned with European Qualifications Framework levels and will be freely available for five years.

Keywords: skills-gaps · education · electrification · CCAM · hydrogen

1 Introduction

The automotive industry is undergoing significant transformation because of advancements in vehicle technology, powertrain development, and evolving mobility preferences. These shifts are directly influencing the knowledge base and skill sets required for vehicle maintenance, repair, and sales, thereby shaping the demands placed on vocational education and the expertise of educators [1, 2]. The transition from traditional petrol and diesel vehicles to hybrid and fully electric models necessitates considerable adjustments to energy infrastructure and the broader energy system [3–5]. The inherent structural differences between battery electric vehicles (BEVs) and conventional vehicles require changes in maintenance services, particularly regarding the spare parts and accessories that must be replaced throughout the lifecycle of an electric vehicle to ensure optimal performance [6]. Furthermore, developments in vehicle automation [8, 9] are

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expected to alter the responsibilities of drivers and create new requirements for vehicle maintenance and sales [9].

2 Changes in Well-Established Field

Ongoing advancements in vehicle powertrains and the growing prevalence of advanced driver assistance systems, and eventually automation, present new challenges for the automotive industry, particularly regarding the skills required of maintenance and sales personnel. Over the past century, extensive understanding and established practices have developed around the operation and use of conventional motor vehicles [10, 11]. These established habits strongly influence societal attitudes towards and usage of motor vehicles. The integration of alternative propulsion technologies necessitates adaptations in these behavioural patterns, with the extent of change dependent on how widely the new technologies are adopted [12].

3 Skills-Gaps Analysis

3.1 Background

The automotive sector plays a vital role in driving both the European economy and technological advancement. As the industry undergoes continual transformation and innovation, it is imperative that the workforce adapts to evolving demands [6]. Nevertheless, even with ongoing progress and technological breakthroughs, the automotive economy continues to encounter a significant obstacle: the skills gap. This issue increasingly stands out as one of the principal challenges for businesses and educational institutions within the automotive field [13, 14].

Skills-gaps refer to the disparities between the competencies present in the labour force and those demanded by the economy [15, 16]. These variances between actual skills and required qualifications not only contribute to imbalances in the labour market, but also hinder organisational efficiency, stifle innovation and competitiveness, and may impede progress towards a greener European transport system.

Technological advancements in the automotive sector are expected to significantly influence the competencies required of personnel in vehicle maintenance, repair, and sales. This, in turn, will have implications for educational programmes within these professions. The transition from one technology to another directly alters the necessary knowledge and skill sets; as outdated technologies are replaced, related expertise may become partly obsolete. Concurrently, the adoption of new technological solutions introduces additional requirements for updated knowledge and skills [12].

3.2 Methodology in AutoCove

Vehicle automation is expected to redefine the responsibilities of drivers and prompt significant changes in vehicle maintenance, repair, and sales processes. Beyond the direct implications for required skills and expertise, it is important to consider secondary effects, such as transformations within the energy sector and evolving business models

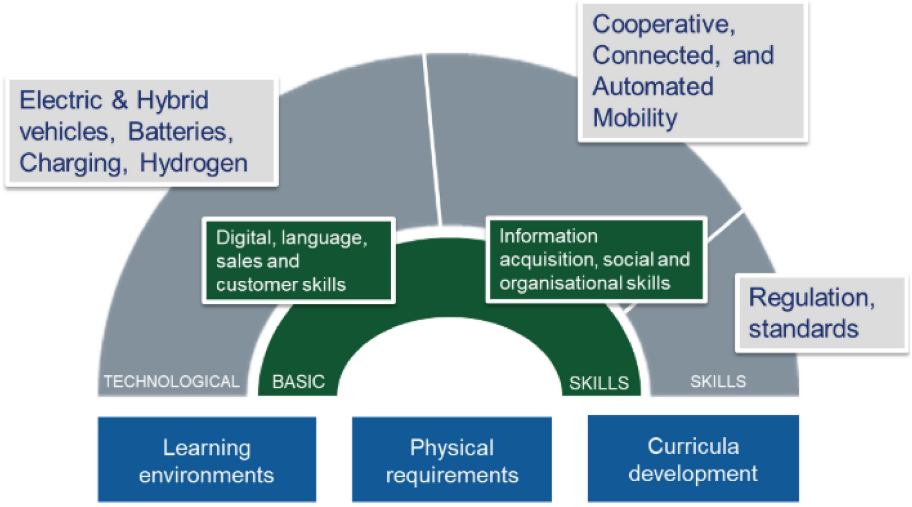


Fig. 1. Framework for skills-gaps analysis in AutoCove. (modified from [17])

among stakeholders. To support the AutoCove project's assessment of skill gaps, a structured framework (see Fig. 1) has been developed.

The framework served as the foundation for designing a comprehensive skills-gaps survey targeting automotive field educators and industry stakeholders across Finland, Estonia, Latvia, Lithuania, Germany, France, and the Netherlands. The analysis of survey responses aimed to address the following key research questions (RQs):

1) Which vehicle technology sectors are presently experiencing a skills-gap, or are likely to face one within the next five years? (RQ1)
2) To what extent is the identified skills-gap evident among teaching, sales, and maintenance personnel? (RQ2)
3) What fundamental competencies are required or prove beneficial for professionals in teaching, sales, and maintenance roles involving emerging vehicle technologies? (RQ3)
4) In what ways do skills-gaps differ across various service and maintenance organisations? (RQ4)

A web-based survey was developed to address the research questions. The survey consisted of the following sections:

- Part 1 – Background information
- Part 2 – Current and future technological skills and competencies relevant to the profession
- Part 3 – Current and future non-technological skills and competencies relevant to the profession
- Part 4 – Significance of information sources for the respondent's position
- Part 5 – Educational background and previous training

3.3 Main Results of the Skills-Gaps Analysis

In total, 375 responses were collected via an online survey (webropol) across Finland, Estonia, Latvia, Lithuania, Germany, France, and the Netherlands. Participants were recruited through the project partners' existing networks within educational institutions and sales organisations. As recruitment was based on convenience sampling, the dataset is not a random sample and the findings should be interpreted accordingly. Nevertheless, this approach enabled rapid data collection, and the country-level responses were considered to reflect the perspectives of the partner organisations. Responses comprised 47% industry professionals and 53% educators in the automotive sector [18].

Analysis of technical competency for sales and maintenance roles indicates significant variation in skill-gaps across countries and job categories. Employees associated with specific industry brands tend to report fewer competency gaps, whereas those occupying more general positions experience substantially larger deficits. This pattern is particularly pronounced in the maintenance sector, where considerable skill-gaps are observed across nearly all technologies. Project insights from an original equipment manufacturer (OEM) revealed that industry brands frequently offer comprehensive training programmes designed to align personnel capabilities with field requirements [18].

For educators, the range of skills-gaps is notably broad. In Germany and the Netherlands, skill shortages tend to be minor or moderate. Conversely, more substantial gaps are evident in Finland, France, and Estonia, particularly concerning vehicle communication systems and regulatory expertise. Latvia demonstrates the most pronounced deficiencies, with nearly all areas of competence affected [18].

Across all occupational categories, three technical fields consistently present the greatest challenges: batteries and charging systems, vehicle communication technologies, and regulatory compliance for alternative powertrains. Further significant gaps are observed, especially among maintenance staff and educators, in hybrid technology, hydrogen applications, and the calibration of advanced driver assistance systems [18].

The assessment identifies several areas for improvement in soft skills, namely IT proficiency, organisational and time management capabilities, financial literacy, and language competency. The survey also highlights preferred learning modalities among respondents. Teachers, sales professionals, and maintenance personnel predominantly favour employer-provided supplementary training, peer-to-peer learning, and the use of books. Given the practical and vocational orientation of these roles, which depend significantly on tacit knowledge, social interaction and shared experience are considered the most effective methods for skill development. Accordingly, employer-led training and insights gained from colleagues are highly valued, while books provide important factual and theoretical context [18].

A significant observation is the differing perspectives on the use of social media as an educational tool: industry professionals regard it as highly beneficial, while educators appear less inclined to utilise these platforms, potentially due to generational gaps or limited familiarity with their capabilities for effective knowledge dissemination. Nonetheless, platforms such as YouTube can provide both explicit content (including battery assembly through infographics and tutorials) and applied, experience-driven knowledge (such as vehicle repair methods). In summary, direct sharing of practical experience remains the preferred approach to knowledge transfer within these groups, whether

facilitated by structured training programmes, workshops, or digital social networks [18].

4 Developing the Educational Courses in AutoCove Project

The identification of skills-gaps informed the selection of topics for development on the e-learning platform. The following courses have been developed by project participants:

1) For battery electric vehicles: battery technologies; charging technologies; fire safety of high-voltage batteries; dismantling and recycling of batteries
2) Hybrid technologies
3) Fundamentals of hydrogen
4) Advanced driver assistance systems (ADAS) and automated driving systems
5) For sales personnel: alternative fuels, ADAS and automated driving systems – courses separately for sales representatives and spare parts sales.

In addition to these courses, which are designed for the Electude platform, supplementary learning materials covering mathematics and physics have also been produced over the course of the project. The implementation and translation process for the platform are going on and will be finalised by the end of 2026, after which the material will be available for free.

The development tasks have been allocated to the partners based on their respective areas of expertise. To ensure alignment of course materials with various EQF levels, development teams convene biannually to review each other's work, offer constructive feedback, and exchange best practices. These workshops are further supported by technical specialists from the e-learning platform, guaranteeing that project-based courses remain consistently coordinated with the other educational resources offered on the platform.

5 Conclusions

The automotive sector is experiencing significant transformation due to advancements in vehicle powertrains and the introduction of enhanced systems to support drivers, paving the way for increased automation. Furthermore, the European automotive industry faces mounting competition from emerging players, particularly Asian car manufacturers. Consequently, it is of outmost importance to remain competitive by ensuring that employees in the automotive sector possess current, relevant knowledge and skills.

The AutoCove project commenced with an assessment of anticipated sector requirements, followed by a thorough analysis of skills-gaps. Project development topics were selected according to these identified needs. By collaborating across industry, educational institutions, and research organisations, the project brings together essential partners to develop educational materials addressing both current and imminent demands. The project's success is driven by effective collaboration among stakeholders.

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References

1. Hötte, K., Somers, M., Theodorakopoulos, A.: Technology and jobs: a systematic literature review. Technol. Forecast. Soc. Chang. **194**, 122750 (2023). https://doi.org/10.1016/j.techfore.2023.122750
2. Macher, G., et al.: A study of electric powertrain engineering - its requirements and stakeholders perspectives. In: Yilmaz, M., Niemann, J., Clarke, P., Messnarz, R. (eds.) Systems, Software and Services Process Improvement. EuroSPI 2020. Communications in Computer and Information Science, vol. 1251. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-56441-4_29
3. European Union: Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 Setting CO_2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. European Union (2019). http://data.europa.eu/eli/reg/2019/631/2021-03-01/eng. Accessed 4 May 2026
4. European Union: Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 Amending Regulation (EU) 2019/631 as Regards Strengthening the CO_2 Emission Performance Standards for New Passenger Cars and New Light Commercial Vehicles in Line with the Union's Increased Climate Ambition (Text with EEA Relevance). European Union (2023). http://data.europa.eu/eli/reg/2023/851/oj/eng. Accessed 4 May 2026
5. Ajanovic, A., Haas, R.: Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. Int. J. Hydrog. Energy. **46**(16), 10049–10058 (2021)
6. Grosso, M., et al.: How will vehicle automation and electrification affect the automotive maintenance, repair sector? Transp. Res. Interdiscip. Perspect. **12**, 100495 (2021). https://doi.org/10.1016/j.trip.2021.100495
7. SAE: J3016_202104 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE International (2021) https://www.sae.org/standards/content/j3016_202104/. Accessed 4 May 2026
8. ERTRAC: Connected, Cooperative and Automated Mobility Roadmap. ERTRAC (2022) https://www.ertrac.org/wp-content/uploads/2022/07/ERTRAC-CCAM-Roadmap-V10.pdf. Accessed 4 May 2026
9. Boelhouwer, A., van den Beukel, A.P., van der Voort, M.C., Hottentot, C., de Wit, R.Q., Martens, M.H.: How are car buyers and car sellers currently informed about ADAS? An investigation among drivers and car sellers in the Netherlands. Transp. Res. Interdiscip. Perspect. **4**, 100103 (2020)
10. Geels, F.W.: The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technol. Anal. Strategic Manag. **17**, 445–476 (2005)
11. Nakicenovic, N.: The automobile road to technological change: diffusion of the automobile as a technological substitution process. Technol. Forecasting Soc. Change. **29**(3), 309–340 (1986)
12. Lilja, J., Seefried, M., Öörni, R.: D2.1 Development trends in vehicle fleet, vehicle sales and maintenance services. In: AUTOCOVE 2.0: Greening Europe

with Support of Clean-tech Vehicle Education. WP2. Research and Development (2024) https://www.autocove.eu/wp-content/uploads/2025/01/Auto-Cove-2.0-D2.1-Development-trends-in-vehicle-fleet-vehicle-sales-and-maintenance-services.pdf. Accessed 4 May 2026
13. Smit, G., Flickenschild, M., Verkennis, N., Martino, A., De Stasio, C., Fiorello, D., et al.: Study on Exploring the Possible Employment Implications of Connected and Automated Driving - Final Report. ECORYS, Rotterdam (2021)
14. Hagman, J., Stier, J.J.: Selling electric vehicles: experiences from vehicle salespeople in Sweden. Res. Transp. Bus. Manag. **45**(Part C), 100882 (2022)
15. Moldovan, L.: State-of-the-art analysis on the knowledge and skills gaps on the topic of industry 4.0 and the requirements for work-based learning. Procedia Manuf. **32**, 294–301 (2019). https://doi.org/10.1016/j.promfg.2019.02.217
16. Rikala, P., Braun, G., Järvinen, M., Stahre, J., Hämäläinen, R.: Understanding and measuring skill gaps in industry 4.0 — a review. Technol. Forecast. Soc. Chang. **201**, 123206 (2024). https://doi.org/10.1016/j.techfore.2024.123206
17. Partnership for 21st Century Learning: Framework for 21st Century Learning. Partnership for 21st Century Learning (2007) http://static.battelleforkids.org/documents/p21/P21_framework_0816_2pgs.pdf. Accessed 4 May 2026
18. Seefried, M. et al.: D2.2 Skills-gaps analysis. In: AUTOCOVE 2.0: Greening Europe with Support of Clean-Tech Vehicle Education. WP2. Research and Development (2024) https://www.autocove.eu/wp-content/uploads/2026/03/Updated-D2.2_SkillGapAnalysis_V5.pdf. Accessed 4 May 2026

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E-Mobility in Germany – A Comparison of Regional Development

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Abstract. In order to reduce emissions in the transport sector, a financial incentive to purchase electrically powered vehicles was introduced in 2016 with the environmental bonus. Based on data from the Kraftfahrt-Bundesamt, this study analyzes its effect on new passenger car registrations with a focus on regional variations as well as on the composition of the vehicle keepers. Particularly in the western German federal states, an increase in pure battery electric vehicles (BEVs) can be observed. Furthermore, private individuals are more inclined towards BEVs, while new registrations of plug-in hybrids are more likely to increase among commercial vehicle keepers. Also, the public charging infrastructure in Germany has expanded significantly. While fewer than 1,000 charging points were publicly available as of January 2014, their number increased to more than 160,000 as of May 2025. Especially in recent years, high-power charging points have grown rapidly, also driven by federal programs. Nevertheless, the charging network remains unevenly distributed, with dense clusters in populous western federal states and along major highways, while eastern and rural regions still show comparatively a lower density.

Keywords: Electric vehicles · Charging infrastructure · Green policy

1 Introduction

The Federal Climate Action Act sets net greenhouse gas neutrality for Germany by 2045 as a target [1]. Electric vehicles play an important role in reducing these emissions within the transport sector [2]. The environmental bonus started in 2016 as a financial incentive to purchase electric cars and was terminated in 2023. As part of a stimulus program, the funding was increased significantly in 2020 to comply with German climate targets and also to support the transformation of the automotive industry [3]. Furthermore, the establishment of a nationwide, user-friendly public charging infrastructure is a central prerequisite for a successful transformation of the transport sector. Various funding programs have been supporting its expansion.

This paper focuses on the spatial variations of how the environmental bonus affected the number of newly registered electric cars and how the public charging infrastructure in Germany has developed.

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2 Funding Programs in Germany

The environmental bonus started on 2 July 2016 to support financially the acquisition of new pure battery electric vehicles (BEVs), externally rechargeable hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), thereby further advancing electromobility in Germany.

Since its start, the environmental bonus had been adjusted several times. While it was initially only for newly registered vehicles, it was also extended to young used vehicles in 2020. The amount of funding was also subject to regular adjustments.

Table 1 gives an overview of the development of the funding amount and of the eligible persons [4–9].

Table 1. Adjustments to the funding amount and the eligible persons

Effective day	Funding amount		Eligible persons
2 July 2016	BEV/FCEV: PHEV:	€ 4,000 € 3,000	Private, commercial
19 February 2020	BEV/FCEV: PHEV:	max. € 6,000 max. € 4,500	Private, commercial
26 June 2020	BEV/FCEV: PHEV:	max. € 9,000 max. € 6,750	Private, commercial
1 January 2023	BEV/FCEV:	max. € 6,750	Private, commercial
1 September 2023	BEV/FCEV:	max. € 6,750	Private
18 December 2023	Termination		

Initially, the environmental bonus amounted to € 4,000 for BEVs/FCEVs, and € 3,000 for PHEVs. In 2020, it gradually increased to a maximum of € 9,000 for BEVs/FCEVs. At the beginning of 2023, funding for BEVs/FCEVs was reduced while promoting the purchase of new PHEVs stopped completely. As of September 2023, only private persons were eligible for funding. The environmental bonus was fully terminated on 18 December 2023.

The charging infrastructure in Germany has also been consistently supported by various public funding programs since 2017. With the introduction of the Fast-Charging Act in 2021, the focus shifted to the development of a fast-charging infrastructure. In particular, starting in 2023 with the 'Deutschlandnetz' (Germany network) program, private companies have been financially supporting in setting up high- power charging points (HPCs) at over 1,000 locations with around 9,000 HPCs [4].

3 Data and Methodology

To analyze the development of newly registered electric cars, data offered by the Research Data Center (FDZ) at the Kraftfahrt-Bundesamt (KBA) are used [10]. The FDZ provides the stock of vehicles in the Central Vehicle Register (ZFZR) as of 1 January of each year

from 2015 onward. These data contain all new registrations within a calendar year that remain in the ZFZR until 1 January of the following year.

Table 2 gives an overview of the passenger car stock as of 1 January 2025 and the number of new registrations in 2024 separately by propulsion system.

Table 2. Distribution of the propulsion system for passenger cars. Source: Official statistics of the KBA

Stock of passenger cars in the ZFZR as of 1 January 2025 (n = 49,339,166)		New passenger car registrations in 2024 (n = 2,817,331)	
Gasoline	29,918,520 (60.6 %)	Gasoline	991,948 (35.2 %)
Diesel	13,829,261 (28 %)	HEV (gasoline)	571,488 (20.3 %)
HEV (gasoline)	1,897,379 (3.9 %)	Diesel	483,261 (17.2 %)
BEV	1,651,643 (3.4 %)	BEV	380,609 (13.5 %)
PHEV (gasoline)	896,109 (1.8 %)	HEV (diesel)	183,998 (6.5 %)
…		…	
FCEV (hydrogen)	1,802 (~ 0%)	FCEV (hydrogen)	158 (~ 0 %)

Gasoline and diesel dominate the passenger car stock with about 89%. BEVs with 3.4% are present to a significantly smaller extent. In terms of new registrations in 2024, gasoline is on the first place with around 35% and BEVs accounting for 13.5%.

Since FCEVs appear in small numbers, they are not considered in the further analysis. It should also be noted that hybrid electric vehicles (HEVs) account for a significant share, especially in the case of new registrations. Since their purchase is excluded from the support of the environmental bonus, HEVs are also not considered in the further analysis.

The basis for the analysis of the public charging infrastructure in Germany is provided by the Charging Station Register of the Federal Network Agency as of the cut-off date 7 May 2025 [11]. The register records all charging points that operate in a publicly accessible manner and must therefore be reported by their operators in accordance with the Charging Station Ordinance in Germany [12]. It thus forms the official reference database.

In addition to location and operator details, the register also contains information on the installed performance of each available charging point. Based on these performance data, the charging points are divided into the following three categories for the analysis (Table 3):

Table 3. Categorization of charging stations according to performance indicators, defined by the National Control Center for Charging Infrastructure [13].

Normal charging points (NCPs)	Fast charging points (FCPs)	High power charging points (HPCs)
$\leq$22 kW	>22 kW and < 150 kW	$\geq$150 kW

These data do not contain all public charging stations that were reported to the Federal Network Agency at the time of publication, but only those with a completed notification procedure [12]. Furthermore, charging points that do not exist anymore at the time of evaluation were excluded from the retrospective examination.

The study aims to assess how changes in the environmental bonus have affected new registrations of electric vehicles, in particular BEVs. This includes differentiated analyses for private and commercial vehicle keepers, as well as a regional differentiation. Additionally, the regional development of public charging infrastructure is considered separately, differentiated by installed performance.

4 Results

Figure 1 shows the share of gasoline/diesel, BEVs and PHEVs in monthly new passenger car registrations from January 2014 to December 2024 for private (top) and commercial (bottom) vehicle keepers. Vertical dotted lines indicate the timings of the adjustments in the environmental bonus listed in Table 1.

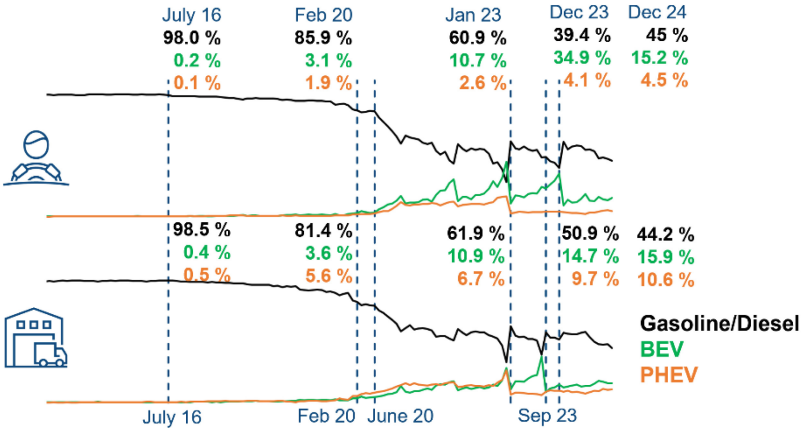


Fig. 1. Monthly new registrations of gasoline/diesel, BEVs and PHEVs for private (top) and commercial (bottom) vehicle keepers.

At the beginning, gasoline and diesel cars dominate in both groups with about 98% of all new registrations. From 2020 onwards, with the increase in the funding from a maximum of € 4,000 to up to € 9,000, the shares of BEVs and PHEVs start to rise. Private keepers are more likely to buy a BEVs than a PHEVs in comparison to commercial keepers.

As of January 2023, support for the purchase of a new PHEV ended and was reduced for BEVs. With these limitations, an increase in the shares of BEVs and PHEVs in the previous month is recognizable. For private keepers, the share of BEVs rises to over 40% in December 2022, for commercial keepers to slightly less than 30% for BEVs and PHEVs. In the latter group, the share of BEVs starts to increase from 2023, while the share of PHEVs decreases with a following stagnation.

With the end of the environmental bonus for commercial keepers in September 2023, a sharp increase in the share of newly registered BEVs up to 37% in August 2023 can be identified. In the months after, the shares of BEVs and PHEVs fluctuate on a significantly lower level between 11%–15% and about 10%, respectively.

For private keepers, after the cut in support as of January 2023, there is again an increase in the BEV ratio in monthly new registrations, which peaks at about 35% in December 2023. With the end of funding, the share of BEVs falls to about 10% and to 2%–5% for PHEVs in 2024.

It should be noted that during the whole period, gasoline and diesel cars remained to be the most frequently new registered in almost all months. However, their share more than halved from 98% in July 2016 to around 45% in December 2024.

For the following regional analysis of the development of new registrations, the period considered is divided into the following sections:

- January 2014 - June 2016: Before the introduction of the environmental bonus
- July 2016 - January 2020: After the introduction of the environmental bonus
- February 2020 - December 2022: Increase in funding amount
- January 2023 - December 2023: Funding restrictions/termination
- January 2024 - December 2024: After the end of the environmental bonus

Figure 2 shows the quantile position of BEV share of new passenger car registrations at NUTS 3 level (counties) for private keepers. The BEV ratios are divided into 8 groups according to their quantile position. The darker the color, the higher positioned is the BEV ratio of a county within the considered time period. The top category includes counties with a ratio positioned at the 87.5% quantile or above. In addition, the smallest and largest ratio are listed.

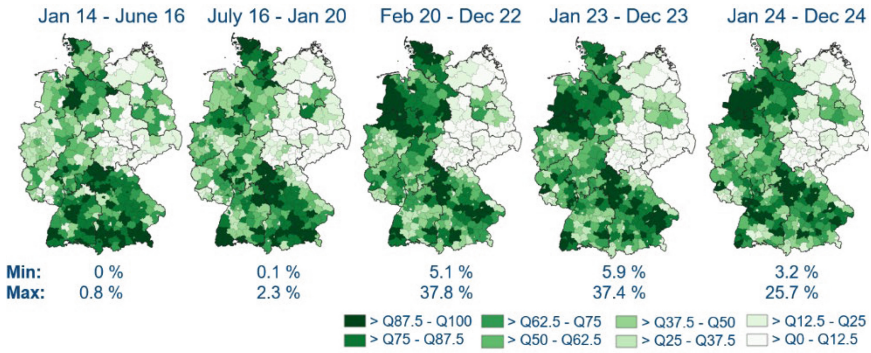


Fig. 2. Quantile position of BEV share of new passenger car registrations at NUTS 3 level for private keepers at different time periods.

In each depicted time period, the smallest BEV ratio increases steadily until the termination of the environmental bonus in December 2023. The share of BEVs in each county tends to increase, especially in comparison with the period before the introduction of the environmental bonus.

Before its introduction, the southern part of Germany in particular has a relatively high share of BEVs. The increase in funding from February 2020 is particularly noticeable, with a disproportionate increase in the BEV ratio in western regions of Lower Saxony and in northern regions of North Rhine-Westphalia.

While eastern regions of Germany only have a slightly smaller share of BEVs in new registrations before the introduction of the environmental bonus compared to the West, this gap widens over time. In all periods, BEV ratios in eastern regions remain positioned in the lower quantile range.

The results for public charging points are as follows. In January 2014 the overall number of public charging points was just under 1,000 in Germany. By May 2025 this number increased non-linearly to 162,443 charging points, with 80% of these charging points built since January 2020.

Furthermore, a significant shift in the range of power output can be seen over time. While NPCs continue to dominate in absolute terms, the shares of FCPs and HPCs have been steadily increasing since 2022. Approximately 70% of all HPCs in operation were created as of January 2023. This development also reflects the policy objective of substantially reducing charging times and facilitating long-distance operation of electric vehicles. Germany-wide support programs such as the 'Deutschlandnetz' to support HPCs also had a noticeably positive influence.

Figure 3 displays the small-scale distribution for all three charging point categories.

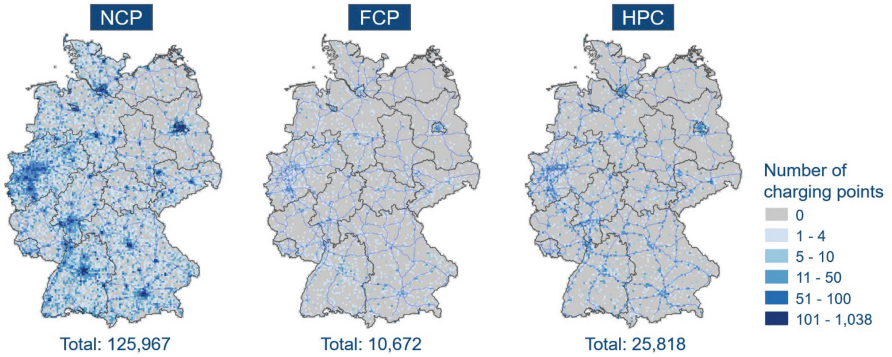


Fig. 3. Small-scale distribution of charging points over 5 km of grid cells (As of May 2025).

Due to their significantly higher numbers, NCPs are generally more widely dispersed across the area compared to FCPs and HPCs. In addition, they are strongly concentrated in the most populous conurbations. It's also evident that in regions with a lower population density, the network of NPCs is considerably thinner. This can be observed in eastern German states, but also in more rural western regions. Comparing the number of NCPs with the total amount of BEVs of private vehicle keepers at the federal state level, the three city-states of Berlin, Hamburg and Bremen rank highest in terms of charging infrastructure. This outcome is also linked to their lower vehicle density. While the majority of NCPs (almost 60%) are located in Bavaria, Baden-Württemberg and North Rhine-Westphalia, Schleswig-Holstein and Hesse also have a high density.

FCPs and HPCs are concentrated among the populous conurbations and along main traffic axes - in particular on highways as shown in Fig. 3. This spatial clustering is particularly evident for the example of HPCs. As of January 2025, more than 50% of all HPC stations are located less than 1 km away from highways, whereas for FCPs it amounts to 26% and 16% for NCP.

When calculating the number of HPCs per kilometer of national highway at federal state level, large parts of East Germany and Saarland are low performers, illustrating an East-West divide.

Setting the total number of BEVs in relation to the available charging points, an opposite distribution occurs. In federal states with a lower number of BEVs, the availability of charging points tends to be higher. This tendency is also evident at county level. Comparing the status on 1 January 2025 with 1 January 2020, a contrary development can be seen. In counties with a strong increase in BEVs since 2020 (such as in the northwest of Lower Saxony), the number of public charging points in 2025 is partially low compared to the locally reported BEVs.

5 Conclusion

New registrations of BEVs and PHEVs respond to changing conditions of the environmental bonus and situations of fear of missing out can be clearly seen in the case of cuts and restrictions on funding. In all regions of Germany, the share of BEVs in new registrations is increasing. In western Germany this increase is much more pronounced than in the East. The environmental bonus seems to have had a positive effect on new registrations of BEVs and PHEVs. At 1 January 2025, approximately 1.65 million BEVs were recorded in the ZFZR.

In terms of public charging infrastructure, it has been significantly expanded both quantitatively and qualitatively in recent years, especially from 2020 onwards. While NCPs initially dominate, FCPs and HPCs increase particularly dynamically from 2023 onwards. This development can also be attributed to strategic steering through funding programs and regulatory measures.

Federal states with a high population and a dense highway network (e.g. Bavaria, North Rhine-Westphalia, Baden-Württemberg) have the largest accumulation of charging points of all service categories. Rural areas continue to have mostly NCPs, which are often located within municipalities. Furthermore, it tends to be seen that a good public charging infrastructure is prevalent in regions with lower shares of electric vehicles, but that there is still room for catching up in areas with high market dynamics for electric vehicles.

This paper only focuses on public charging infrastructure. About 80% of all charging operations, however, take place at non-public charging points [14]. Thus, the question remains to what extent private charging can compensate possible supply deficits in the public sector.

Declaration of Generative AI and AI-Assisted Technology in the Writing Process. The authors used eTranslation in order to check grammar and spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content.

References

1. Federal Climate Action Act. https://www.gesetze-im-internet.de/englisch_ksg/englisch_ksg.html. Accessed 20 Feb 2026
2. Hausfather, Z.: Factcheck: how electric vehicles help to tackle climate change. https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change. Accessed 20 Feb 2026
3. Federal Ministry of Finance. https://www.bundesfinanzministerium.de/Content/DE/Downloads/Europa/DARP/2-02-klimafreundliche-mobilitaet.pdf. Accessed 20 Feb 2026
4. Federal Gazette. BAnz AT 01.07.2016 B1. https://www.bundesanzeiger.de/pub/de/amtlicher-teil?7&edition=BAn+z+AT+01.07.2016. Accessed 20 Feb 2026
5. Federal Gazette. BAnz AT 18.02.2020 B2. https://www.bundesanzeiger.de/pub/de/amtlicher-teil?26&edition=BAnz+AT+18.02.2020. Accessed 20 Feb 2026
6. Federal Gazette. BAnz AT 07.07.2020 B2. https://www.bundesanzeiger.de/pub/de/amtlicher-teil?30&edition=BAnz+AT+07.07.2020. Accessed 20 Feb 2026
7. Federal Gazette, BAnz AT 30.12.2021 B1. https://www.bundesanzeiger.de/pub/de/amtlicher-teil?31&edition=BAnz+AT+30.12.2021. Accessed 20 Feb 2026
8. Federal Gazette, BAnz AT 09.12.2022 B1. https://www.bundesanzeiger.de/pub/de/amtlicher-teil?32&edition=BAnz+AT+09.12.2022. Accessed 20 Feb 2026
9. Kraftfahrt-Bundesamt. https://www.bafa.de/DE/Energie/Energieeffizienz/Elektromobilitaet/Neuen_Antrag_stellen/neuen_antrag_stellen.html. Accessed 20 Feb 2026
10. Federal Motor Transport Authority. https://www.kba.de/DE/Statistik/Forschungsdaten zentrum/Datenangebot/Zentrales_Fahrzeugregister/Querschnitt/On/zentrales_fahrzeugregister_querschnitt_on_node.html. Accessed 23 Feb 2026
11. Federal Network Agency. https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/start.html. Accessed 26 Mar 2026
12. Federal Network Agency. https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/_DL/HandbuchMeldeportal.pdf?__blob=publicationFile&v=6. Accessed 24 Feb 2026
13. National Control Centre for Charging Infrastructure c/o NOW GmbH (ed.). ö-LIS-Report May–July 2025. https://nationale-leitstelle.de/wp-content/uploads/2025/08/oelis-report-pbi-2025-mai-jul.pdf. Accessed 24 Feb 2026
14. Federal Cartel Office. https://www.bundeskartellamt.de/SharedDocs/Publikation/DE/Sektoruntersuchungen/Sektoruntersuchung_Ladesaeulen_Abschlussbericht.pdf?__blob=publicationFile&v=3%20. Accessed 24 Feb 2026

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Innovative Battery-Operated Trains on Partially Electrified Lines: Some Case Studies and Applications in Italy

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Abstract. SI-C Power electronics is boosting the miniaturization and efficiency of converters that are involved in the energy management of trains. Mass production of high-performing lithium storage systems offers the possibility of implementing smart energy management both on rolling stock and infrastructures. Sustainable power sources are offering the possibility of a local production of electric energy with a limited environmental impact.

These innovative technologies are unlocking infinite new possibilities and functionalities for the power management of rolling stock: energy can be generated, accumulated, or transferred on board or interacting with different kinds of infrastructures with a level of freedom that was almost unthinkable ten or twenty years ago. This evolution allows the operation of trains with electric traction systems along partially electrified and non-electrified lines. A series of functionalities aiming to improve efficiency is now possible for both electrified and non-electrified lines. In this work, the authors focus their attention on the modelling of battery-operated rolling stock, introducing some case studies and simulation models related to the optimal design of these systems with respect to expected mission profiles. Small optimizations in the disposition of recharge islands can really improve the performance and durability of key components like traction batteries.

Keywords: Battery-Operated Rolling Stock · Recharge Islands · Non-electrified lines

1 Hybrid and Battery-Operated Rolling Stock: Introduction

Railway is one of the most efficient and sustainable means of transportation with high loading capabilities and modest motion resistances. From the beginning of the XX° the adoption of electric traction power has really contributed to further increase efficiency and sustainability. A complete electrification of every railway line is not feasible,

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especially when traffic intensities are relatively low. Additional factors, such as orography, cost of infrastructure, and energy sources, limit the diffusion of electrified lines. About a half of European railway lines is still not electrified [1], in many extra-European countries' electrification is much less diffused. When lines are not electrified, rolling stock is conventionally powered by an ICE (Internal Combustion Engine) with electric or hydraulic transmission systems. A natural evolution is represented by series hybrid solutions [2] in which an additional storage system is used to improve efficiency and autonomy of the ICE source by allowing regenerative braking and multi-modal service on partially electrified lines. More sustainable solutions involve the substation of fossil fuels with green Hydrogen [3] or another kind of renewable fuel. In Battery-operated rolling stock, the installed storage assures the desired mission autonomy [3–5]. All the above-described solutions can be easily described as particular cases of a series hybrid systems according to standard IEC 62864–1:2016 [6] as shown in Fig. 1a:

1. Primary sources: this is the main external power source of the system, such as an ICE-powerpack, a fuel cell system, or the power collected from the catenary.
2. Storage: electric energy is stored in a device such as a battery. The secondary storage works as a power buffer in terms of regenerative braking and peak shaving. If the storage is big enough, a full battery-operated service is possible.
3. Traction and Braking Loads: loads and power flows due to traction and braking.
4. Auxiliaries: additional loads associated to services (such as HVAC, pneumatic compressors etc)
5. Braking Choppers: recovered electric braking power that exceeds battery capacity is dissipated by dedicated resistors.

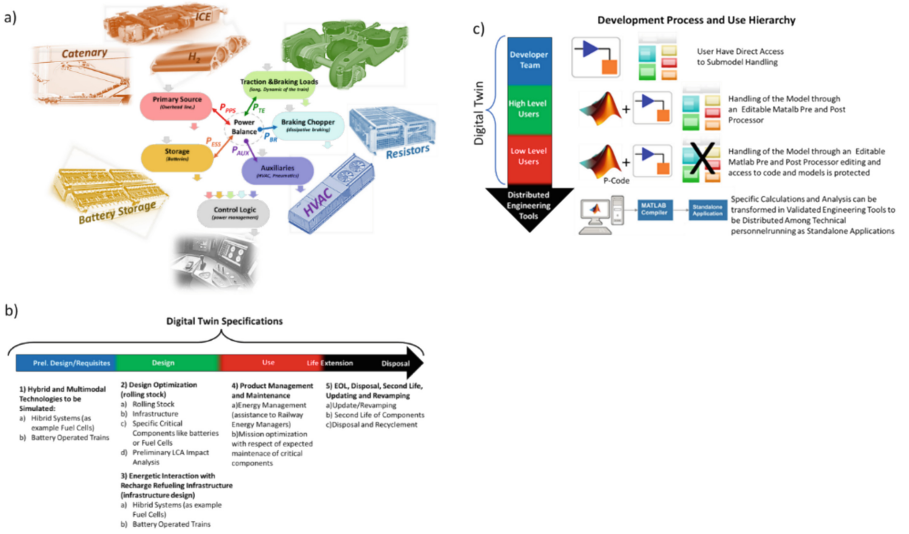


Fig. 1 Series Hybrid System according to IEC 62864-1:2016 [6] a), main features of proposed DIGITAL TWIN b), Development Process c)

Battery-operated rolling stock can be treated as a particular case in which the primary source is the pantograph connected to the overhead line, and the battery assures desired autonomy on non-electrified lines. Considering the wide variety of different solutions and operational scenarios, described by IEC 62864-1:2016 [6], There is a need for general tools able to help involved stakeholders to optimize their choices with respect to different technical, economic, and environmental constraints.

2 A Digital Twin for Multimodal Hybrid and Battery-Operated Trains

As shown in Fig. 1, a DTWIN (Digital Twin) [7] is proposed. DTWIN is able to reproduce the behavior of multimodal rolling stock according to IEC 62864-1:2016 [6]. Like any DTWIN [8], the model allows the choice of different approaches to fit different simulation scenarios following product life and consequently the continuous evolution of available input data and desired outputs. So, DTWIN is implemented in MATLAB-Simulink™ using variant or configurable subsystems. This approach, as shown in Fig. 1c, assures the possibility of scalable usage according to the needs and skills of the subjects involved. Special attention has been dedicated to updating and revamping activities: the expected life of rolling stock has a mean value of 25–30 years, prescribed life, and the technological availability of some critical components, such as fuel cells and batteries, is much shorter. Current literature predicts radical improvements for battery cells (for example, transition to solid or semi-solid electrolytes or new chemistries) for the next 5–10 years. DTWIN can help to manage updating and life extension, further regenerating the sustainability of the railway with respect to competitors.

3 Performed Simulation Campaigns

As shown in Fig. 2, it was defined a population of scenarios able to exploit and verify the functionalities of the DTWIN:

- Firenze Faenza Line: this is a steep-gradient railway line with a length of about one hundred kilometers. The line was used to analyses different hybrid [8] and full battery solutions [10, 11] also evaluating the optimized positioning of recharge-infrastructures [9–11].
- Firenze Siena and Siena Grosseto Lines: with a length of about 100 km and smoother grade, these case studies have been used for design optimization (hybridization ratio) of hybrid rolling stock (H2 fuel cells) also in terms of foreseen duration of key components like fuel cells [12]. The same benchmark has been used battery-operated rolling stock [13].
- Cagliari Sassari Line: This mission profile was proposed as worst-case benchmark (length of about 180 km, steep gradients) to evaluate applicability of hybrid [14] and battery-operated rolling stock.
- Electric and Energetic Interactions: these are some realistic scenarios to test interactions between battery operated trains and conventional ones under partially electrified lines of southern Italy. This activity is still in progress; however recent publications have demonstrated functionality and feasibility of the proposed approach [15].

- Reggio Calabria-Catanzaro Lido: this line, was investigated as a possible scenario for the application of battery-operated rolling stock since it satisfies some potentially interesting features. The line is long enough (about 180 km) to justify the study of recharging or partially electrified sections along the line. Gradients are modest, making the optimization of recharge points easier. The interested territories have great environmental value so their social and economic development can be improved by sustainable transportation. Performed analysis compared performances of different cell chemistries (LiNMC-LiFePO4) also in terms of cycle and calendar aging [16]. Mission profiles has been also used for HIL testing [17] of cells and storage systems.

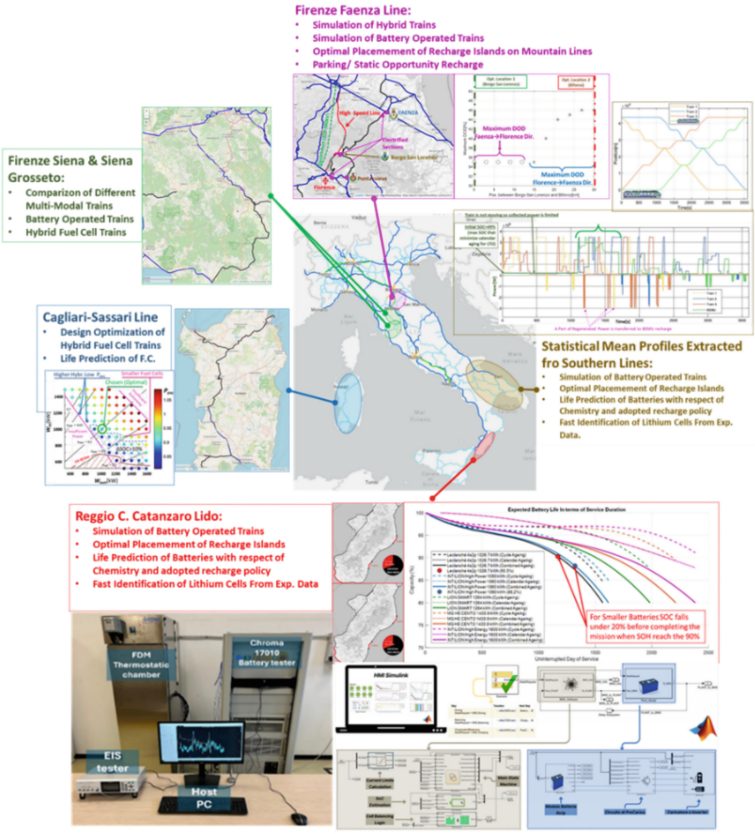


Fig. 2 A summary of case studies and corresponding analysis performed with various sub models and functionalities available on the proposed Digital Twin

As shown in Fig. 3, in this work, authors focused their attention on some more recent results, currently unpublished, which regards foreseen performances of a BEMU (Battery Electric Multiple Unit) version of the HTR412 Masaccio-Blues rolling stock, which is a train with a weight of about 190–195 tons, an installed traction power of about 1.5 MW, an onboard LTO Storage of about 660kWh. The maximum discharge-recharge rate of

the storage is about 3C. For what concern auxiliary consumptions, these loads have cautiously overestimated, considering unfavorable hot weather and a bit degraded/worn condition. Data are approximated since at the time when the analysis was performed, the train prototype was still not completed and tested, and some access to some information was restricted or uncertain. The aim of the activity was a preliminary investigation of the combined effects of calendar and cycle aging on batteries. This estimation should be really verified and improved when the data recorded in service is available. As far as data regarding the aging of LTO cells, calibration was performed on public data concerning cells with the same LTO chemistry [18–20].

Performed mission profile was coherent with existing timetables and performance constraints of the BEMU. To perform the combined analysis of calendar and cycle aging further cautious assumptions are introduced:

- Two complete round trips every day (about 700–720 km a day).
- Auxiliary consumptions when the train is stopped are also computed; an additional preparation time of the train of about 30–40 min at each terminus station is considered.
- Missions are performed every day cautiously considering an availability of 100% every day, neglecting maintenance periods or other reasons that normally justify a scheduled interruption or reduction of performed service.
- Dynamic recharge is performed at maximum rate (about 3C), exploiting the maximum performance of installed converters and cells, further stressing the cell in a cautious way.
- The expected autonomy cannot be more than 70–80 km (cautiously), so considering the length of the non-electrified section (about 150 km), two intermediate recharge islands (length of about 7–8 km) are installed along the line. Combined calendar and cycle aging was calculated with the following approach:
- Cycle aging is treated as cumulative damage associated to charge and discharge cycles (like mechanical fatigue). Cycle aging is calculated by applying the simulated load profiles to batteries. After the application of a known number of cycles (discretization step), battery capacity is updated for the next iteration.
- Calendar aging is substantially a weighted function of elapsed time, where the introduced weights are non-linear functions of State of Charge, Current, Temperature etc. The aging calculation is performed according to the tabulated model of DE HOOG [21], which is based on experimental data, and it is often used and cited in tech. literature. Regarding aging, isothermal behaviour is assumed (it is supposed to be an ideal thermal conditioning plant for batteries).
- Combined aging is performed by calculating the cycle aging associated to the execution of a few missions (discretization step). Since the mission profile is available, the elapsed time and the other parameters for the calculation of calendar aging are known. Both calendar and cycle aging can be calculated separately and summed up to update battery health at each discretization step. By repeating this process hundreds or thousands of times (according to the adopted discretization step in terms of performed missions) it is possible to foresee life and performances of the simulated storage system. Thanks to the relatively fast execution of the proposed model this iterative procedure is relatively fast.

In Fig. 3a and b behaviors of the battery SOC (state of charge) at BOL (Beginning Of Life) and EOL (End Of Life) during a simulated mission are compared. EOL is associated to a reduction of battery capacity to the 80% with respect of BOL.

Since SOH (State Of Health) of a battery is defined as the ratio between the current battery capacity and the nominal one, when the storage reaches EOL, the SOH is equal to 80%. In Fig. 3c the associated aging process in terms of SOH is represented with respect to equivalent charging-discharging cycles, elapsed time, and number of performed missions. Considering the cautious/penalizing conditions in which the simulation is performed, a life over 8 years seems to be more than feasible. It's interesting to notice the near-bilinear behavior of the aging process that is a bit accelerated when the storage reaches a SOH of about 92–93%. This can be explained considering that a reduction of battery capacity produces an acceleration of the aging process since the same mission profile is more severe if applied to storage with reduced capacity and increased impedance.

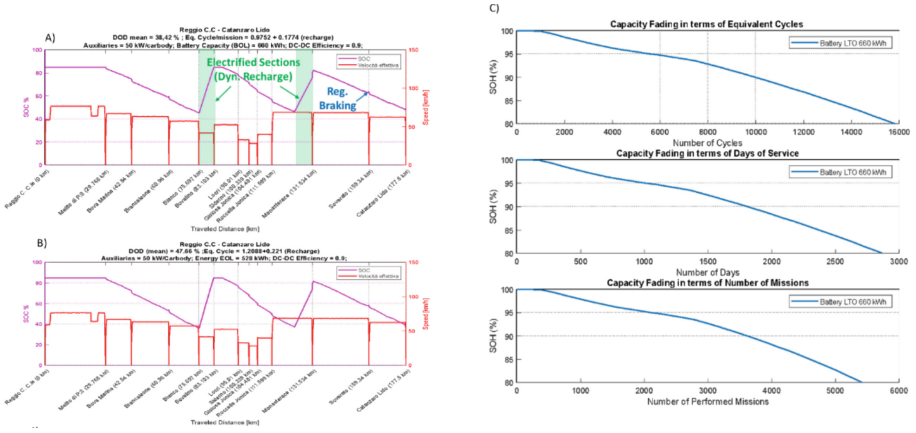


Fig. 3 Behavior of the storage in terms of SOC during a simulated mission, when battery is in BOL (a) and EOL (b) conditions, compared with corresponding aging in terms of SOH (c).

4 Conclusions and Future Developments

In this work, a DTWIN able to be simulate various kinds of Hybrids and Battery-Operated Rolling Stock has been presented. The proposed model is applied to the aging analysis of a battery-operated train on a partially electrified line, producing results that are quite relevant for the industrial exploitation of the investigated BEMU.

Since the calibration of the proposed results is mainly based on data from free technical literature, the authors are waiting for more experimental data that should be accessible when the prototype of full battery train completes a significant period of service. However, the performed simulations give a clear idea of the potentialities of the proposed approach and how a complete DTWIN like the proposed one can support the decision process of involved stakeholders.

Future activity will probably focus on the refinement and validation of the calibrated models with test field data, so the usage of AI tools should be very useful for classification of experimental data, model fitting, and extended evaluation of results.

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References

1. Rail. European alternative fuels Observatory (n.d.). https://alternative-fuels-observatory.ec.europa.eu/transport-mode/rail#:%E2%88%BC:text=Regardingmainlines%2C60%25of,isrunningontheselines. Accessed 25 Sep 2025
2. Garcia-Garre, A., Gabaldon, A.: Analysis, evaluation and simulation of railway diesel-electric and hybrid units as distributed energy resources. Appl. Sci. **9**(17), 3605 (2019)
3. Bohm, M., et al.: Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies. Int. J. Hydrogen Energy. **47**(89), 38003–38017 (2022)
4. Ogura, K.: Next-generation battery-driven light rail vehicles and trains. In: Electric Vehicles: Prospects and Challenges, pp. 169–206. Elsevier (2017)
5. Barbosa, F.-C.: Battery electric rail technology review-a technical and operational assessment. Current status, challenges and perspectives. In: ASME/IEEE Joint Rail Conference, p. V001T05A002. American Society of Mechanical Engineers (2022)
6. IEC 62864-1: 2016 Railway Applications - Rolling Stock - Power Supply with Onboard Energy Storage System - Part 1: Series Hybrid System. IEC (2016)
7. Crespi, N., Drobot, A.T., Minerva, R.: The Digital Twin. Springer (2023)
8. Liu, X., et al.: Object-oriented modeling mechanism for digital twin workshop elements. Adv. Eng. Inf. **68**, 103635 (2025)
9. Pugi, L., Carcasci, C., Poli, F., Mati, A., Berzi, L.: Application of static parking recharge to multi modal fuel cell trains. In: IEEE EUROCON 2023 - 20th International Conference on Smart Technologies, Torino, Italy, vol. 2023, pp. 653–658 (2023)
10. Pugi, L., di Carlo, L.: Multi-modal battery-operated trains on partially electrified lines: a case study on some regional lines in Italy. Proc. Inst. Mech. Eng. Part F: J. Rail Rapid Transit. **238**(7), 873–885 (2024)
11. Pugi, L.: Synergic design and simulation of battery-operated trains on partially electrified lines: a case study regarding the Firenze Faenza line. Energies. **17**(1), 24 (2024)
12. Pugi, L., Berzi, L., Spedicato, M., Cirillo, F.: Hydrogen for railways: design and simulation of an industrial benchmark study. Int. J. Modell. Identif. Control. **43**(1), 43–53 (2023)
13. Pugi, L., di Carlo, L., Kociu, A., Berzi, L., Delogu, M.: A tool for design and simulation of battery operated trains. In: Applications in Electronics Pervading Industry, Environment and Society Lecture Notes in Electrical Engineering, 1110 LNEE, pp. 431–436. Springer (2024)

14. Pugi, L., Berzi, L., Cirillo, F., Vecchi, A., Pagliazzi, V.: A tool for rapid simulation and sizing of hybrid traction systems with fuel cells. Proc. Inst. Mech. Eng. Part F: J. Rail Rapid Transit. **237**(1), 104–113 (2023)
15. Pugi, L., Calandroni, L., Lozito, G.M., Grasso, F.: Fast and modular implementation of railway lines models for RT and HIL testing of BEMU trains. In: 2025 IEEE International Conference on Environment and Electrical Engineering and 2025 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Chania, Greece (2025)
16. Pugi, L., Povolato, T.E., Tiezzi, N.: Simulation of combined aging effects for battery operated trains: a benchmark case study on the line between Reggio Calabria and Catanzaro. Energies. **18**(5), 1143 (2025)
17. Pugi, L., Kociu, A., Scardina, A., Berzi, L., Tiezzi, N., Delogu, M.: Fast identification of LiNMC cells for railway applications. Energies. **18**(13), 3300 (2025)
18. SoltaniI, M., et al.: Degradation behaviour analysis and end-of-life prediction of lithium titanate oxide batteries. J. Energy Storage. **68**, 107745 (2023)
19. Nemeth, T., et al.: Lithium titanate oxide battery cells for high-power automotive applications–Electro-thermal properties, aging behavior and cost considerations. J. Energy Storage. **31**, 101656 (2020)
20. Chen, H., et al.: Thermodynamic and kinetic degradation of LTO batteries: Impact of different SOC intervals and discharge voltages in electric train applications. eTransportation. **21**, 100340 (2024)
21. de Hoog, J. et al.: Combined cycling and calendar capacity fade modeling of a Nickel-Manganese-Cobalt Oxide Cell with real-life profile validation. Appl. Energy. **200**, 47–61 (2017)

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ECODRIVE Project: Managing and Controlling Traffic to Mitigate Pollution from Private Road Transport

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Abstract. In recent decades, the growing demand for mobility—driven by population growth and supported by investments in infrastructure and technological advancements in the automotive industry—has led to the widespread use of private vehicles as the dominant mode of transportation and to an extensive road network. This has made the transportation sector a significant contributor to pollution levels, with road transport emerging as the main source of emissions and noise pollution caused by traffic. In the ECODRIVE project, the problem has been addressed at its source by implementing a series of policy combinations through a simulation-based approach. These policies were designed to manage traffic flow variables and transportation demand, with the objective of simultaneously reducing emissions and noise. While encouraging more sustainable driving behaviours, these policies also aim at improving the environmental impact of road transport without compromising the level of service of the infrastructure. The results, presented in this paper, highlight the potential of an integrated approach for mitigating the overall road-related pollution. At the same time, they underscore the challenges of addressing emissions and noise simultaneously, due to their differing relationships with traffic flow parameters, and the need to balance environmental goals with system performance.

Keywords: Traffic Management · Road Traffic Pollution · Road Traffic Noise

1 Introduction

In recent decades, European cities have undergone significant population growth, leading to an expansion of urban areas and an increased demand for services. As a result, residents have been required to travel longer distances to satisfy both essential and non-essential needs [1]. This increased demand for mobility has been met primarily through investments in road infrastructure and technological advances in the automotive industry. These developments have produced a dense road network across Europe and improved the efficiency, affordability, and accessibility of cars, which have consequently become the dominant mode of transport [2].

The extensive reliance on private vehicles, however, has generated negative externalities in terms of mobility, safety, and environmental sustainability. Among these,

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environmental impacts have emerged as a central concern of the European Commission, particularly within the framework of recent policies aimed at reducing the ecological footprint of human activities [3]. The transport sector is a major contributor to both air pollution [4] and noise pollution [5], frequently exceeding legal thresholds. Road transport, when considered separately, represents an even more critical source of these pressures. Immediate mitigation measures are therefore required to limit its environmental impact [6].

Previous interventions have focused on both infrastructure design and vehicle technology. In addition, several studies have examined the influence of traffic parameters [7] and user behaviour [8] on emissions, with the objective of identifying effective mitigation strategies. Within this context, the ECODRIVE Project was established. The project investigates the evolution of environmental performance following the application of several traffic management and control policies. These policies, conventionally employed to improve traffic flow, are here evaluated for their potential to achieve simultaneous reductions in vehicle emissions and noise.

This article provides an overview of the project and summarizes its principal findings. Section 2 describes the materials and methods, Sect. 3 presents the main results, and Sect. 4 discusses conclusions and potential directions for future research.

2 Materials and Methods

The ECODRIVE Project investigates the combined effects of traffic management and control policies designed to modify traffic flow conditions and travel demand. The objective is to identify optimal policy combinations capable of simultaneously reducing road traffic emissions and noise. In this study, the policies were applied to a simulated vehicle fleet representative of that circulating in the city of Rome (Italy). The fleet composition was derived by cross-referencing data from ANAS detectors with vehicle registration data provided by the Automobile Club d'Italia (ACI), which operates in the field of fleet management. The resulting fleet is structured as follows:

- 19.94% of High-Emitting Cars (HE), covering all vehicles from EURO 0 to EURO 3.
- 33.45% of Medium-Emitting Cars (ME), including EURO 4 and EURO 5 vehicles.
- 25.55% of Low-Emitting Cars (LE), entirely composed of EURO 6 vehicles.
- 20.86% of Heavy Vehicles (HV).
- 0.20% of Motorbikes (Moto).

The selection of traffic policies considered the geometrical, functional, and technical characteristics of the road segment chosen as a case study. The test network corresponds to the South-Eastern Quadrant of the A90 motorway in Rome (Fig. 1). This section consists of two main carriageways running in opposite directions, each approximately 19 km long and composed of three regular lanes flanked by an emergency lane. The emergency lane narrows intermittently to accommodate entry and exit ramps, which occur at intervals of roughly 2 km.

As one of Rome's main traffic arteries, the A90 motorway carries substantial traffic volumes, particularly during peak hours. The South-Eastern Quadrant is the most congested section, with the external carriageway experiencing slightly higher traffic demand

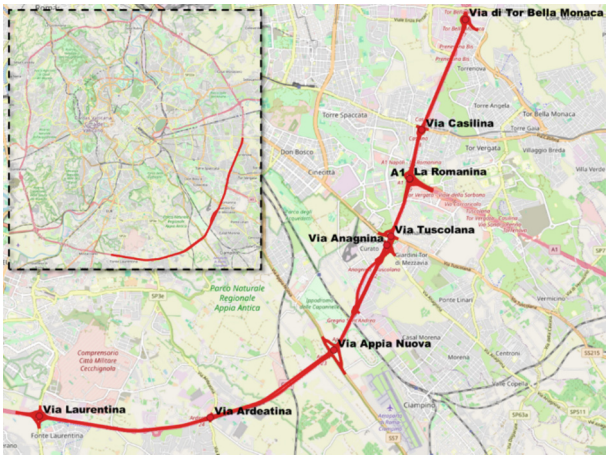


Fig. 1. The test network

than the internal one. The network was implemented within a simulation tool while preserving its geometry and elevation profile. Model calibration [9] was then performed using real traffic data collected from ANAS detectors [10, 11] distributed along the section.

On this road segment, two distinct sets of policies were applied, targeting supply-related variables and traffic flow conditions. The first set, referred to as "Speed Policies" (detailed in Table 1), introduces a progressive reduction of speed limits differentiated by vehicle class, with the objective of penalizing the most polluting categories.

Table 1. Speed Policies (Definitions: LE stands for Low-Emitting cars, ME for Medium-Emitting Cars, HE for High-Emitting Cars and HV for Heavy Vehicles)

	Speed [Km/h]					Speed [Km/h]			
Policy	LE	ME	LE	HV	Policy	LE	ME	LE	HV
01	130	130	130	80	11	100	100	90	80
02	130	130	120	80	12	100	90	90	80
03	130	120	120	80	13	90	90	90	80
04	120	120	120	80	14	90	90	80	80
05	120	120	110	80	15	90	80	80	80
06	120	110	110	80	16	80	80	80	80
07	110	110	110	80	17	80	80	70	80
08	110	110	100	80	18	80	70	70	80
09	110	100	100	80	19	70	70	70	70
10	100	100	100	80					

Speed limits range between 130 km/h and 70 km/h. In total, nineteen policies were implemented, each identified with a progressive code from 01 to 19.

The second set of measures, referred to as "Closure Policies" (described in detail in Table 2), restricts one or more vehicle classes from accessing specific lanes. Twelve closure schemes were defined; each identified with the acronym CH followed by a progressive number from 1 to 12. Table 2 can be conceptually divided into two sections. In the upper sect. (CH1–CH6), restrictions are first applied to the left lane, progressively excluding Heavy Vehicles, High-Emitting cars, and Medium-Emitting cars. The same scheme is subsequently applied to the central lane. The lower sect. (CH7–CH12) mirrors the previous one, with the addition that the emergency lane is opened to regular traffic. All scenarios were built combining one-to-one all the policies reported in Tables 1 and 2.

Table 2. Closure Schemes (Definitions: LE stands for Low-Emitting cars, ME for Medium-Emitting Cars, HE for High-Emitting Cars and HV for Heavy Vehicles). The check mark symbol indicates that the vehicle class is permitted to use the lane, while the X symbol indicates that the vehicle class is not permitted to use the lane.

Is the vehicle class allowed to travel?																
	Left lane				Central lane				Right lane				Emergency lane			
Policy	LE	ME	HE	HV	LE	ME	HE	HV	LE	ME	HE	HV	LE	ME	HE	HV
CH1	✓	✓	✓	**X**	✓	✓	✓	✓	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH2	✓	✓	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH3	✓	**X**	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH4	✓	**X**	**X**	**X**	✓	✓	✓	**X**	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH5	✓	**X**	**X**	**X**	✓	✓	**X**	**X**	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH6	✓	**X**	**X**	**X**	✓	**X**	**X**	**X**	✓	✓	✓	✓	**X**	**X**	**X**	**X**
CH7	✓	✓	✓	**X**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH8	✓	✓	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH9	✓	**X**	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH10	✓	**X**	**X**	**X**	✓	✓	✓	**X**	✓	✓	✓	✓	✓	✓	✓	✓
CH11	✓	**X**	**X**	**X**	✓	✓	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓
CH12	✓	**X**	**X**	**X**	✓	**X**	**X**	**X**	✓	✓	✓	✓	✓	✓	✓	✓

The study employed a simulation-based approach, summarized in Fig. 2. A baseline scenario was first defined, consisting of the road network, an origin–destination (OD) matrix, and the vehicle fleet composition. A traffic simulation was then performed to obtain key outputs: travel times, traffic volumes, and speeds. Traffic volumes and speeds were subsequently used as inputs for emission models, which provided estimates of energy consumption (used as a proxy for emissions) and noise levels.

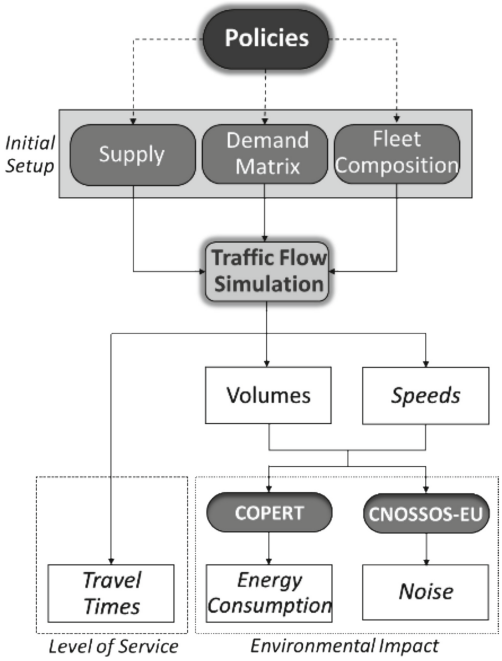


Fig. 2. The methodology

Following this baseline assessment, one of the scenario components was modified according to the policies described above, and the simulation process was repeated. At the end of the procedure, travel times, energy consumption, and noise levels were analyzed to evaluate how the system evolved in terms of both operational and environmental performance.

Energy consumption was assessed using the COPERT methodology [12], while noise levels were estimated with the CNOSSOS-EU model [13]. Both methodologies are standardized and officially endorsed by the European Commission.

3 Results

By combining all the policies reported in Tables 1 and 2, a total of 228 scenarios were simulated. All simulations were performed with the microsimulation software PTV Vissim™, considering an OD matrix reflecting the morning peak hour (07:00–08:00 AM) of an average working day. The results, presented as mean values for the entire road section and therefore displayed in aggregated form, are shown in Fig. 3. For illustrative purposes, the data from the internal carriageway are reported as a representative example.

Figure 3 summarizes the simulation results. The left panel (part a) reports the percentage variations in travel times and energy consumption, while the right panel (part b)

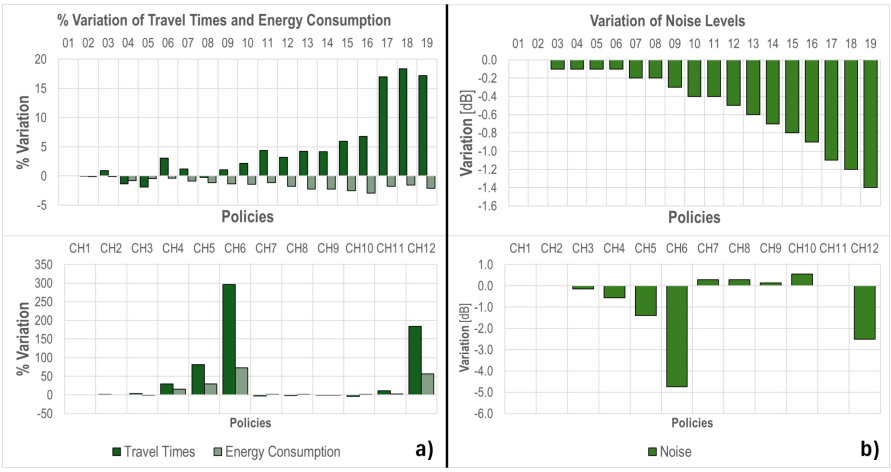


Fig. 3. Percentage variation of Travel Times and Energy Consumption – left part a) – and Variation in Noise levels – right part b) – after the application of policies.

shows the corresponding variations in noise levels following the application of the policies. When considering the results for the internal carriageway, the main observations can be summarized as follows:

- As regards the Speed Policies, increases in travel time remain limited as long as speed limits do not fall below 80 km/h. When increases occur, they seldom exceed 5% compared with the baseline scenario. Such marginal variations can be considered acceptable to be suffered by road users, provided that demonstrable environmental benefits are achieved. Progressive speed reductions appear effective in improving the environmental performance of road transport, particularly in terms of energy consumption and related emissions. However, the observed reductions are not statistically significant. Two main factors may explain this outcome: (i) the results are influenced by Heavy Vehicles, which were not subject to the speed policies; and (ii) the analysis relies on aggregated data, which may have masked more substantial effects. A disaggregated analysis would likely reveal stronger impacts. Conversely, noise levels exhibit a more consistent response. Due to the strong dependence of acoustic emissions on vehicle speed, reducing speed limits—even when differentiated by vehicle class—systematically lowers noise levels. Nevertheless, the maximum reduction achieved is limited to 1.4 dB, which is considerably lower than expected for the speed range examined.
- In contrast, the analysis of the Closure Policies highlights the difficulty of simultaneously reducing both emissions and noise. Lane closures substantially restrict the road capacity available to specific vehicle classes, thereby limiting the potential for reducing overall energy consumption. Detrimental effects on pollutant emissions are observed only when closures prevent vehicle use of the emergency lane. Conversely, opening the emergency lane to regular traffic—an approach already recognized for improving traffic fluidity—has a neutral effect: it does not generate environmental benefits but also avoids negative impacts on emissions and network performance,

resulting in stable travel times. In the most restrictive scenarios, however, the associated increase in travel times becomes excessive, severely deteriorating flow conditions. The concentration of most vehicle classes in the rightmost lane not only slows traffic but also reduces manoeuvrability at entry and exit ramps, even for vehicle categories not directly affected by the closures. This further aggravates congestion, particularly under already critical traffic conditions. From an acoustic perspective, the closure schemes prove markedly effective. In the most constrained scenarios, noise reductions exceed 4 dB, a substantial outcome considering that slower vehicles are confined to the lanes located closest to the noise receivers.

4 Conclusions and Outlooks

The ECODRIVE Project investigated the effectiveness of traffic management and control policies in simultaneously mitigating pollutant emissions and noise from road transport. Results from the simulation of 228 scenarios revealed a complex trade-off between environmental performance and system efficiency.

For the Speed Policies, a consistent but limited reduction in noise levels was achieved, while reductions in energy consumption were observed but not statistically significant. Increases in travel time associated with these policies remained marginal, rarely exceeding the baseline up to 80 km/h. Such limited increases can be considered acceptable when offset by measurable environmental benefits.

Conversely, Closure Policies impeded reductions in vehicular energy consumption due to restricted road capacity and became detrimental to emissions when prohibiting the use of the emergency lane. Allowing regular traffic on the emergency lane had a neutral impact, avoiding negative effects on emissions or flow conditions and maintaining stable travel times. However, the most restrictive closure schemes produced unacceptable increases in travel time, primarily due to the concentration of vehicles in the rightmost lane, which slowed traffic and severely compromised ramp manoeuvrability, thereby exacerbating congestion. Despite these drawbacks, closure schemes proved highly effective in terms of acoustic performance, achieving noise reductions exceeding 4 dB in the most constrained scenarios. However, a disaggregation of the HVs would likely further highlight these performance trends.

In conclusion, the findings indicate that the joint mitigation of air pollution and noise requires a differentiated policy approach: while speed policies deliver modest environmental benefits with preserved traffic fluidity, closure schemes provide substantial acoustic gains at the cost of significantly reduced system performance. Future research will expand the analysis beyond supply side measures by testing demand-oriented interventions and fleet electrification. Policies targeting fleet composition or network traffic volumes may yield stronger effects and merit further investigation.

References

1. Reddy, B.S., Balachandra, P.: Urban mobility: a comparative analysis of megacities of India. Transp. Policy. **21**, 152–164 (2012). https://doi.org/10.1016/j.tranpol.2012.02.002
2. ACEA: ACEA Report – Vehicles in Use, Europe. ACEA (2023) https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf. Accessed 25 Feb 2026

3. European Parliament: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions: the European Green Deal. European Parliament (2019) https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC. Accessed 25 Feb 2026
4. European Environmental Agency: Emissions of Air Pollutants from Transport in Europe. European Environmental Agency (2025) https://www.eea.europa.eu/en/analysis/indicators/emissions-of-air-pollutants-from. Accessed 25 Feb 2026
5. European Environmental Agency: Environmental Noise in Europe, 2025. European Environmental Agency (2025) https://www.eea.europa.eu/en/analysis/publications/environmental-noise-in-europe-2025. Accessed 25 Feb 2026
6. Haider, M., Descornet, G., Sandberg, U., Pratico, F.G.: Road traffic noise emission: recent developments and future. In: Proceedings of the 4th International SIIV Congress, Palermo, Italy (2007)
7. Chiou, Y., Chen, T.: Direct and indirect factors affecting emissions of cars and motorcycles in Taiwan. Transportmetrica. **6**(3), 215–233 (2010). https://doi.org/10.1080/18128600903168108
8. Shahariar Hasan, G.M., Bodisco, T.A., Zare, A., Sajjad, M., Jahirul, M.I., Van, T.C., et al.: Impact of driving style and traffic condition on emissions and fuel consumption during real-world transient operation. Fuel. (2022). https://doi.org/10.2139/ssrn.4012807
9. Onorato, T.: ECODRIVE: ECO-Driving to Reduce Infrastructures Vehicular Emissions. PhD Thesis. Università degli Studi Roma Tre, Rome (2025)
10. Anas S.p.A.: Osservatorio del traffico. https://www.stradeanas.it/it/osservatorio-del-traffico. Accessed 26 Feb 2026
11. Anas S.p.A.: DYNAMAP. https://www.stradeanas.it/it/dynamap. Accessed 26 Feb 2026
12. EMEP/EEA: EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023. EMEP/EEA (2023)
13. European Parliament: Commission Directive 2015/996 of 19th May 2015 Establishing Common Noise Assessment Methods According to Directive 2002/49/EC of the European Parliament and of the Council. European Parliament (2015) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L0996. Accessed 26 Feb 2026

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Applications in Port Logistics: Mapping Global Use Cases to Support the Transition of North Sea Ports

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Abstract. Ports play an important role in the energy transition and represent a particularly promising area for further deployment of hydrogen solutions. Within this context, the Interreg project "North Sea Hydrogen Valley Ports" aims to develop hydrogen-roadmaps in four European ports (Brest, Esbjerg, Bremen, and Den Helder) for a future maritime Hydrogen Valley. This paper presents the first phase of the project, focusing on the identification of potential hydrogen use cases in port areas, that will later be applied and further developed in the aforementioned four ports. The results show that the readiness to implement hydrogen applications varies among the analyzed ports and is closely related to local infrastructure conditions and energy constraints. While some ports are linked to the ongoing development of hydrogen infrastructure, others focus on initial use cases or solutions driven by specific challenges such as grid congestion. Overall, the study highlights that hydrogen technologies can play a key role in reducing emissions in port operations, particularly in mobile and heavy-duty applications.

Keywords: H2 Port · Hydrogen · Decarbonization · Use Case

1 Introduction

As international trade continues to expand, ports have become significant sources of greenhouse gas (GHG) emissions and other pollutants, not only from transport but also from terminal, warehousing and other logistical activities.

While increasing electrification efforts significantly support the reduction of CO_2 emissions, ports regularly face grid congestion and infrastructure limitations that restrict large-scale electrification [1]. Therefore, hydrogen may serve as a complementary solution for achieving emission reduction and decarbonization goals [2] by potentially enabling energy storage, grid balancing, and direct use in various port applications, from shore power to heavy-duty machinery.

The research is conducted within the Interreg project North Sea Hydrogen Valley Ports (NS H2V Ports), which aims to further develop hydrogen strategies for the ports of Brest (France), Esbjerg (Denmark), Bremen (Germany), and Den Helder (Netherlands) [3]. These strategies will be translated into concrete roadmaps that form the foundation

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for establishing a maritime Hydrogen Valley, with the overarching goal of accelerating the transition towards sustainable solutions in the maritime sector.

This paper presents the initial phase of the project, focusing on the identification of potential hydrogen use cases in port environments, which will be further assessed and developed in the four selected ports. By systematically mapping hydrogen use cases in port environments and linking them to port-specific conditions across four North Sea ports, this research contributes to the existing literature on hydrogen deployment in port contexts. These ports differ in terms of access to renewable energy sources (e.g., offshore wind in Esbjerg), grid constraints (e.g., grid congestion in Den Helder), scale and intensity of cargo operations (e.g., Bremen/Bremerhaven), and level of hydrogen infrastructure development (e.g., early-stage deployment in Brest), which directly influence the suitability of hydrogen applications. In later stages, these use cases will be further developed into concrete implementations within the four participating ports.

2 Methodology

Potential hydrogen applications in ports were investigated through comprehensive desk research and consultations with domain experts from the participating ports. Use cases include on-shore power supply, congestion management, grid balancing, hydrogen-powered cargo handling equipment, heavy-duty port machinery, as well as other hydrogen-powered port applications. These were analyzed with a focus on emission reduction potential, economic feasibility, infrastructure and energy supply requirements. The analysis focuses mainly on hydrogen-based solutions and does not aim to provide an exhaustive overview of all possible decarbonization measures. Other options may also be relevant but fall outside the scope of this study. The resulting insights form the basis for developing implementation scenarios tailored to four North Sea ports: Bremen/Bremerhaven, Esbjerg, Brest, and Den Helder.

3 Results

3.1 On-Shore Power Supply, Congestion Management and Grid Balancing

This section considers three general use cases in the context of port energy systems: on-shore power, congestion management and grid balancing (energy equilibrium in the broader power grid).

On-Shore Power Supply. The use of shore power is a very recent and largely discussed topic. Seagoing vessels also need energy in the harbor, whether to operate the on-board systems or to cool containers. Currently, ships are mostly using their so-called diesel-powered auxiliary engines to generate the required energy directly on board. According to the Fourth IMO GHG Study [4], an average of 16% of CO_2 emissions occur while ships are at berth or at anchorage.

An alternative for providing the ships at berth with energy is the use of shore power and therefore connecting the ships to the power grid on the land side of the port. Even though carbon footprints of grid power vary widely around the world, the global electricity mix has reached a 30% share of renewable energies in 2023 [5]. In the EU, the

share of renewable energy in the electricity mix reached 47% in 2024, according to Eurostat [6]. If nuclear energy is included, 71% of the EU electricity supply was based on low-carbon sources [7].

One example for on-shore power systems is the hydrogen-based on-shore power system from the Port of Esbjerg, which is developed in collaboration with Esbjerg-based technology company CS electric A/S. The system utilizes green hydrogen, produced from surplus wind energy, which is converted into electricity using fuel cells supplied by Ballard. Once installed, ships docked at the port will be able to draw electricity from this 100% CO_2-neutral source [8]. For on-shore power supply, hydrogen-based systems require relatively high initial investments (approx. €1–4 million for 0.3–1 MW systems), and entail operating costs of around €140–210/MWh, while offering key benefits such as zero-emission docking and reduced air pollution [9].

Although the use of shore power appears to be an effective and comparably fast-to-realize way of significantly reducing CO_2 emissions from shipping, there are a number of obstacles to its practical implementation such as low economic feasibility of shore power, volatile international fuel and electricity costs, high investment costs for port operators, high retrofitting costs for ship owners, the need for additional onshore electrical facilities due to various types of ships and ship sizes, etc. [10].

Congestion Management and Grid Balancing. As electricity demand increases, managing power flows becomes more complex. Congestion management focuses on managing power in the local grid, while grid balancing ensures that electricity supply and demand remain stable in real time.

For example, the Port of Den Helder is suffering from severe grid congestion issues. Hydrogen can help mitigate grid congestion in ports by providing flexible, local power generation. During peak demand, for example, when multiple ships connect to onshore power, fuel cells or hydrogen combustion engines can supply electricity without requiring costly grid reinforcements. While batteries should be the first option for short-term balancing, hydrogen offers an additional, reliable backup to maintain stability when storage alone is insufficient. Ideally, electricity is fed into the power grid at the moment it is generated. Any imbalance must be compensated in real-time through the use of power reserves. Traditionally, this was addressed by requiring power plants to maintain reserves that could be rapidly deployed in cases of overproduction or excessive demand. However, this approach is becoming increasingly complex with the rising share of electricity generated from Renewable Energy Sources (RES). The intrinsic variability in RES production, which is strongly dependent on factors such as time of day, seasonality, and weather conditions, further exacerbates these challenges [11, 12].

Consequently, the ongoing electrification of all transport modes, coupled with the increasing integration of RES into global power grids, poses significant difficulties in maintaining grid stability. One potential solution to reconcile rising energy demand due to electrification with the growing share of RES while ensuring grid stability is the deployment of energy storage systems. These systems store surplus electricity during periods of overproduction and release it during times of heightened demand. While battery storage systems offer a direct method of storing and discharging electricity, long-term battery storage solutions designed to balance seasonal fluctuations in RES generation remain highly expensive [11].

In this context, hydrogen represents a viable alternative to battery storage. Hydrogen production via electrolysis can serve as a mobile storage medium. The stored hydrogen can later be reconverted into electricity when additional energy is required or used directly, either in its pure form or as hydrogen derivatives, across various applications, which are discussed in the following sects [11]. Ports, which may host electrolyzers and hydrogen storage, are well positioned to become energy hubs [11].

While hydrogen production from surplus energy is often considered a viable option for balancing energy grids, it is important to assess where and when energy surpluses occur. In areas near ports and industrial zones, energy surpluses tend to be minimal, as these areas consistently draw large amounts of power from the grid. In such cases, importing hydrogen from regions with high energy surpluses could be an effective solution.

3.2 Cargo Handling Equipment

Ports, as critical hubs of global trade, rely on a wide range of vehicles and machinery to keep goods moving. This is particularly relevant for ports such as Bremen/Bremerhaven, where intensive cargo handling operations generate high energy demand. Cargo handling equipment (CHE) is central to these operations, including reach stackers, straddle carriers, gantry cranes, forklifts, etc. for containerized cargo, as well as loaders, cranes, and forklifts for bulk cargo [13]. According to the white paper "Reaching a tipping point in Battery-Electric Container Handling Equipment", Container Handling Equipment (CHE) may be categorized as either tethered (~30% of units are tethered) or untethered [14]. Tethered equipment, such as ship-to-shore cranes (STS), rail-mounted gantry cranes (RMG), and certain rubber-tyred gantry cranes (RTG), are already largely electrified and connected to the local grid. This setup allows for emission-free operation when powered by renewably sourced electricity [14]. In fact, a study published by Ramboll GmbH in 2022 confirms that RMGs and STS cranes are among the most electrified units in port operations, typically drawing power directly from the grid [15].

In contrast, untethered equipment (including straddle carriers, terminal tractors, reach stackers, forklifts, and mobile harbor cranes) remains largely dependent on diesel engines. These vehicles are mobile and operate over larger terminal areas, making electrification more challenging.

Although fuel cell electric (FCE) drives are the most commonly discussed option for hydrogen utilization, several other approaches exist. In FCE vehicles, the fuel cell is powered by hydrogen, which can be supplied in either compressed gaseous or liquid form. Within the fuel cell, the chemical energy of hydrogen is converted into electrical energy and heat. The electrical energy then powers the electric motor. The most common types of fuel cells are proton exchange membrane fuel cells (PEMFC) for vehicles and stationary power applications, and solid oxide fuel cell (SOFC), for stationary power applications. Additionally, hydrogen derivatives such as ammonia or methanol can be utilized in specialized FCs. For untethered equipment with long operating hours and heavy loads, this can be advantageous due to the higher volumetric and gravimetric energy densities of these derivatives compared to hydrogen, as well as simplified refueling and handling procedures. However, the use of hydrogen derivatives typically results in lower overall energy efficiencies.

To illustrate how these technologies translate into practice, reach stackers provide a representative example. Reach stackers remain predominantly diesel-powered and are essential in container terminals and intermodal yards due to their high flexibility and heavy lifting capacity. According to the study conducted by Ramboll GmbH [15], these vehicles are a major contributor to emissions in inland ports. Comparative technical data from the U.S. National Renewable Energy Laboratory (NREL) [16] provides additional insight into the operational performance of various reach stacker powertrains. According to NREL [16], FCE reach stackers are still in earlier stages of market entry, i.e., Technology Readiness Level (TRL) [17] is 6. They provide a typical operational range of 8–10 h and consume around 1,588 kWh per shift. Refueling times are fast, ranging from 10 to 15 min (0.16–0.25 h), but current energy costs are higher (estimated at US$334 per shift) due to hydrogen production and infrastructure limitations [16]. Despite these challenges, fuel cell systems are actively being tested in real-world port settings and offer a viable path toward zero-emission heavy-duty equipment. In this respect, FCE reach stackers are being tested in the Port of Valencia (the Hyster H2 Reach stacker). These vehicles offer fast refueling within 10 to 15 min [18], although limited hydrogen infrastructure remains a key deployment barrier.

Beyond FCs, hydrogen and its derivatives can also be used in ICEs. Since SoA diesel-powered machines are equipped with ICEs, hydrogen-powered combustion engines could enable the continued use of existing fleets through retrofitting measures. This approach is particularly relevant for fleets with long operational lifetimes, as retrofitting can facilitate rapid emission reductions. However, ICEs generally achieve an overall efficiency of approximately 40%, which is significantly lower than the average efficiency of fuel cells at around 60%. Consequently, ICEs have lower overall efficiency and higher hydrogen or derivative consumption [19]. Also, while they do not emit any CO_2, ICEs do still emit NOx, which can impact air quality in ports and coastal areas. In parallel, hybrid alternatives are also being explored, such as CMB.TECH **hydrogen dual-fuel** straddle carrier.

Although hydrogen FCE remains at the core of this analysis, Battery-electric solutions must also be considered, as they differ significantly in technological readiness. A comparative assessment is therefore provided in Fig. 1, showing that battery-electric options are around 14% more expensive than diesel, while hydrogen-electric options are about 80% more expensive, mainly due to higher energy and vehicle costs.

3.3 Other Hydrogen-Powered Port Applications

Beyond the previously discussed hydrogen use cases in the port environment, additional applications include tugs, pilot vessels, barges, and dredging, but also H2 refueling stations. In the case of Brest, one of the first identified applications is the development of hydrogen refueling infrastructure for trucks, which is also linked to its role as a node in the TEN-T network, where the deployment of H2 refueling stations is required.

Another important application is related to tugboats, which play a critical role in port operations, assisting with vessel maneuvering, towing, and emergency support. Traditionally, tugboats rely on diesel engines, contributing to maritime emissions. Hydrogen-powered tugboats provide an opportunity to transition toward zero-emission port operations while maintaining performance and efficiency [20]. One key project in this area

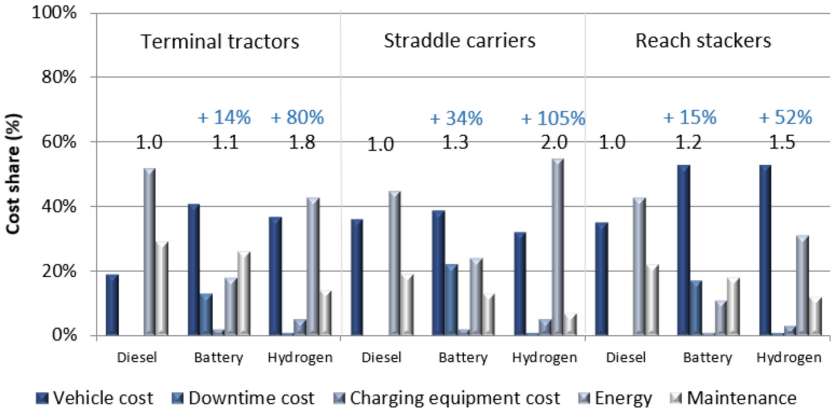


Fig. 1: Cost Comparison of Diesel, Battery-Electric, and Hydrogen-Electric CHE by Equipment Type, adapted from [14]. Values are presented as normalized cost indices (diesel = 1.0), enabling a relative comparison of costs across different technologies and equipment types.

is the Hydrogen Zero-Emission Tugboat Project [21], which is developing a hydrogen FC-powered tugboat capable of performing regular towing operations with minimal environmental impact. Another example is the Hydrotug 1 that consists of two innovative dual-fuel BeHydro engines that can run on either hydrogen or traditional fuel [20]. According to Fan et al. [22], out of the 50 hydrogen-fueled vessels identified, 10 originated as conventional diesel vessels and were subsequently retrofitted. The authors also claimed that high-pressure hydrogen refueling technology for land-based vehicles is already a mature technology. Building on this experience and considering maritime-specific risks (e.g., vessel motion and the handling of large hydrogen volumes) can enable the safe implementation of high-pressure hydrogen bunkering for vessels.

3.4 Discussion and Conclusion

This paper presents the initial phase of the project, focusing on identifying potential hydrogen use cases in port environments. These use cases will be further developed and applied in the four selected ports.

Although electrification efforts strongly contribute to reducing CO_2 emissions, ports often experience grid congestion and infrastructure constraints that hinder large-scale implementation. In this context, hydrogen can complement electrification, particularly in applications where grid limitations restrict further electrification. A comparison between Battery-Electric Cargo Handling Equipment and Hydrogen-Electric Cargo Handling Equipment was provided. Hydrogen-electric cargo handling equipment is particularly relevant in environments with unreliable grid access or extreme operational conditions. Battery-electric technologies are currently the preferred option due to their increasing availability, cost-efficiency, and compatibility with existing infrastructure.

Although ports are typically perceived as cargo handling hubs, their functions can differ significantly. Den Helder, for example, which is part of this project, serves, among others, as an offshore maintenance and supply hub. This underlines the importance of first

analyzing the strategic role of a port before identifying and investing in the most suitable decarbonization technologies. In this respect, further research is needed to examine how the strategic role of ports influences the feasibility of different hydrogen applications. The next stages of the NS H2V Ports project will provide this opportunity by further evaluating selected use cases in Brest, Esbjerg, Bremen, and Den Helder.

References

1. Chen, P.S.-L. et al.: Opportunities and challenges of hydrogen ports: an empirical study in Australia and Japan. Hydrogen. **5**(3), 436–458 (2024). https://doi.org/10.3390/hydrogen5030025
2. Zhong, X., Li, Y., Tang, D., Arasteh, H., Guerrero, J.M.: Realizing the role of hydrogen energy in ports: evidence from Ningbo Zhoushan port. Energies. **18**(15), 4069 (2025). https://doi.org/10.3390/en18154069
3. Interreg North Sea: NS H2V Ports. Interreg North Sea (2025) https://www.interregnorthsea.eu/ns-h2v-ports. Accessed 25 Sep 2025
4. International Maritime Organization: Fourth IMO GHG Study 2020 – Full Report. International Maritime Organization (2021) https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FourthIMOGHGStudy2020-Fullreportandannexes.pdf. Accessed 3 Sep 2025
5. Enerdata: Anteil der erneuerbaren Energien an der Stromerzeugung. Enerdata (2025) https://energiestatistik.enerdata.net/erneuerbare-energien/erneuerbare-anteil-in-strom-produktion.html. Accessed 3 Sep 2025
6. Eurostat: Electricity from Renewable Sources Reaches 47% in 2024. Eurostat (2025) https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250319-1. Accessed 3 Sep 2025
7. EMBER: Chapter 1: 2024 at a Glance. https://ember-energy.org/latest-insights/european-electricity-review-2025/2024-at-a-glance/. Accessed 3 Sep 2025
8. Larsen, S.H.: The World's First Hydrogen Solution for Shore Power. MARITIME (2022) https://www.maritime.direct/cs-electric-a/s-english-featured/the-worlds-first-hydrogen-solution-for-shore-power/1696133. Accessed 9 Sep 2025
9. NSH2V Ports: Deliverable D 1.8 Development of Alternative Use Cases of H2. NSH2V Ports (2025) https://www.interregnorthsea.eu/sites/default/files/2026-01/NSH2VD1.8DevelopmentofAlternativeUseCasesofHydrogen.pdf. Accessed 18 Mar 2026
10. Kim, K.: Characteristics of economic and environmental benefits of shore power use by container-ship size. J. Mar. Sci. Eng. **10**(5), 622 (2022). https://doi.org/10.3390/jmse10050622
11. Abu Bakar, N.N., Bazmohammadi, N., Vasquez, J.C., Guerrero, J.M.: Electrification of onshore power systems in maritime transportation towards decarbonization of ports: a review of the cold ironing technology. Renew. Sust. Energ. Rev. **178**, 113243 (2023). https://doi.org/10.1016/j.rser.2023.113243
12. Zenith, F., Flote, M.N., Santos-Mugica, M., Duncan, C.S., Mariani, V., Marconitini, C.: Value of green hydrogen when curtailed to provide grid balancing services. Int. J. Hydrog. Energy. **47**(84), 35541–35552 (2022). https://doi.org/10.1016/j.ijhydene.2022.08.152
13. Argonne National Laboratory: Cargo Handling Equipment at Ports. Argonne National Laboratory (2022) https://www.anl.gov/sites/www/files/2022-03/CargoHandlingEquipmentAtPortsFINAL3-23-22b%5B75%5D.pdf. Accessed 23 Sep 2025

14. APM Terminals, DP World: White Paper "Reaching a Tipping Point in Battery-Electric Container Handling Equipment". APM Terminals, DP World (2023) https://www.dpworld.com/-/media/project/dpwg/dpwg-tenant/corporate/global/media-files/whitepapers/reaching-a-tipping-point-whitepaper.pdf?rev=b76c90d2c4494ecaab3682a13c48651d, Accessed 9 Sep 2025
15. Ramboll: Studie alternative Antriebe für Hafenumschlaggeräte: Abschlussbericht. Ramboll (2022) https://www.now-gmbh.de/wp-content/uploads/2022/12/20221213-Abschlussbericht-alternative_Antriebe_Hafenumschlag-Studie.pdf. Accessed 9 Sep 2025
16. NREL: Hydrogen Infrastructure Analysis for Port Applications. NREL (2024) https://docs.nrel.gov/docs/fy25osti/91396.pdf. Accessed 9 Sep 2025
17. U.S. Department of Energy: Technology Readiness Assessment Guide. U.S. Department of Energy (2015). https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a-admchg1/@@images/file. Accessed 22 Sep 2025
18. Hyster: Hyster Ships Hydrogen Fuel Cell Reachstacker to the Port of Valencia. Hyster (2023) https://www.hyster.com/en-gb/emea/why-hyster/press-releases/hyster-ships-hydrogen-fuel-cell-reachstacker-to-the-port-of-valencia/. Accessed 22 Sep 2025
19. Schönfeld, M.: Brennstoffzelle oder Wasserstoff-Verbrenner? (2023). https://www.auto-motor-und-sport.de/tech-zukunft/unterschied-wasserstoff-brennstoffzelle-verbrennungsmotor/. Accessed 22 Sep 2025
20. Port of Antwerp-Bruges: Hydrotug 1: The Very First Hydrogen-Powered Tug. https://www.portofantwerpbruges.com/en/hydrotug-1-very-first-hydrogen-powered-tug. Accessed 23 Sep 2025
21. Lee, B.: The Hydrogen Zero-Emission Tugboat Project. California Energy Commission (2024) https://www.energy.ca.gov/sites/default/files/2024-05/CEC-500-2024-051.pdf, Accessed 23 Sep 2025
22. Fan, H., et al.: Two decades of hydrogen-powered ships (2000-2024): evolution, challenges, and future perspectives. Renew. Sust. Energ. Rev. **219**, 115878 (2025). https://doi.org/10.1016/j.rser.2025.115878

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Integrating Safety and Sustainability: A Grid-Independent Ultralight Quadricycle for Secure Urban Mobility

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Abstract. Light electric vehicles (LEVs) offer sustainable urban mobility through low energy consumption and compact design. However, broader adoption requires integrating energy autonomy and road safety assessments into the initial design phase. This study introduces a novel combined evaluation of grid independence and crash safety for a pedal-assisted quadricycle featuring vehicle-integrated photovoltaics (VIPV). A Florence-based case study first optimises geometry and VIPV placement to maximise solar yield under urban conditions. Second, simulations quantify occupant injury risk in heterogeneous traffic with increasing LEV market penetration, addressing the scarcity of real-world crash data. Results show that roof-oriented VIPV and parking-agnostic geometry significantly reduce external charging reliance. Concurrently, safety analyses confirm the vehicle's suitability for low-speed environments, specifically 30 km/h zones. This research establishes a generalisable methodology: while calibrated on Florence's topology and solar irradiance, the framework provides a scalable tool to minimise grid dependency and enhance safety across diverse climatic and traffic contexts.

Keywords: Pedal Assistance · Photovoltaics · Road Impacts · Geometry Optimisation · Sustainable Mobility

1 Introduction

Road transport accounts for over 70% of global CO_2 emissions [1,2]. Light Electric Vehicles (LEVs), specifically L1e-L7e quadricycles, offer a sustainable alternative through compact, energy-efficient designs that minimize mechanical losses and resource consumption compared to conventional cars [3–6]. Their reduced dimensions further optimize urban space and mitigate congestion [7].

Vehicle-Integrated Photovoltaics (VIPV) enhance LEV sustainability by enabling grid independence. Due to low power requirements, LEVs can continuously trickle-charge, reducing infrastructure reliance and range anxiety. Simulations indicate VIPV can meet up to 50% of daily commuting needs, potentially

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eliminating plug-in requirements [8–10], despite urban shading and durability challenges [11].

However, LEV adoption is hindered by safety concerns. Different crash standards between L-category vehicles and passenger cars [12] increase Injury Risk (IR) for occupants, particularly in collisions with larger and heavier vehicles [13]. Small crumple zones and mass incompatibility can lead to fatality risks 14 times higher than cars, particularly in frontal impacts [2,14,15]. Addressing these gaps is further complicated by the scarcity of real-world accident data [13].

To bridge these challenges, this work proposes a joint assessment of energy autonomy and road safety for a VIPV-equipped quadricycle. First, the study optimizes vehicle geometry and photovoltaic placement for Florence's solar irradiance to maximize annual energy yield and naturally minimize external charging requirements, directly addressing the goal of grid independence within urban environments. Second, to overcome the scarcity of real-world crash data for light vehicles, a validated simulation tool is used to model the gradual integration of LEVs into historically reconstructed collisions from the IGLAD database, quantifying severe injury risk across the operational domains where these vehicles circulate. Ultimately, these analyses converge into a preliminary vehicle concept that synthesizes energy efficiency and safety-by-design, specifically optimized for the operational requirements and safety dynamics of 30 km/h urban zones.

2 Grid Independence Analysis

This chapter quantifies the extent to which a road vehicle can rely on VIPV rather than the electricity grid. The analysis uses a MATLAB model fed by PVGIS data for Florence. A simplified vehicle geometry provides the active PV area and surface normals. The model converts plane-of-array irradiance into usable battery energy, accounting for angle-of-incidence, optical/thermal losses, shading, MPPT efficiency (95%), DC/DC conversion (95%), and battery charge acceptance. Parking orientation and daylight availability are treated stochastically, as most energy harvest occurs while parked.

Interpretation of grid independence requires coupling the solar clock (irradiance availability) and the mobility clock (parking vs. driving). If parked outdoors around solar noon, VIPV replaces a large fraction of grid energy; conversely, garaging or driving during peak sun yields less practical independence despite identical annual insolation.

2.1 Method and Energy Assumptions

Hourly irradiance and temperature data are taken from PVGIS for Florence. This database accounts for daily weather variability; based on 2020–2024 data, Florence experiences approximately 160 to 180 full sunny days per year.

Regarding losses, the optical chain is represented by a lumped factor of 40% of total harvested energy, while a parasitic load of 2% covers thermal management and telemetry while parked. The year is populated with a reference urban travel

schedule: a 3 km trip with a 100 m slope, driven back and forth daily. VIPV energy first serves auxiliaries, then powers the motor, and finally charges the battery subject to SOC and thermal limits. For each simulation, the model outputs SOC trajectories based on area allocation, tilt, and parking assumptions.

2.2 Results of Geometry Optimization

Geometry optimization aims to maximize annual VIPV energy within a vehicle envelope of $2.4 \times 1.1 \times 1.3$ m. The objective function weights midday, unshaded, parkable surfaces higher than raw irradiance. The geometry is divided into patches (roof, lateral, rear) defined by orientation angles (α, β, γ), as shown in Fig. 1. Mean solar kilometres for a vehicle with 50 Wh/km consumption are calculated as total energy production divided by vehicle-specific consumption.

The roof dominates production due to favorable incidence and minimal shading. The hood contributes significantly when flat; lateral surfaces perform better when vertical during low sun elevation. A rear surface angle of 60° balances energy conversion with cabin space. Dividing the array into multiple Maximum Power Point Tracker domains reduces shading penalties from roof rails. Efficiency is adjusted by a 0.42% reduction for each degree above Standard Test Condition.

The resulting design guidelines prioritize maximizing the unshaded horizontal roof area ($\gamma = 0°$), inclining lateral surfaces at $\beta = 60°$, and ensuring robustness to stochastic parking orientations rather than a fixed azimuth. This configuration is specific to Southern European regions; in higher-latitude areas with persistent cloud cover (<50 sunny days/year), grid independence is not achievable with standard storage, and added VIPV weight may even reduce overall efficiency. However, in favorable climates, grid energy becomes a seasonal backup, with the vehicle achieving zero grid import for extended summer periods.

3 Road Safety Assessment

3.1 Method – Impact Simulation and Injury Risk Functions

This section describes the framework used to assess the safety implications of introducing LEVs into car-to-car collision scenarios.

Accident Database (IGLAD). The study employs the IGLAD database [16], which aggregates standardized accident data from 13 countries. Representative European collision patterns were derived primarily from the German GIDAS dataset, with sampling applied to maintain proportional injury distributions. The dataset includes car-to-car impacts categorized by type (e.g., front-to-front, front-to-rear) and speed limits: 90 km/h (L7e max speed), 50 km/h (urban), and 30 km/h (L1e limit and low-speed zones [17]). As shown in Table 1, front-to-rear impacts are the most frequent, occurring 2–4 times more often than front-to-front collisions.

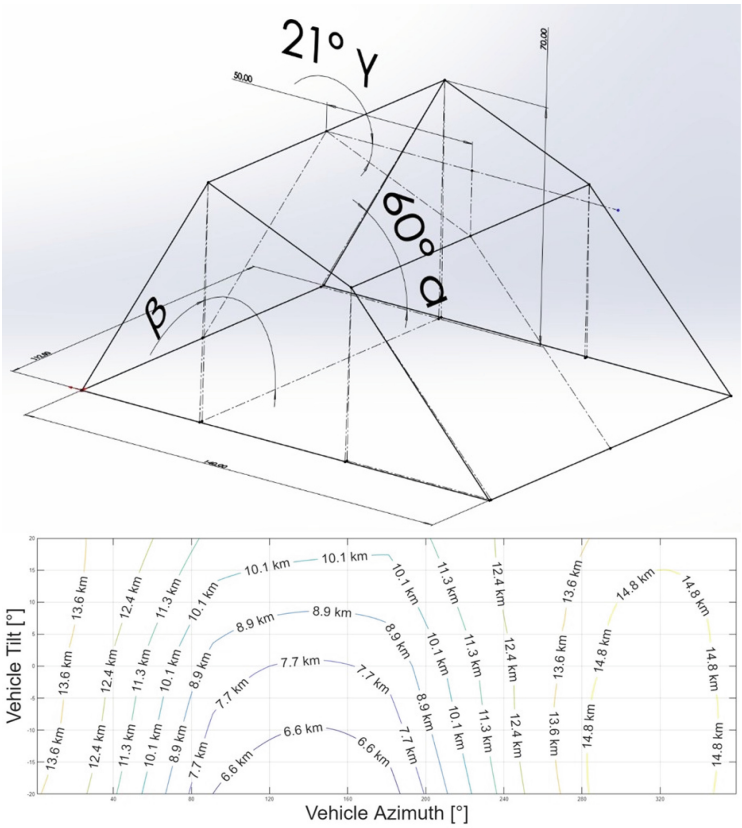


Fig. 1. Angles for geometry optimisation (top) and mean solar kilometres in Florence (bottom).

A validated 2D simulation tool was used to calculate velocity changes (ΔV) and occupant injury risk (IR). Vehicles were modeled as rigid bodies with structural nodes; the software showed high accuracy with average ΔV errors under 3 km/h compared to real-world data [18]. To define LEV structural properties, EuroNCAP protocols for heavy quadricycles (L7e) were applied to a reference vehicle (Ligier Ixo, 540 kg). Stiffness parameters were extracted from frontal and lateral tests, while rear stiffness was estimated via sensitivity analysis.

The fleet penetration effect was evaluated by systematically replacing passenger cars with quadricycles in simulated crashes using random sampling for 30% and 50% rates. Injury risk for severe lesions (MAIS 3+) was computed using the Jurewicz model [19], which estimates the probability of severe injury based on ΔV and impact type. In the absence of LEV-specific models, this car-based logit model provides a conservative estimate of occupant risk.

Table 1. Impact data distribution by collision type and speed scenario.

Collision Type	90 km/h	50 km/h	30 km/h
All	666	466	159
Front-to-Front	141	94	24
Front-to-Rear	348	260	105
Front-to-Side	125	85	22
Sliding	52	27	8

3.2 Results of Future Road Scenarios

Simulation results (Fig. 2) show that in 90 km/h scenarios, ΔV for quadricycles decreases as their penetration rises, yet the overall fleet average increases. IR follows this trend, peaking at 50–60% penetration ($\Delta V = 14.2$ km/h). Despite the higher risks at high speeds, IR remains relatively low (0.5–2%) due to the prevalence of front-to-rear impacts, which carry lower risk.

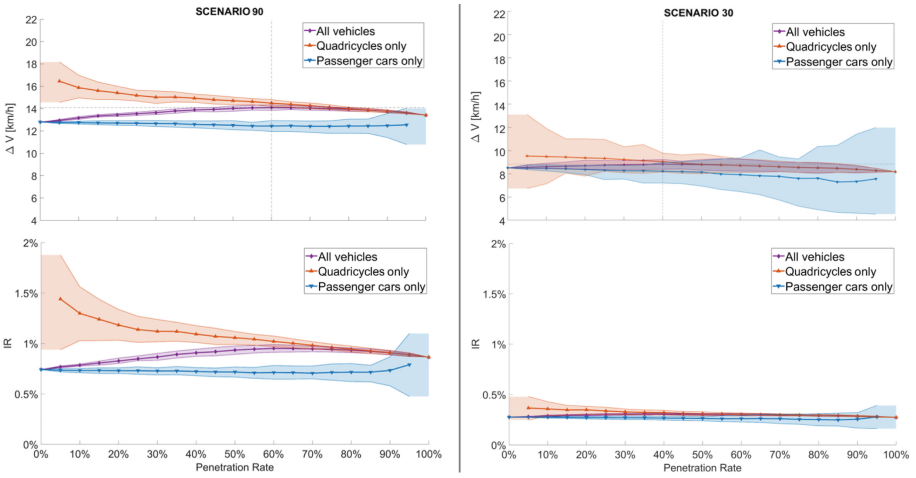


Fig. 2. ΔV (top) and IR (bottom) as a function of penetration rate for 90 km/h (left) and 30 km/h (right) scenarios.

In urban contexts (50 km/h and 30 km/h), LEV safety significantly improves. At 30 km/h, ΔV remains stable regardless of penetration rate, and IR is approximately one-fourth of that recorded at 90 km/h. Widespread adoption of quadricycles in 30 km/h zones could thus reduce fleet-wide IR. Conversely, in 90 km/h scenarios, quadricycle introduction lowers overall safety, doubling the IR for occupants transitioning from cars to LEVs. Consequently, the 30 km/h urban

environment is identified as the optimal operational domain for safe LEV integration.

4 Discussion and Vehicle Concept Proposal

The results demonstrate a clear synergy between energy autonomy and urban safety. The choice of an L1e-category vehicle for 30 km/h zones is strategically justified: while heavier L6e/L7e quadricycles allow for higher speeds, their increased energy demand and mass would negate the benefits of VIPV, requiring significantly more grid-charging. In contrast, the L1e concept maximizes grid independence by aligning low energy consumption with solar harvest. Also, the 30 km/h limit reduces IR to a stable baseline regardless of fleet penetration, making it the most viable domain for safe LEV integration with limited weight.

The resulting vehicle concept (Fig. 3) integrates these findings into a cohesive design. It features a 2 m^2 photovoltaic system with a horizontal roof ($\gamma = 0°$) and lateral panels inclined at 60° to maximize annual solar capture. Addressing the high frequency of rear impacts identified in the IGLAD database, the battery system is positioned as far forward as possible to minimize fire risk and structural intrusion during collisions. While the current optimization is calibrated for the solar irradiance of Florence, the developed framework is generalizable; for higher-latitude regions with lower insolation, the concept remains valid as a "solar-assisted" hybrid that reduces grid burden even when full independence is seasonally restricted. We currently estimated a kerb mass of 390 kg, that will be further reduced by the use of sustainable, recycled or organic-based composites.



Fig. 3. Vehicle concept resulting from the integrated energy and safety analysis.

5 Conclusions

The study focused on the design of a photovoltaic-supplied, ultralight quadricycle optimised for urban environments with 30 km/h speed limits. This choice was driven by simulation results, which demonstrated that the 30 km/h context is by far the most favourable for LEVs in terms of Injury Risk (IR) for the occupants. In these scenarios, IR is significantly lower compared to higher-speed environments and remains constant at whatever stage of fleet penetration, making it unnecessary to pursue heavier L6e and L7e vehicles, which would entail higher mass and energy inefficiencies. The vehicle design integrates VIPV through the placement of a 2 m^2 photovoltaic system, with geometry optimised to maximise solar energy capture year-round and minimise reliance on external power grids. To enhance safety, the battery was positioned away from the rear section, addressing risks identified in the analysis of frequent real-world rear impacts. While calibrated on the specific conditions of Florence, this research establishes a generalisable methodology adaptable to diverse climatic conditions and traffic dynamics. Further refinements will be devoted to frame optimisation to increase structural resistance and further weight reduction. Ultimately, this solution combines energy efficiency, occupant safety, and sustainability, offering an innovative option for secure and grid-independent urban mobility.

Declarations and Contributions

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Authors Contribution. Conceptualization: M.S.G., G.Z., D.V.; methodology: M.S.G., M.L., D.V.; software: G.V., M.L., L.P.; formal analysis: M.S.G., G.V., M.L., D.V.; investigation: M.S.G., G.Z.; writing—original draft: M.S.G., M.L.; writing—review and editing: G.Z., G.V., L.P., D.V.; visualization: M.S.G., G.V., M.L., L.P.; supervision: M.S.G., G.Z., D.V.

Data Availability. Data provided by the authors upon request.

Competing Interests. The authors declare no competing interests.

References

1. Chandrakar, N., Sekhar, C.C., Mageshwari, S., Daniel, S.A.: Electric vehicle progression in the society and their consequences. In: Advanced Technologies in Electric Vehicles, pp. 127–160. Elsevier (2024). https://doi.org/10.1016/B978-0-443-18999-9.00005-3
2. Davies, H.C., Bastien, C.: An approach for the crash safety assessment of smaller and lightweight vehicles. Transp. Policy **105**, 12–21 (2021). https://doi.org/10.1016/j.tranpol.2021.02.009

3. Ewert, A., Brost, M.K., Schmid, S.A.: Framework conditions and potential measures for small electric vehicles on a municipal level. World Electric Veh. J. **11**(1), 1 (2019). https://doi.org/10.3390/wevj11010001
4. Homsnit, T., Kongwat, S., Ruangjirakit, K., Noykanna, P., Thuengsuk, T., Jongpradist, P.: Optimizing stiffness and lightweight design of composite Monocoque sandwich structure for electric heavy quadricycle. Latin Am. J. Solids Struct. **20**, e485 (2023). https://doi.org/10.1590/1679-78257537
5. Wen, Y., Chen, Y., Wang, P., Rassol, A., Xu, S.: Photovoltaic–electric vehicles participating in bidding model of power grid that considers carbon emissions. Energy Rep. **8**, 3847–3855 (2022). https://doi.org/10.1016/j.egyr.2022.03.010
6. Suh, J.: Economic analysis of a solar roof as an optional extra to electric vehicles in Korea: a case study. Renew. Energy **239**, 122098 (2025). https://doi.org/10.1016/j.renene.2024.122098
7. Teibinger, A., et al.: Holistic approach for improved safety including a proposal of new virtual test conditions of small electric vehicles. Technical report, SAE Technical Paper (2015). https://doi.org/10.4271/2015-01-0571
8. Bhati, N., Kalla, U.K.: A solar PV based onboard range extension scheme for low power electric vehicles. In: 2023 First International Conference on Cyber Physical Systems, Power Electronics and Electric Vehicles (ICPEEV), pp. 1–6. IEEE (2023). https://doi.org/10.1109/ICPEEV58650.2023.10391931
9. Helera, C., Stoichescu, D.A.: The solar boost: pushing hybrid car limits with photovoltaic energy. In: Proceedings of the Proceedings of the World Congress on Electrical Engineering and Computer Systems and Science, Barcelona, Spain, pp. 19–21 (2024). https://doi.org/10.11159/eee24.119
10. Pochont, N.R., Sekhar, Y.R., Brito, M.C., Rao, V.T.: Assessing the scope of vehicle integrated photovoltaics in urban driving conditions–case study of a tier-ii city in southern india. Sustainable Energy Technol. Assess. **72**, 104040 (2024). https://doi.org/10.1016/j.seta.2024.104040
11. Diahovchenko, I., Petrichenko, L., Borzenkov, I., Kolcun, M.: Application of photovoltaic panels in electric vehicles to enhance the range. Heliyon **8**(12) (2022). https://doi.org/10.1016/j.heliyon.2022.e12425
12. Kongwat, S., Homsnit, T., Padungtree, C., Tonitiwong, N., Jongpradist, P., Jongpradist, P.: Safety assessment and crash compatibility of heavy quadricycle under frontal impact collisions. Sustainability **14**(20), 13458 (2022). https://doi.org/10.3390/su142013458
13. Kolk, H., Kirschbichler, S., Tomasch, E., Hoschopf, H., Luttenberger, P., Sinz, W.: Prospective evaluation of the collision severity l7e vehicles considering a collision mitigation system. Transp. Res. Procedia **14**, 3877–3885 (2016). https://doi.org/10.1016/j.trpro.2016.05.474
14. Homsnit, T., Jongpradist, P., Kongwat, S., Jongpradist, P.: Application of artificial neural networks for prediction of crushing performance of a quadricycle's s-rail. In: AIP Conference Proceedings, vol. 3086, p. 060001. AIP Publishing LLC (2024). https://doi.org/10.1063/5.0206304
15. Harrison, A., Christensen, J., Bastien, C., Kanarachos, S.: Crashworthy structures for future vehicle architecture of autonomous pods and heavy quadricycles on public roads: a review. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. **234**(1), 3–16 (2020). https://doi.org/10.1177/0954407019841195
16. IGLAD database. https://www.iglad.org/. Accessed 27 Mar 2026
17. Yannis, G., Michelaraki, E.: Review of city-wide 30 km/h speed limit benefits in Europe. Sustainability **16**(11), 4382 (2024). https://doi.org/10.3390/su16114382

18. Gulino, M.S., Vichi, G., Vangi, D.: Validation of a virtual forward simulation tool for ADAS assessment. Eur. Transp. Res. Rev. **17**(1), 25 (2025). https://doi.org/10.1186/s12544-025-00724-x
19. Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., Corben, B.: Exploration of vehicle impact speed–injury severity relationships for application in safer road design. Transp. Res. Procedia **14**, 4247–4256 (2016). https://doi.org/10.1016/j.trpro.2016.05.396

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From Innovators to Early Adopters: Implications of Different Charging Strategies on the Expansion of Charging Infrastructure in Urban Areas

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Abstract. Global sales of electric vehicles peaked in 2024, accounting for more than 20% of worldwide car sales. In Germany, the largest market in the European Union and the third largest globally, electric vehicles made up 6.4% of the fleet in January 2026, of which 4.1% were battery electric vehicles. According to Roger's theory of technology adoption, the earliest users, known as innovators, tend to be older males, well-educated with an above-average income, and preferred wallbox charging at their detached homes equipped with solar panels. The next group, early adopters, is generally younger, more often female, and resides in urban areas with limited access to private parking. Therefore, effective planning of future charging infrastructure must consider the different charging behaviors of early adopters. Our analysis, using the charging demand model CHARGIN, reveals distinct charging patterns for an average week and various location types. While traditional approaches typically focus on established charging patterns, our findings highlight the necessity of incorporating early adopters' requirements to ensure efficient infrastructure development.

Keywords: electric vehicles · charging demand · charging behavior · multinominal logit modeling · urban areas

1 Introduction

The rapid growth of electric vehicles (EV) sales reached a record high in 2024, accounting for more than 20% of all new passenger-car registrations worldwide [9]. Germany, EU's largest automotive market and the third-largest globally, hit a fleet share of 6.4% EVs (4.1% battery-electric vehicles (BEV)) in January 2026 [11]. This expansion is expected to accelerate as governments tighten emissions standards and introduce purchase incentives [5].

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According to Rogers' theory "Diffusion of innovations", the adoption of a new technology shifts from the group of innovators to early adopters when approximately 2.5% of the potential user base has adopted it [17]. Germany recently reached this critical threshold, signaling a transition in EV adoption dynamics. Early EV users relied on private wallbox charging installed in single-family homes, often paired with rooftop solar panels [19]. However, existing literature has anticipated a shift in the socio-demographic profiles of new EV users as adoption expands. In 2010, when the market was still dominated by innovators [15] found that individuals intending to purchase an EV within the next five years tended to be younger, more often female, and living in medium- and large-sized cities compared to current EV owners. These trends were even stronger when considering individuals interested in EVs, but without immediate purchase plans. In Norway, where EV penetration is high, [4] examined the influence of socio-demographic factors on EV adoption to inform policy for countries aiming to promote EV uptake. Their findings aligned with those of [15], showing that innovators typically lived in smaller households, while early adopters more often belonged to households of three to four people rather than two or fewer. Similarly, [14] linked EV adoption to negative correlations with semi-detached/terraced housing and socially rented dwellings in UK early markets.

Building on previous research, a growing proportion of EV adopters are now concentrated in medium to large cities with higher building densities. For Germany, this shift is closely linked to changes in the availability of parking spaces on private property. In 2017, when EVs accounted for less than 0.1% of Germany's car fleet [12], 92% of these vehicles were usually parked on private property (i.e., garage, carport, driveway), compared with only 75% in the total fleet; the rest were parked on public streets or in publicly accessible garages [10]. Parking patterns also vary regionally: private parking is predominant in small towns and villages, while on-street parking is most common in urban areas [10] Hence, alternative charging strategies – such as charging at workplaces, retail locations, or other publicly accessible sites – are crucial for accommodating new EV users who lack access to private wallbox chargers. These new charging patterns influence both the temporal and spatial distribution of charging demand. While home charging typically occurs in residential neighborhoods during the evening or night hours, workplace and retail charging typically take place during the day [8]. Additionally, the charging power of the available chargers shapes the aggregated load profile and determines the grid capacity required [7]. Overlooking these behavioral nuances could result in suboptimal infrastructure planning, under- or over-investment, and an increased risk of local grid congestion.

This paper addresses the research gap on charging behavior by early adopters using Germany as case-study for this paper as the largest car market in the European Union. We analyze how different charging infrastructure strategies affect the charging demand in urban areas ("metropolitan urban region" and "regiopolitan urban region" classified by RegioStaR [6]). Using the CHARGIN model, we generate high-resolution demand profiles, compare them among different user groups without private parking, and derive insights for two public

charging pricing strategies. The findings provide actionable insights for city planners, grid managers, charge point operators, and policymakers seeking to align infrastructure roll-out with evolving EV user groups.

2 Methodology

As the German EV market shifts from innovators to early adopters, accurately modeling charging demand is essential to understand the charging behaviors of new user groups. For this study, we utilize the CHARGIN model to analyze time- and location-specific charging demand. This model is used to evaluate different user groups and two pricing scenario settings.

2.1 The CHARGIN Model

The charging demand model CHARGIN (**C**onsumer **H**abits based **A**pproach to model **R**echarging and **G**rid **IN**tegration) enables a microscopic view of the charging demand in Germany [3]. Based on individual passenger car driving patterns, time- and location-specific charging demands of EVs on a microscopic level are modeled including information about occupied charging stations, the energy demand, and the connected charging power of a vehicle fleet. In order to consider different factors influencing the charging decision (i.e. price, power or charging place), a utility-based approach is chosen, as described in more detail in [18]. The aggregation of microscopic results enables an hourly resolution over the course of a week. The calculations are based on a vehicle diary derived from the travel patterns recorded in a National Travel Household Survey (NHTS). A charging decision based on location, availability, charging price and charging power is calculated for each charging opportunity.

In this study, the coefficients for the charging utility calculation were derived from a stated preference survey, which was conducted among more than 4,000 German EV owners between October and November 2020 [1]. The authors found that charging behavior is dominated by home charging as public charging infrastructure is not sufficiently available or is perceived to be not available. Furthermore, charging preferences differed among user groups, but the majority of users were open to new technologies such as controlled charging given that a certain flexibility for spontaneous trips was maintained.

By weighting and scaling the modeled vehicles, the hourly charging demand over an average week was calculated for different vehicle segments considering structural information (i.e., work, shopping, home, other) and the accessibility (i.e., private, semi-public, public).

2.2 Scenario Assumptions in CHARGIN Runs

The modeling presented in this study is based on the NHTS "Mobility in Germany 2017," which provides detailed data on passenger car travel patterns, temporal vehicle usage, and parking type locations (e.g., home, work, shopping)

across Germany [10]. Aggregated and weighted datasets from this survey serve as base for simulating time and location-specific charging demands on a microscopic level (see Sect. 2.1). We used various assumptions on future charging options to model the charging behavior. The most relevant assumptions are listed in Table 1 for different charging locations.

Nominal charging power differs between AC and DC charging. AC charging with 11 kW can be used on all private and public charging opportunities. Although most public charging points in Germany are capable of providing 22 kW, the majority of BEVs only support 11 kW AC charging. DC or fast charging is available at parking during shopping or as HPC hubs during the ride.

Availability of charging infrastructure describes the probability to find a free charging point. For BEV users, it is especially important to find charging infrastructure where they normally park throughout the day [16]. If a private parking spot is available at home this is the cheapest and most desired option [1]. We assumed a charging possibility at 8 out of 10 parking events during shopping. In public or at work we defined a free charging spot at 6 out of 10 parking events.

Charging price is perceived as the most important aspect of a charging decision [1]. Especially for persons in urban areas without access to a private parking spot at home the charging price can make a significant difference in charging behavior. We model two scenarios:

1. *Baseline*: Public charging prices are based on an market study of Lichtblick [13] while home charging assumes the average household electricity tariff [2]. For charging at work we assumed a reduced price since charging at work is tax free in Germany under §3 46 EStG and employers often get better conditions from their energy suppliers.
2. *Incentive*: Public charging prices are reduced to the level of home charging. Matching the charging price for public and private home charging ensures that people with access to a private wallbox have no incentive to use public charging stations instead of home charging.

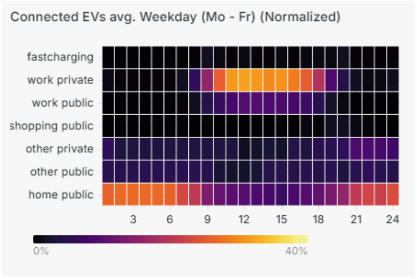
Table 1. Charging power, availability, and charging prices by location for the modeled scenarios.

	Scenario	Home private	Work private	Shopping	Public	Fast charging
Charging power (kW)	All	11	11	100	11	350
Availability (%)	All	100	60	80	60	–
Charging price (€ct/kWh)	1: Baseline	40	20	52	52	60
	2: Incentive	40	20	40	40	60

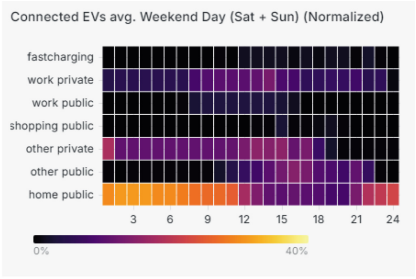
3 Results

The following analysis focuses on car users living in urban areas without a private parking spot at home. In Fig. 1, the normalized amount of connected BEVs by

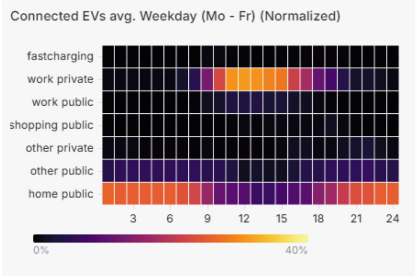
location is represented for young households (below age of 35) (see Fig. 1a and 1b) and families (see Fig. 1c and 1d) for an average weekday (left) and an average weekend day (right). The four heatmaps highlight that both young households and families predominantly rely on public charging infrastructure in residential areas. Furthermore, the results indicate that the majority of the observed users has access to a private parking spot at work where they tend to charge during workdays. During weekends families show high dependence on charging at home, while people in young households (average age of 35 or less) utilize charging at other locations on public and private ground.



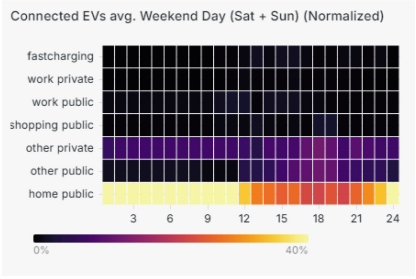
(a) Avg weekday: Young households



(b) Avg weekend day: Young households



(c) Avg weekday: Family households

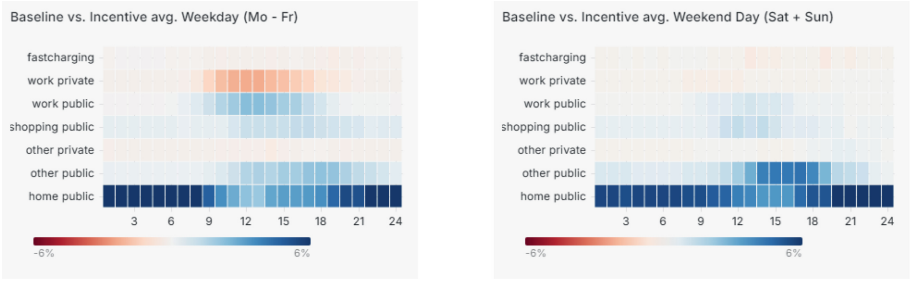


(d) Avg weekend day: Family households

Fig. 1. Connected EVs of urban drivers without home parking by charging location (young households top, families bottom, average weekday left, average weekend day right). Own analysis.

In Fig. 2, the normalized change between the *Baseline* and the *Incentive* scenario of connected BEVs by location is represented for an average weekday (left) and an average weekend day (right). The comparison reveals that equalizing the prices for public and private charging has a substantial impact on user behavior, particularly with increased demand for public home charging during both weekdays and weekends. On the other hand, demand for fast charging and other private locations is reduced. During average weekdays and weekend days the demand for public charging at home increases by up to 7% points, particularly

over night. During daytime the demand for charging at work changes from private (−2% points) to public (+3% points). On weekend days users are more likely to use public charging during their activities (i.e., work, shopping, and other) or near their residences.



(a) Avg weekday (b) Avg weekend day

Fig. 2. Normalized change in connected BEVs of urban drivers without home parking by charging location: *Baseline* vs. *Incentive* (average weekday left, average weekend day right). Own analysis.

4 Discussion

Our analysis identifies a shift in socio-demographic characteristics of new EV users within the early adopter group, resulting in distinct charging patterns compared to innovators, with implications for infrastructure planning. The observed user groups rely heavily on charging options beside private home charging. The CHARGIN simulations reveal three critical shifts:

1. Spatial and temporal redistribution: Workplace charging dominates weekday demand (peaking at 8–12 AM; Fig. 1a, 1c), while public/residential charging surges during night and weekends (Fig. 1b, 1d). Unlike innovators' home charging, this shifts grid load to commercial zones, creating daytime peaks.
2. Price sensitivity: Equalizing public and home charging costs (*Incentive* scenario) increases public charging demand by up to 7% points (Fig. 2), underscoring cost as a barrier for early adopters. This aligns with stated-preference studies [1], confirming that affordability drives public infrastructure usage. This incentivizes charge point operators to expand public charging infrastructure, accelerating spatial coverage as a societal goal.
3. Grid congestion risks: Cheaper public charging concentrates urban residential demand (Fig. 2), which might increase grid stress requiring controlled charging for long parking time or proactive grid expansion. The need for controlled charging may conflict with charge point operator utilization goals.

These findings resolve a key research gap: conventional infrastructure models, optimized for innovators' home charging, underestimate urban car owners' dependence on shared infrastructure. Socio-demographic factors like the availability of private parking spots help to understand the charging behavior. Only 40% of metropolitan car users have access to private home parking (vs. 88% in rural areas), forcing them to adapt multi-location charging strategies. While CHARGIN captures these dynamics through its utility-based framework, the model is limited: (1) stated-preference data from innovators may underestimate real-world price elasticity, and (2) travel diaries from pre-COVID combustion-era data may need recalibration as early majority adoption accelerates and concepts like working from home might change travel patterns.

5 Conclusion and Outlook

This study emphasizes the need for an adapted infrastructure planning, influenced by urban living constraints, and price sensitivity. The key findings show that workplace and public charging are the most preferred options among these users. By shaping the attractivity of these charging options, grid loads can be redistributed to commercial areas during the day and residential zones during night. Equalizing prices between public and home charging significantly boosts public infrastructure use, suggesting tariff reforms to accelerate adoption. Additionally, localized grid reinforcement or forced controlled charging might be necessary in urban areas to manage grid congestion. Recommendations include prioritizing capacity upgrades in commercial and high-density residential zones, advising charging infrastructure in new development areas, and deploying AC chargers in residential areas without hindering overnight charging (e.g., blocking fees) to match residents' preferences. Future research should focus on the impact of dynamic pricing on peak shaving, integrating mobility patterns and the charging behaviors of the early majority, and exploring vehicle-to-grid technology for mitigating grid stress. As EV adoption reaches the early majority phase, strategic infrastructure planning that considers user diversity will be crucial for a resilient and equitable transition to electric mobility.

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Author contributions. All authors have read and approved the final version of the manuscript. **Moritz Bergfeld:** Conceptualization, Methodology, Investigation, Formal Analysis, Visualization, Writing - original draft, Writing - Review & Editing; **Jens Hellekes:** Conceptualization, Project administration, Writing - original draft, Writing - Review & Editing; **John E. Anderson:** Supervision, Funding acquisition, Project administration, Writing - Review & Editing

References

1. Anderson, J.E., Bergfeld, M., Nguyen, D.M., Steck, F.: Real-world charging behavior and preferences of electric vehicles users in Germany. Int. J. Sustain. Transp. **17**(9), 1032–1046 (2023)
2. BDEW: Bdew-strompreisanalyse juli 2025 (2025). https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/
3. Bergfeld, M., Marianna, R., Krajzewicz, D.: Consumer habits based approach to model recharging and grid integration (Chargin) (2025, under review)
4. Bjørge, N.M., Hjelkrem, O.A., Babri, S.: Characterisation of Norwegian battery electric vehicle owners by level of adoption. World Electric Veh. J. **13**(8), 150 (2022)
5. Eurpean Comission: 'fit for 55': delivering the EU's 2030 climate target on the way to climate neutrality (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550
6. Federal Mnistry of Transport and Digital Infrastructure: Regiostar: Regional statistical spatial typology for mobility and transport research. https://www.bmv.de/SharedDocs/DE/Anlage/G/regiostar-raumtypologie-englisch.pdf?__blob=publicationFile
7. Fischer, D., Harbrecht, A., Surmann, A., McKenna, R.: Electric vehicles' impacts on residential electric local profiles. Appl. Energy **233–234**, 644–658 (2019)
8. Hoyer-Klick, C., et al.: Impact of charging behavior of electric vehicle users on the energy system. SSRN Electron. J. (2022)
9. IEA: Global ev outlook 2025 (2025). https://www.iea.org/reports/global-ev-outlook-2025
10. infas, DLR, IVT und infas 360: Mobilität in deutschland: im auftrag des bmvi (2018). https://www.mobilitaet-in-deutschland.de/archive/pdf/MiD2017_Ergebnisbericht.pdf
11. Kraftfahrt-Bundesamt: Bestand an personenkraftwagen nach kraftstoffarten in den jahren 2017 - 2026 (2026). https://www.kba.de/DE/Statistik/Fahrzeuge/Umwelt/umwelt_node.html
12. Kraftfahrt Bundesamt: Fahrzeugzulassungen (FZ 13): Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen (2026). https://www.kba.de/DE/Statistik/Produktkatalog/produkte/Fahrzeuge/fz13_b_uebersicht.html?nn=835828
13. Lichtblick SE: Ladesäulencheck 2025 (2025). https://www.lichtblick.de/ladesaeulencheck/
14. Morton, C., Anable, J., Yeboah, G., Cottrill, C.: The spatial pattern of demand in the early market for electric vehicles: evidence from the United Kingdom. J. Transp. Geogr. **72**, 119–130 (2018)
15. Peters, A., Dütschke, E.: How do consumers perceive electric vehicles? A comparison of German consumer groups. J. Environ. Policy Plan. **16**(3), 359–377 (2014)
16. Potoglou, D., Song, R., Santos, G.: Public charging choices of electric vehicle users: a review and conceptual framework. Transp. Res. Part D: Transp. Environ. **121**, 103824 (2023)
17. Rogers, E.M.: Diffusion of Innovations, 5th edn. Free Press, New York (2003)

18. Steck, F., Anderson, J.E., Kuhnimhof, T., Hoyer-Klick, C.: Comprehensive transportation and energy analysis: a price sensitive, time-specific microsimulation of electric vehicles. In: Transportation Research Board, Conference Proceedings Volume 1 (2019). https://elib.dlr.de/127475/
19. Verbist, D., van den Steen, N., Vanhaverbeke, L.: European alternative fuel observatory consumer monitor 2023 (EAFO 2023) (2024)

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Quantifying Uncertainty in Transport CO2e Reporting: A Simulation-Based Approach for Reliable Emission Accounting

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Abstract. Reliable CO_2e emission reporting is essential for climate-neutral freight transport, yet standards such as CSRD and ISO 14083 lack provisions for quantifying input uncertainty. This study applies Monte Carlo simulation and an analytical method (GUM) to telematics data from nine European trailers to systematically assess uncertainties in distance, payload, and emission intensity. Both methods yield nearly identical mean emissions, with relative 95% confidence intervals below 1.6%. Although payload shows higher measurement uncertainty, its impact on overall emission variability is minor due to the inverse relationship with emission intensity. The GUM approach matches Monte Carlo accuracy while requiring less than 1% of the computation time, making it suitable for large-scale, real-time applications. Explicit uncertainty quantification using these models enables more credible and comparable emission reporting and supports digital innovation in logistics.

Keywords: CO2e Emissions · Uncertainty Quantification · Monte Carlo Simulation · Telematics · Sustainable Logistics

1 Introduction

The decarbonization of freight transport is a central challenge for ambitious climate targets at both European and global levels. Accounting for 21.1% of global greenhouse gas emissions, the transport sector is increasingly the focus of regulatory and societal demands [11]. Precise and transparent CO_2e emission reporting along logistics value chains is therefore gaining importance, serving as the basis for assessing and reducing logistics-related emissions, and as a decisive factor for operational and political management of sustainable supply chains [7,9]. Standards and regulatory frameworks (e.g., CSRD, ISO 14083, GLEC) improve methodological harmonisation but generally omit explicit uncertainty quantification for inputs such as distance, payload, and emission intensity. This is problematic, as CO_2e figures without adequate uncertainty quantification and

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communication are ultimately not comparable and can undermine trust in emissions data and compliance reports [13]. New regulatory reporting adds burden for cost-sensitive logistics: small carriers often comply using recorded fuel consumption [8], but larger international firms frequently lack systematic consumption data due to heterogeneous fleets and complex operations [10]. They rely on telematics, which introduces methodological uncertainties for CO_2e comparability. This paper develops models to quantify and integrate these uncertainties to support transparent, regulatory-compliant reporting. While digitalization and telematics enable automated data collection, substantial uncertainties remain in data quality and translation into emissions—measurement errors, noise, missing streams, or uncertain emission intensities can impair CO_2e estimates [5].

Against this background, the following scientific research question forms the focus of this paper:

What is the quantitative impact of uncertainty in distance, payload, and emission intensity on the total reported CO_2e emissions in road freight, and which method (Monte Carlo or GUM) provides the most efficient and accurate uncertainty estimation?

This contribution addresses a central gap in current and forthcoming regulatory reporting by developing and validating a high-resolution Monte Carlo model for robust quantification of measurement and model uncertainties. Additionally, a practical and low-complexity implementation based on the Guide to the Expression of Uncertainty in Measurement (GUM) is proposed. Transport CO_2e accounting is predominantly grounded in established frameworks like the Greenhouse Gas (GHG) Protocol, the sector standard EN 16258 and its successor ISO 14083, and the Global Logistics Emissions Council (GLEC) Framework which explicitly covers multimodal supply chains [14]. These references standardise system boundaries, functional units and emission factors and thus support comparability and regulatory reporting [12]. However, they typically deliver point estimates and provide little guidance on propagating measurement and model uncertainty. As a consequence, reported emissions often lack confidence intervals or error estimates—a shortcoming also observable in industry tools such as EcoTransIT [4]. Evidence from Life Cycle Assessment (LCA) and related fields show that neglecting input uncertainty can vastly affect footprint results [13]. Although uncertainty methods (e.g. Monte Carlo, GUM) are established in other domains, their routine application to operational freight telemetry has been limited to isolated studies [1,2]. This paper therefore investigates how to integrate uncertainty analyses into existing calculation frameworks to improve transparency and robustness of CO_2e inventories in the transport sector.

2 Methodology

This study follows established accounting principles from the GLEC Framework and the GHG Protocol and is grounded in DIN EN ISO 14083. We assess direct

operational emissions on a well-to-wheel basis for individual trips. Broader life-cycle sources (e.g. vehicle manufacture, infrastructure, refrigerant losses, end-of-life) are outside the present scope. The calculation is defined in the methodology as follows:

$$E = d \cdot EI \cdot m \tag{1}$$

where E represents the total emission in kilograms of CO_2 equivalent (kg CO_2e), d denotes the transport distance in kilometers (km), EI is the payload-dependent emission intensity in kilograms CO_2e per ton-kilometer (kg CO_2e/t km), and m represents the payload in tons (t). The emission intensity EI is determined based on the proportion of empty runs and the load factor. A detailed breakdown of these dependencies is provided in Table 18 of Appendix 1 of the GLEC Framework. The parameters for distance, payload and emission intensity are based on measurements and may be uncertain. Typical sources of the uncertainty include odometry/GPS inaccuracies, sensor noise, intermittent data streams, variable fuel consumption and uncertain emission intensity factors; these errors propagate through Eq. (1) and may considerably affect reported footprints. The goal is assessing the extent to which individual input uncertainties influence the overall uncertainty of CO_2e calculations. Monte Carlo simulations provide a powerful statistical approach to compute statistical distributions of CO_2e emissions by generating a probabilistic distribution of possible emission values [15]. This probabilistic assessment enables a more comprehensive understanding of the range and likelihood of potential deviations. Additionally a second approach, based on the Guide of the Expression of Uncertainty in Measurement, is evaluated to calculate the uncertainty, with less computational resources.

2.1 Uncertainty Calculation Using Monte Carlo Simulation

Monte Carlo simulation is a computational technique that relies on repeated random sampling to obtain numerical approximations of complex mathematical models. This method is particularly useful for investigating the propagation of uncertainty in deterministic or stochastic systems, where analytical solutions may be infeasible due to model complexity, high-dimensional parameter spaces, or intricate interdependencies among input variables [3]. The core principle of Monte Carlo simulations is to generate a large number of random realizations of uncertain inputs, propagate them through a given model, and analyse the resulting distribution of outputs to derive statistical properties such as expectation, variance, and confidence intervals. Therefore the model function represented in Eq. 1 is considered the starting point for the uncertainty calculation. The first step involves defining appropriate probability distributions for each input parameter. For the purposes of this analysis, it is assumed that these parameters follow normal distributions with specified means and standard deviations. Subsequently, n independent random samples are drawn from these distributions. Thus, for each iteration j, the distance $d^{(j)} \sim \mathcal{N}(\mu_d, \sigma_d^2)$ and the payload $m^{(j)} \sim \mathcal{N}(\mu_m, \sigma_m^2)$ are treated as normally distributed random variables. In each case, the emission intensity is computed as $\mathrm{EI}^{(j)} = \mathrm{EI}\big(m^{(j)}\big)$, and the resultant

segment CO_2e emissions are given by $E^{(j)} = d^{(j)} \cdot \mathrm{EI}^{(j)} \cdot m^{(j)}$. Collectively, the ensemble $\{E^{(j)}\}_{j=1}^{n}$ provides estimates of the mean, standard deviation, and confidence intervals as reported in the Results section. Previous studies have demonstrated that conducting $n = 400$ simulations is sufficient for modelling the associated uncertainties for each route [6]. Figure 1 summarises the sampling workflow. Because the direct fuel-consumption measurements are not available, GLEC reference values provide baseline emission intensities. Here $\mathrm{EI}(m)$ is computed from the payload-dependent parametrisation and adjusted by trip-specific utilisation derived from axle-load telemetry. An explicit uncertainty term can be attributed to EI (grey box) to represent model or literature-derived uncertainty.

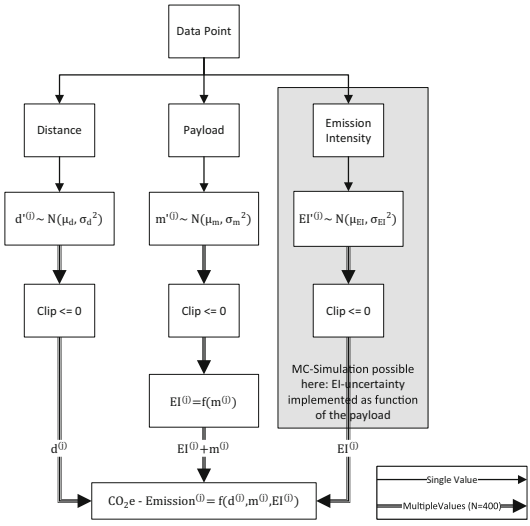


Fig. 1. Algorithm for Monte Carlo simulation

2.2 Uncertainty Calculation Using GUM

The Monte Carlo results indicate an approximately linear propagation of input uncertainties into the CO_2e outcome, which permits an additional analytical approach using the Guide to the Expression of Uncertainty in Measurement (GUM). In general, for a function $Y = f(X_1, X_2, \ldots, X_n)$, the combined standard uncertainty $u_c(Y)$ is determined by:

$$u_c(Y) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial X_i} u(X_i) \right)^2} \tag{2}$$

In the present implementation, the emission associated with a single discrete segment i is modelled by $E_i = d_i \, m_i \, \mathrm{EI}(m_i)$, where d_i denotes the segment

distance, m_i the payload, and $\mathrm{EI}(m_i)$ the emission intensity, which is explicitly expressed as a function of payload. The standard uncertainties of these input quantities are represented as $u(d_i)$, $u(m_i)$, and $u(\mathrm{EI}_i)$. The relative input uncertainties are specified according to $u(d_i) = r_d\, d_i$, $u(m_i) = r_m\, m_i$, and $u(\mathrm{EI}_i) = r_{EI}\, \mathrm{EI}_i$, with r_d, r_m, and r_{EI} being the relative uncertainties provided for the current Monte Carlo run. Applying the law of propagation of uncertainty and considering the functional dependence $\mathrm{EI} = \mathrm{EI}(m)$, the sensitivity coefficients for the segment model are given by $\frac{\partial E_i}{\partial d_i} = m_i\, \mathrm{EI}(m_i)$, $\frac{\partial E_i}{\partial \mathrm{EI}_i} = d_i\, m_i$, and $\frac{\partial E_i}{\partial m_i} = d_i\, (\mathrm{EI}(m_i) + m_i\, \partial_m \mathrm{EI}(m_i))$. The derivative $\partial_m \mathrm{EI}(m_i)$ is evaluated numerically within the code. Hence, the combined standard uncertainty of the emission of segment i is computed as

$$u(E_i) \;=\; \sqrt{\big(m_i\, \mathrm{EI}_i\, u(d_i)\big)^2 + \big(d_i\, m_i\, u(\mathrm{EI}_i)\big)^2 + \big(d_i \big(\mathrm{EI}_i + m_i\, \partial_m \mathrm{EI}(m_i)\big)\, u(m_i)\big)^2} \tag{3}$$

Assuming statistical independence between different segments, the total emission and its combined standard uncertainty are obtained by summation of segment contributions:

$$E_{\mathrm{total}} = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} d_i\, m_i\, \mathrm{EI}_i \tag{4}$$

$$u_{c,\mathrm{total}}(E) = \sqrt{\sum_{i=1}^{n} \big(u(E_i)\big)^2} \tag{5}$$

To express the overall uncertainty as an interval, GUM recommends the expanded uncertainty:

$$U_E = k \cdot u_{c,\mathrm{total}}(E) \tag{6}$$

where k is the coverage factor. In practice, a choice of $k = 2$ corresponds approximately to a 95% confidence interval under the assumption of normally distributed data.

3 Application and Results

The dataset comprises telemetry from nine trailers over two years of European freight operations. Data were nominally transmitted every 15 min, although gaps

Table 1. Example routes used to illustrate uncertainty propagation.

Route	*Distance (km)*	*Mean Payload (t)*	*Mean EI (g CO_2e/t km)*	*Total Emission (kg CO_2e)*
1	247	8.644	128.59	274.48
2	270	18.570	70.58	353.7
3	259	8.600	129.1	287.56
4	290	15.204	82.21	359.72
5	335	7.516	141.56	356.42

Table 2. Comparison of Monte Carlo (MC) and GUM uncertainty estimates for CO_2e emissions for all routes.

Route	Scenario	Mean [kg]		95% CI [kg]		Rel. Dev. [%]	
		MC	GUM	MC	GUM	MC	GUM
1	Distance	274.49	274.48	[270.88, 278.11]	[270.60, 278.36]	±1.32	±1.41
	Payload	273.58	274.48	[272.11, 275.04]	[273.14, 275.82]	±0.54	±0.49
	Combined	273.55	274.48	[269.24, 277.87]	[270.37, 278.58]	±1.58	±1.50
2	Distance	353.73	353.70	[349.22, 358.25]	[348.89, 358.50]	±1.28	±1.36
	Payload	353.92	353.70	[351.95, 355.89]	[351.21, 356.19]	±0.56	±0.70
	Combined	354.13	353.70	[349.21, 359.04]	[348.29, 359.11]	±1.39	±1.53
3	Distance	287.51	287.56	[283.57, 291.45]	[283.55, 291.56]	±1.37	±1.39
	Payload	286.58	287.56	[285.02, 288.14]	[286.15, 288.97]	±0.54	±0.49
	Combined	286.82	287.56	[282.67, 290.97]	[283.31, 291.80]	±1.45	±1.48
4	Distance	359.67	359.72	[355.21, 364.12]	[355.15, 364.29]	±1.24	±1.27
	Payload	359.63	359.72	[357.97, 361.29]	[357.73, 361.71]	±0.46	±0.55
	Combined	359.69	359.72	[354.98, 364.40]	[354.74, 364.70]	±1.31	±1.39
5	Distance	356.24	356.42	[351.90, 360.58]	[352.03, 360.81]	±1.22	±1.23
	Payload	355.43	356.42	[352.94, 357.92]	[353.84, 359.00]	±0.70	±0.72
	Combined	355.44	356.42	[350.66, 360.22]	[351.32, 361.51]	±1.35	±1.43

occurred due to network availability. Distances were derived from GPS positions, payloads from air-suspension pressure sensors, and emission intensities from GLEC lookup tables. In total, the series contain $n_{\text{payload}} = 76{,}698$ payload and $n_{\text{distance}} = 144{,}921$ distance records. Standard preprocessing included timestamp alignment, column renaming, and per-segment distance calculation. Measurement uncertainties were determined on separate test routes via Graphhopper map-matching and time-series comparison of GPS distances and air-suspension payloads. Representative relative standard deviations of $\sigma_{d,\text{rel}} \approx 4.3\%$ for distance and $\sigma_{m,\text{rel}} \approx 6.5\%$ for payload were derived from validation routes and applied as input to both analyses. Five representative routes (Table 1) were selected to illustrate the impact of input uncertainties on emission calculations. Table 2 summarizes the results for mean emission, 95% confidence intervals (CI), and relative deviations across all routes and input scenarios, based on both Monte Carlo and GUM analyses. Across all routes and scenarios, the combined case produced the largest emission uncertainties (±1.31% to ±1.58%), while the contribution from payload was consistently smallest (±0.46% to ±0.72%), and distance uncertainties showed intermediate effects. Relative 95% confidence intervals and rankings were remarkably similar for both Monte Carlo and GUM, with mean emission values remaining stable between methods. Small numeri-

cal differences result from the different mathematical treatments of uncertainty propagation but do not affect the overall findings. Computational requirements differ substantially: a single Monte Carlo simulation required 0.0035–0.0043 s per route (about 1.4–1.7 s for 400 runs), while a GUM calculation needed just 0.002–0.003 s, corresponding to less than 0.2% of the MC runtime. Thus, GUM is approximately as many times faster as the number of simulations, making it a robust and efficient alternative for large-scale or real-time applications, especially when uncertainty propagation needs to be repeated frequently.

4 Discussion and Outlook

Figure 2 visualizes the distribution of CO_2e emission uncertainties for Route 2, enabling a direct comparison between Monte Carlo and GUM approaches. Both methods yield nearly identical estimates: Monte Carlo captures the full variability through random sampling, while GUM provides a computationally efficient, deterministic calculation. In all scenarios, parameter interactions—especially between payload and emission intensity—determine the total uncertainty, which is not simply the sum of individual effects. Although payload shows the highest relative input uncertainty, its impact on total CO_2e emissions is limited, due to the inverse link between payload and emission intensity. This is evident in the boxplots, where the payload-related uncertainty band is narrower than those for distance or combined cases. The recent revision of the GLEC framework has raised default emission intensities, potentially resulting in conservative estimates that may exceed those based on actual fuel use, emphasizing the importance of vehicle-specific measurements where feasible. GUM calculations require only a fraction of the computation time compared to Monte Carlo, making them well suited for large-scale or real-time reporting. Monte Carlo simulations, however, retain value for scenarios where detailed distributional information is necessary. Using the GUM framework, a predetermined overall uncertainty allows the definition of permissible input parameter uncertainties and the corresponding specifications of their measurement instruments, which is particularly advantageous for on-the-edge calculations. Comprehensive assessment of input uncertainties remains essential, as demonstrated here by applying both modelling frameworks to real-world fleet data. Future research should address correlated uncertainties, extend application to multimodal supply chains, and incorporate validated, route-specific emission factors. Integrating explicit uncertainty quantification into reporting standards, supported by digitalization and advanced telematics, will be central to providing transparent and reliable emission data for robust benchmarking and climate-neutral freight transport initiatives.

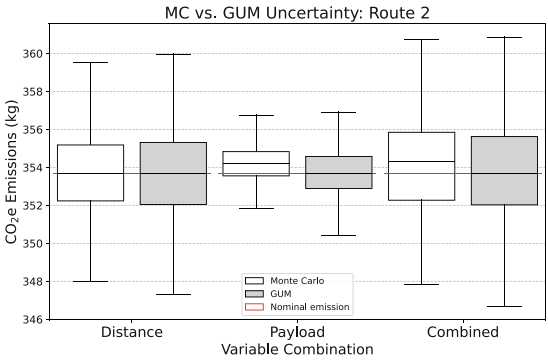


Fig. 2. Distribution of the emission uncertainty for Route 2.

References

1. Barahmand, Z., Eikeland, M.S.: Life cycle assessment under uncertainty: a scoping review. World **3**(3), 692–717 (2022)
2. Bayazit, N., Marschall, M., Straka, M., Schmelter, S.: A novel framework for the uncertainty evaluation of virtual flow meters. Meas. Sci. Technol. **36**(7), 076012 (2025)
3. Betz, W., Papaioannou, I., Straub, D.: Bayesian post-processing of Monte Carlo simulation in reliability analysis. Reliab. Eng. Syst. Saf. **227**, 108731 (2022)
4. Du Plessis, M.J., van Eeden, J., Goedhals-Gerber, L., Else, J.: Calculating fuel usage and emissions for refrigerated road transport using real-world data. Transp. Res. Part D: Transp. Environ. **117**, 103623 (2023)
5. Ghaffarpasand, O., Burke, M., Osei, L.K., Ursell, H., Chapman, S., Pope, F.D.: Vehicle telematics for safer, cleaner and more sustainable urban transport: a review. Sustainability **14**(24), 16386 (2022)
6. Leskow, J., Greiser, S., Gregorc, L., Damalas, S.: Monte Carlo simulation to analyse the impact of uncertain telemetry data on the calculation of co2e emissions for trailer traffic. In: Wirtschaftsinformatik 2024 Proceedings 35 (2024)
7. Mohammadizadeh, M., Mozhdehi, A., Wang, X.: EcoRouteQ: a reinforcement learning framework for green route recommendations. Int. J. Transp. Sci. Technol. (2025)
8. Ortiz, E., Marín, S., Thompson, P.: The role of small- and medium-sized practices in the sustainable transition of SMEs. Environ. Dev. Sustain. **26**, 19299–19323 (2024)
9. Runst, P., Höhle, D.: The German eco tax and its impact on co2 emissions. Energy Policy **160**, 112655 (2022)
10. Smart Freight Centre: Data access for logistics emissions (2023). https://www.smartfreightcentre.org/en/our-programs/emissions-accounting/global-logistics-emissions-council/digitalization-program/data-access-for-logistics-emissions-accounting-and-reporting/
11. Statista Research Department: Distribution of co_2 emissions worldwide by sector 2023 (2025). https://de.statista.com/statistik/daten/studie/167957/umfrage/verteilung-der-co-emissionen-weltweit-nach-bereich/

12. Vitiello, D., Serra, P., Fancello, G.: Assessing greenhouse gas emissions arising from intermodal freight transport chains using the ISO14083 standard. Transp. Res. Procedia **90**, 464–471 (2025)
13. Wang, J., Li, X., Yang, D.: Uncertainties in life cycle assessment of renewable fuels for green shipping corridors. Transp. Res. Part D: Transp. Environ. **147**, 104916 (2025)
14. Yin, Y., Wang, H., Deng, X.: Real-time logistics transport emission monitoring-integrating artificial intelligence and internet of things. Transp. Res. Part D: Transp. Environ. **136**, 104426 (2024)
15. Zhang, J.: Modern Monte Carlo methods for efficient uncertainty quantification and propagation: a survey. Wiley Interdisc. Rev. Comput. Stat. **13**(5), e1539 (2021)

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Methodology for Multi-Domain Data Integration and Modelling to Support Zero-Emission Logistics Use Cases

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Abstract. The Shift2Zero project (GA 101192375) is a Horizon Europe research initiative aimed to accelerate the transition to zero-emission logistics through right-sized, mission-focused N1 e-LCVs. Within this project, a robust data validation methodology has been established to support the project's digital and impact assessment components. The methodology begins by defining and consolidating requirements from the project's pilots, focusing on data structure and semantics. It integrates diverse, multifunctional data sources, including operational (e.g. trip planning, travel and stop times, driver rest periods), economic (e.g. vehicle total cost of ownership components), and technical (e.g. battery autonomy, charging time, payload, and freight-specific temperature requirements). Business Process Model (BPM) diagrams are developed for each use case to map involved actors and operational workflows. This process follows enhancing KPI analytics by structuring data to feed the impact assessment framework. Input from all pilot sites and end-users is used to define relevant data models. This is achieved through the creation of entity-relationship diagrams per pilot, detailing data classes, attributes, and relationships. These models are aligned with the functional needs of the S2Z Platform and will support upcoming large-scale simulation activities. The approach ensures both interoperability and scalability of the data architecture across pilots and use cases.

Keywords: Multi-domain data integration · Zero-emission logistics · Business Process Modelling

1 Introduction

The decarbonisation of freight transport and urban logistics is a cornerstone of the European Union's climate neutrality ambitions, as set out in the European Green Deal and the Sustainable and Smart Mobility Strategy [1, 2]. Logistics accounts for a substantial share of greenhouse gas (GHG) emissions, particularly from light commercial vehicles (LCVs), which dominate last-mile delivery and urban freight operations [3]. The

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transition to zero-emission vehicles (ZEVs), especially electric light commercial vehicles (e-LCVs), is thus essential to mitigating environmental impacts while ensuring the resilience and competitiveness of supply chains. Despite the technological progress of electric mobility, the large-scale deployment of e-LCVs in logistics remains challenged by operational, technical, and economic barriers. Range limitations, charging requirements, payload constraints, and total cost of ownership (TCO) considerations often reduce their attractiveness compared to conventional vehicles. At the same time, the logistics sector is characterised by a high degree of fragmentation and diversity of stakeholders, ranging from vehicle manufacturers and fleet operators to municipalities and end-users, each with distinct priorities and data needs [4]. These complexities underline the need for integrated data-driven approaches that can model, evaluate, and optimise zero-emission logistics solutions across multiple domains.

The Shift2Zero (S2Z) project responds to these challenges by promoting the adoption of right-sized, mission-focused N1 e-LCVs tailored to specific use cases. Within this framework, data integration [5] plays a central role, enabling digital tools and impact assessments that inform both operational decision-making and policy recommendations. In particular, a multi-domain data methodology has been developed to harmonise heterogeneous sources—operational, technical, and economic—into interoperable models. This approach supports pilot demonstrations, KPI monitoring, and large-scale simulation activities, ultimately ensuring the scalability and replicability of project results.

This paper presents the methodological framework for multi-domain data integration and modelling adopted in Shift2Zero. After outlining the methodological steps, the paper discusses how the approach has been applied to pilot use cases, with a focus on interoperability, data structuring, and support for zero-emission logistics evaluation.

2 Methodology

The methodological framework developed within Shift2Zero is designed to address the integration of heterogeneous data sources from multiple pilot sites, ensuring both interoperability and scalability. It follows a progressive process that moves from the definition of requirements to the modelling of integrated datasets and their application in impact assessment and simulation activities. Similar approaches have been applied in transport research, where structured frameworks have been used to align technical, operational, and economic dimensions of logistics systems [6, 7].

Step 1: the first step consists of defining the requirements emerging from the different pilots. This activity is not limited to collecting technical specifications but extends to operational and economic dimensions. Operational requirements include routing strategies, travel and stop times, or driver rest periods, which are widely recognised as critical determinants of last-mile delivery performance. Technical requirements focus on vehicle performance parameters—battery autonomy, charging profiles, payload capacity, and temperature-controlled freight conditions—elements often highlighted as barriers to the adoption of electric light commercial vehicles. Economic requirements are structured around the components of the total cost of ownership (TCO), including acquisition, energy, and maintenance costs, in line with standard evaluation approaches for e-mobility solutions [8]. By consolidating these dimensions, a common basis is established for structuring the subsequent data integration process.

Step 2: once the requirements are consolidated, the methodology turns to the formalisation of operational workflows. For each pilot use case, business processes are mapped using Business Process Model and Notation (BPMN). BPMN is widely applied in logistics research and practice to provide a structured representation of actors, activities, and interactions, ensuring clarity in the modelling of complex systems [9]. In the context of Shift2Zero, BPMN diagrams allow the identification of stakeholders—fleet operators, drivers, logistics managers, municipalities—and the mapping of workflows such as order management, routing, and charging events. The adoption of BPMN ensures that technical and operational data are contextualised within the broader business processes that characterise urban logistics operations.

Step 3: the integration of data represents the next methodological step. Here, the diversity of sources—ranging from vehicle telematics and fleet management systems to cost models and external datasets such as traffic conditions—is addressed through harmonisation efforts. Data harmonisation has been recognised as a key enabler of innovation in smart mobility, as it allows cross-comparison and interoperability between heterogeneous datasets [10]. In this stage, semantic consistency is achieved by aligning terminologies across pilots, while structural consistency is ensured through the design of a unified schema that represents operational, technical, and economic dimensions in a coherent way. This integration step ensures that data collected at different sites can be compared and analysed within a common analytical framework.

Step 4: building on this foundation, the methodology proceeds with data modelling. For each pilot, entity–relationship (ER) diagrams are developed to capture the key data classes, their attributes, and the relationships that connect them. ER modelling is a well-established approach for representing logistics and mobility systems [11], allowing for a structured depiction of entities such as vehicles, trips, charging events, energy consumption, costs, and logistics activities. By explicitly defining relationships—for example, linking a vehicle entity to multiple trips and associating these with corresponding charging events—the models ensure that dependencies are systematically represented. Importantly, these models are designed to reflect pilot-specific requirements while remaining aligned with the functional needs of the Shift2Zero digital platform, which serves as the main environment for data exploitation.

Step 5: the final stage of the methodology concerns the integration of structured data into the project's analytical and simulation tools. The data models feed directly into the impact assessment framework, enabling the calculation of performance indicators across energy, environmental, economic, and operational domains. Indicators are harmonised across pilots to guarantee comparability of results, reflecting the recommendation from previous research that common KPI frameworks are essential for evaluating sustainable logistics measures [12]. Moreover, the structured datasets serve as input for large-scale simulation exercises, where alternative deployment and operation strategies for zero-emission logistics solutions can be tested under different scenarios. Simulation-based approaches have proven particularly useful in evaluating urban freight innovations before full-scale deployment (Fig. 1).

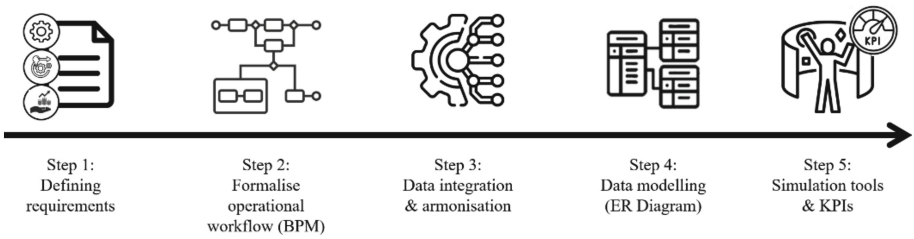


Fig. 1. Five-step methodology for data integration and modelling

3 Analytical implementation

Chapter 3 describes how each of the five steps described in the Methodology chapter was carried out in practice and outlines the outputs produced at this stage of the work. The chapter therefore moves from the methodological framework to its analytical implementation, providing the basis for the results presented in the following section.

Step 1: Definition of Pilot Requirements. First step focused on defining pilot requirements through the logic of the S2Z engines, understood as the digital modules that support operational planning, monitoring and scenario assessment. In this framework, the project considered nine engines: Road Data Extraction, Order Data Communication, Vehicle Communication, Vehicle Model Consumption, Cargo Loading, Charging Scheduling, VRP, Decision Analytics and Simulation. Rather than imposing a uniform specification from the outset, the pilots were used to identify which engines were relevant to each use case and which data were needed to support them. This was done through workshops, bilateral technical meetings and a shared mapping spreadsheet linking each data point to the relevant engine, together with practical information on data provision, update frequency, availability, exchange modality and priority. The exercise also clarified the logic of interaction among engines: road, order and vehicle data form the main input layer; planning engines use these inputs to generate operational outputs; the consumption model refines energy-related estimates; and the resulting information feeds analytics and simulation activities.

Step 2: BPMN-Based Mapping of Pilot Operations. Pilot use cases were represented through BPMN-based process models. The purpose was to formalise the main operational logic of each pilot in a consistent way. The BPMN diagrams were used to identify the key actors, the main process phases, the relevant decision points, and the moments in which data are generated, exchanged, or required for analysis. This made it possible to connect real operational workflows with the information needs of the S2Z engines and to create a common interpretative layer across pilots with different organisational and logistical configurations (Fig. 2).

Step 3: Cross-Pilot Data Harmonisation. Given the heterogeneity of the Shift2Zero pilots, data harmonisation was required to make information comparable across different operational settings. This step focused on semantic alignment, with data requirements defined according to their analytical function rather than their original source system.

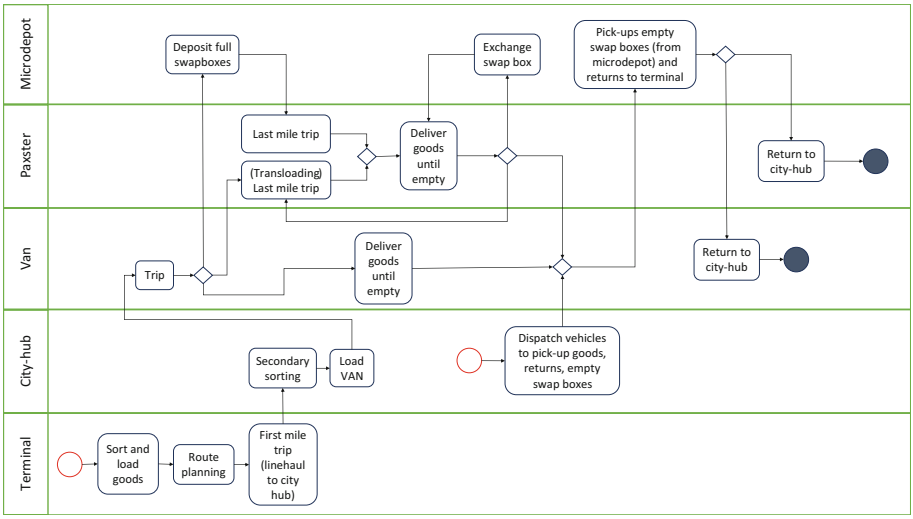


Fig. 2. BPM representation of the Oslo pilot operational workflow

Recurring concepts across pilots were therefore consolidated into a limited set of common descriptors, including vehicles, orders, trips, charging events and depots. A minimal canonical structure was adopted to distinguish core variables needed for cross-pilot analysis from optional fields linked to specific use cases.

Step 4: Development of the Entity–Relationship Model. The harmonised data requirements were then reorganised into an entity–relationship (ER) model. At this stage, data points were no longer treated only as inputs for individual engines, but as attributes of broader logistics objects and of the relationships connecting them. This shift made it possible to move from an engine-oriented inventory to a common conceptual structure linking demand, execution, vehicles, charging assets, network conditions and operational constraints. The main value of the ER model is that it goes beyond the logic of any single pilot: it abstracts from local configurations and defines a reusable core data structure that can support comparison, replication and future onboarding of additional use cases (Fig. 3).

Step 5: Preparation of Data Inputs for KPI Estimation and Simulation. The final step focused on preparing the data inputs needed for KPI estimation and for the analytical tools. At this stage, the work did not consist in producing final KPI values, but in defining how the variables structured in the data model could support the impact assessment framework and the project's simulation activities. In practice, this meant linking pilot data to the indicators to be assessed, while also accounting for secondary data generated by the S2Z engines. This step established a common input logic through which observed operational data and model-based outputs can be used within the same assessment framework.

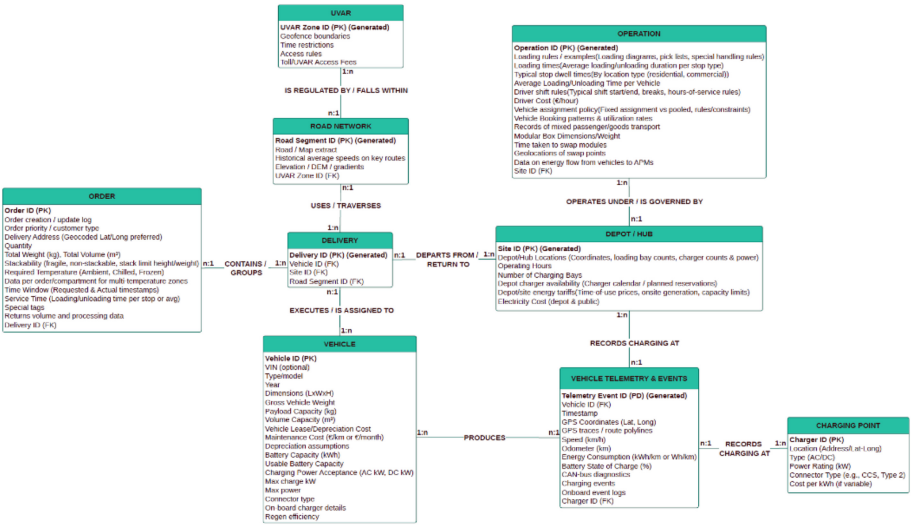


Fig. 3. ER model developed from pilot-defined data requirements

4 Results

At the current stage of Shift2Zero, the main results are methodological and structural rather than performance-based. No cross-pilot quantitative validation is reported yet, as the framework is still being prepared for implementation with pilot data. The results achieved so far consist in the production of a shared requirement base, a generalised data model and a first alignment between pilot data, S2Z engines and KPI needs.

A first result is the consolidation of pilot requirements into a shared data inventory. This output organises the information needed by the project according to analytical use, data provider, frequency, availability and expected exchange format. The inventory covers the needs of the engines, the KPI framework and the simulation activities, making visible both recurring requirements across pilots and gaps linked to specific use cases. This provides a clearer basis for data collection and reduces ambiguity in the interpretation of pilot inputs.

A second result is the definition of a core entity–relationship model that abstracts from individual pilot configurations. Rather than keeping data points attached only to single engines or local processes, the model reorganises them around a limited set of generic logistics entities such as orders, deliveries, vehicles, telemetry and events, depots or hubs, charging points, road network, UVAR and operations. This is a relevant result because it moves the work beyond the description of single pilot cases and establishes a reusable data backbone for comparison, replication and future onboarding of additional use cases.

A third result is the explicit linkage between the common data model and its analytical use within Shift2Zero. The mapping exercise connects ER entities and data points to the different engines, while also identifying how the same information can support KPI estimation and simulation. In practical terms, this creates a shared input logic across

operational data collected in the pilots and secondary outputs generated by project tools. The result is not yet a validated assessment framework, but a coherent basis for future KPI computation, scenario analysis and cross-pilot comparison.

These results define the data architecture needed to support the next project phases, but they also reflect the current maturity of the work. The framework has not yet been fully validated against large-scale real-world pilot datasets, and some dimensions remain only partially integrated, especially regulatory constraints, grid-related aspects and broader urban context variables. These elements will need to be refined in the implementation phase in order to test the robustness of the model under real operating conditions.

5 Discussion and Conclusions

The work presented in this paper provides a structured way to move from heterogeneous pilot configurations to a common analytical basis for zero-emission logistics. Its main contribution is not a new optimisation algorithm, but a transferable integration framework that connects pilot requirements, process representations, engine needs, data modelling and KPI preparation within a single logic. This is relevant in a project such as Shift2Zero, where comparison across pilots depends less on uniform operations than on the ability to describe different use cases through a consistent data structure.

At the same time, the current contribution remains preliminary. The framework has been defined before full pilot implementation and is therefore still based in part on expected datasets and anticipated exchange conditions. For this reason, the paper should be read as a methodological and infrastructural contribution rather than as a validation study. Some dimensions also remain only partially operationalised, particularly the full treatment of regulatory conditions, grid-related interactions and wider urban context variables. The robustness of the proposed structure can only be assessed once real pilot data are collected and processed through the relevant Shift2Zero engines. Within these limits, the work already offers a clear result: it establishes a common backbone that can support data collection, model interoperability and future impact assessment across different pilot settings. This reduces the risk of fragmented data development and creates a more solid basis for subsequent simulation and evaluation.

The next phase of the project will focus on implementation and validation. This includes testing the data model against real pilot datasets, refining the alignment between engines and KPIs, and verifying whether the proposed structure is sufficiently robust to support scenario analysis and cross-pilot comparison. If this step is successful, the methodology may provide a useful reference for other projects facing similar integration challenges in zero-emission urban logistics.

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References

1. European Commission: Sustainable and Smart Mobility Strategy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0789. Accessed 20 Mar 2026

2. European Commission: New EU Urban Mobility Framework. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0811. Accessed 20 Mar 2026
3. McKinnon, A.: Decarbonizing Logistics: Distributing Goods in a Low Carbon World. Kogan Page, London (2018)
4. Dablanc, L., Giuliano, G., Holliday, K., O'Brien, T.: Best practices in urban freight management: lessons from an international survey. Transp. Res. Rec. J. Transp. Res. Board. **2379**(1), 29–38 (2013)
5. Cossu, P., Astegiano, P., Fergadiotou, I., Ayfantopoulou, G., Franklin, R.: Data-driven and dynamic land use for physical internet-led urban logistics and planning. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility Lecture Notes in Mobility, pp. 569–575. Springer, Cham (2025)
6. Taniguchi, E., Thompson, R.G., Yamada, T.: Recent trends and innovations in modelling city logistics. Procedia – Soc. Behav. Sci. **125**, 4–14 (2014)
7. Holguín-Veras, J., Sánchez-Díaz, I.: Freight demand management and the potential of receiver-led consolidation programs. Transp. Res. Part A: Policy Pract. **84**, 109–130 (2016)
8. Bubeck, S., Tomaschek, J., Fahl, U.: Perspectives of electric mobility: total cost of ownership of electric vehicles in Germany. Transp. Policy. **50**, 63–77 (2016)
9. Chinosi, M., Trombetta, A.: BPMN: an introduction to the standard. Comput. Stand. Interfaces. **34**(1), 124–134 (2012)
10. Batty, M. et al.: Smart cities of the future. Eur. Phys. J. Spec. Top. **214**(1), 481–518 (2012)
11. Elmasri, R., Navathe, S.B.: Fundamentals of Database Systems, 7th edn. Pearson, Hoboken, NJ (2016)
12. Cherrett, T., Allen, J., McLeod, F., Maynard, S., Hickford, A., Browne, M.: Understanding urban freight activity – key issues for freight planning. J. Transp. Geogr. **24**, 22–32 (2012)

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Analysis of Remotely Measured NO_x and SO_x Emissions of Ships at the Port of Rotterdam

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Abstract. Internal combustion engines onboard seafaring vessels are major sources of nitrogen oxides (NO_x) and sulphur oxides (SO_x) in port areas. These pollutants have detrimental effects on human health and the environment. Remote measurement techniques offer an efficient alternative for estimating NO_x and SO_x emissions across numerous vessels, which would be impractical through on-board measurements alone. Since 2019, TNO runs an onshore measurement station at the entrance of the Port of Rotterdam. It measures the concentrations of NO, SO_2, and CO_2 in the atmosphere, and logs information on the vessels passing the station as well as wind conditions. This data is used to calculate NO_x emissions and estimate the sulphur content in the fuel used. Based on several years of data, this study investigates NO_x and SO_x emissions of ships depending on properties like Tier level, engine type, and installed aftertreatment systems. Focus is given to Tier III-certified vessels since previous studies have shown that these vessels often fail to comply with the applicable limits.

Keywords: Nitrogen oxides (NO_x) · Remote measurement · Seafaring vessels

1 Introduction

The maritime sector continues to pose a challenge for emissions reduction, especially compared to other transport modes where significant progress has been made. Addressing this issue requires strong international regulations, such as the MARPOL protocol [1], introduced by the International Maritime Organization (IMO) in response to growing concerns about the environmental impact of maritime transport. MARPOL aims to reduce pollution from ships by setting strict limits on sulphur oxides (SO_x) and nitrogen oxides (NO_x). In addition, it introduced Emission Control Areas (ECAs) where even stricter emission standards apply to further protect sensitive marine environments.

MARPOL Annex VI regulates NO_x emissions from marine diesel engines with an output power above 130 kW, using a tiered system. The limits vary depending on the ship's construction date and the engines' rated speed. While Tiers I and II apply globally, the more stringent Tier III standard is only applicable for ships operating within ECAs. To ensure compliance with these limits, the NO_x Technical Code [2] specifies a series of test

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cycles with weighting factors. For Tier III certification, NO_x emissions measured during any individual mode of the test cycle – excluding idling and 10% load modes – must not exceed 150% of the corresponding limit. This Not-To-Exceed (NTE) requirement does not apply to Tiers I and II. SO_x emissions, on the other hand, are regulated through limits on the sulphur mass content in marine fuels. The global sulphur cap is 0.5% m/m (5.0 g/kg-fuel), within ECAs 0.1% m/m (1.0 g/kg-fuel) apply.

In the Netherlands, maritime shipping was the largest source of NO_x emissions within the mobility sector in 2020 [3]. Since 2019, TNO has been conducting remote measurements at the Port of Rotterdam to monitor NO_x and SO_x emissions, using instrumentation installed at the port entrance to derive emission factors that can be compared with regulatory limits. In the analysis of data from Tier I and Tier II vessels [4] it was found that while most Tier I ships complied with NO_x emission standards, a significant number of Tier II vessels exceeded them, particularly at low engine loads.

Similar remote monitoring initiatives have revealed that actual vessel emissions often exceed IMO regulatory limits. For instance, a study for the Danish Environmental Protection Agency [5] found Tier II vessels emitting more brake-specific NO_x than Tier I ships, with even Tier 0 engines performing better at low engine loads. Supporting this, a six-year study [6] of ships passing under the Great Belt Bridge observed elevated NO_x emissions from Tier II vessels at low loads, while Tier I emissions remained stable and Tier 0 emissions decreased with decreasing engine load. Comparable trends were also reported in Belgian waters [7], where rising NO_x emissions between 2020 and 2022, correlated with an increasing share of Tier II ships, suggesting the presence of high-emitting, non-compliant vessels within this category. These patterns were further confirmed in the Mediterranean [8], where Tier II vessels exhibited higher NO_x emission factors than older Tier I ships, with approximately half of the Tier II measurements exceeding the IMO weighted average limits. Building on these findings, studies have also examined emissions from Tier III-certified vessels under real-world operating conditions. A Canadian submission to the 80th session of the Marine Environment Protection Committee [9] highlighted the issue of significantly elevated NO_x emissions from Tier III-compliant engines operating at low loads in Canadian coastal waters and the St. Lawrence River. Supporting this, PPR 11/INF.2/Rev.1 [10] references 2022 remote sensing data from the SCIPPER project, which monitored vessels across Denmark, the Netherlands, and Germany. Of the sixty-five Tier III vessels sampled, only one-third complied with NO_x emission limits, while half exceeded the limits by more than a factor of two. However, the specific engine load conditions during these measurements were not clearly documented. Similarly, research conducted for the Dutch Ministry of Infrastructure and Water Management [11], found that actual NO_x emissions from Tier III vessels exceeded regulatory limits.

Sulphur regulations have demonstrated greater effectiveness, though challenges persist. In the Yangtze River estuary, unmanned aerial vehicle-based monitoring of twenty-seven ships identified twelve exceeding the 0.5% m/m limit, with fuel samples from four vessels confirming the violations [12]. On the other hand, the analysis of 3 910 sniffer measurements from individual ships at the Great Belt Bridge between December 2019 and November 2020, reported a sulphur compliance rate of 98.6% [13, 14]. Similarly, Van Roy et al. [7] evaluated over 110 000 remote measurements of ocean-going vessels

operating within European ECAs from 2015 to 2022. Their study showed a consistent decline in non-compliance with fuel sulphur limits, reaching the lowest levels following the 2020-reduction of the global sulphur cap. However, a slight uptick in non-compliance was observed beginning in 2022 across multiple monitoring operations, underscoring the continued need for enforcement and oversight.

In light of growing evidence that real-world vessel emissions often exceed the levels expected based on applicable emission limits, this study builds upon and extends the work of Van Dinther et al. by utilizing a more comprehensive dataset of remote emission measurements collected at the Port of Rotterdam. Spanning from 2019 to 2025, the dataset includes significantly more measurements of Tier III vessels than has been available in previous studies. The analysis examines emission factors in relation to engine type and the presence of aftertreatment systems and includes a brief assessment of the sulphur content of ships passing the measurement site.

2 Methods

In this study, NO_x emission factors of vessels entering or leaving the port of Rotterdam are determined using remote sensing data. Air quality measurements are conducted using a sniffer system installed in the tower of an island-based measurement station at the port entrance. The system draws in air from ten meters above the ground level and continuously monitors SO_2, NO, and CO_2 concentrations, while simultaneously recording wind speed and direction. Ship plumes are detected by an increase in NO concentration. At the same time, data originating from vessels' Automatic Identification System (AIS) provides real-time information of ships in the immediate vicinity of the tower, including GNSS coordinates. When a plume is detected, software combines the wind data with AIS information to identify the emitting ship. This method is generally reliable, however, in situations where multiple vessels are located upwind of the tower it can be difficult to attribute the plume to a specific vessel. In such cases, those measurements are excluded from the analysis [4].

The measurement data was enriched by adding static information about the ships, sourced from Clarksons' World Fleet Register (WFR) [15]. For the research presented in this paper, only vessels with diesel engines as the main means of propulsion were considered, as Tier limits do only apply for marine diesel engines. Furthermore, measurements from tugs and other small watercraft were removed, and only seafaring merchant vessels were retained for further analysis. Since the remote sensing station is equipped with an analyser that measures only NO concentration and not NO_2, the NO_x concentration in a vessel's plume had to be estimated. In previous studies [4, 11] it was assumed that 20% of the NO_x concentration was NO_2. This share has been determined in the SCIPPER project [16, 17]. However, analysis carried out during this study indicated that multiplying the concentration of NO by 1.35 yields more representative results for NO_x. The work-specific NO_x emission $\frac{NO_x}{W}$ in g/kWh were calculated by using

$$\frac{NO_x}{W} == \frac{\int_0^T \left([NO_x]_{ppb} - [NO_x]_{ppb,bg.}\right) \cdot dt}{\int_0^T \left([CO_2]_{ppb} - [CO_2]_{ppb,bg.}\right) \cdot dt} \cdot \frac{M_{NO_2}}{M_C} \cdot CC_{fuel} \cdot SFOC(load) \quad (1)$$

where $[s]_{ppb}$ denotes the measured concentration of species s in parts-per-billion and the index bg. refers to the background concentration. The time span T represents the duration of raised NO concentration due to the plume. M_s is a species' molar mass and CC_{fuel} is the carbon content of the main engine fuel based on [18]. The specific fuel-oil consumption has been calculated based on the engine load, which in turn has been estimated from vessel speed, by applying the method described in [19]. Where no information about the service speed of a vessel was available, the baseline SFOC was used. The method used for the calculation of (equivalent) fuel sulphur content is described in [20]. Essentially, it is equivalent to Eq. (1); the only difference is that SFOCis not used.

Since the NO_x ECA in the North Sea took effect on January 1st, 2021, and the Tier III NO_x limits only apply to vessels the keel of which was laid on or after this date, there are ships which are capable of complying with Tier III limits, but which are not obliged to do so in the North Sea. In this study, these vessels have been grouped together and are referred to as Tier "II (III)". According to the World Fleet Register [15], no ships of the categories Tier I and Tier II were equipped with NO_x aftertreatment systems like EGR and SCR. On the other hand, all ships in the categories II (III) and Tier III were equipped with NO_x-aftertreatment technology or used alternative fuels like LNG.

3 Results

Figure 1 shows a boxplot of the calculated work-specific NOx emissions of all valid measurements categorized by Tier level and grouped by main engine cycle.

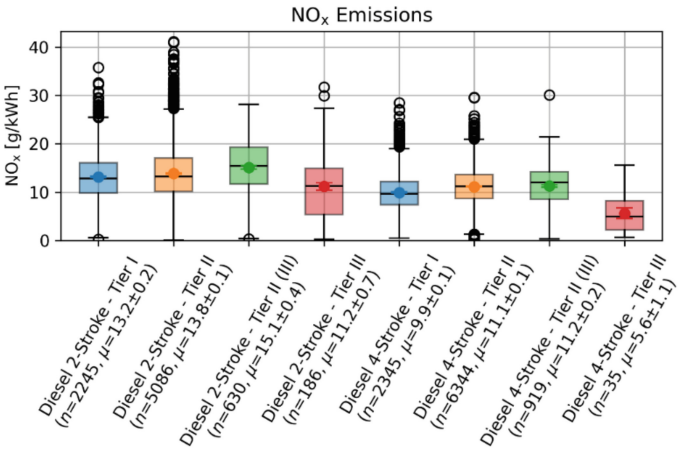


Fig. 1. Distribution of NO_x emission factors per engine type and Tier-level (measurements)

The data shown represents the fleet entering and leaving the Port of Rotterdam and the schedules of the ships, rather than emission factors per individual vessel. Therefore, ships with many port calls at Rotterdam – like, for example, ferries – are overrepresented in Fig. 1. The labels on the abscissa state the groups, numbers of valid measurements, and the estimated means along with their 90% confidence intervals. These estimated

means and confidence intervals are also displayed on the boxplots as coloured dots with errorbars. Most of the measurements involved Tier II ships followed by Tier I and the group of II (III)-vessels. The numbers of measurements of Tier III ships are still low. The work-specific NO_x emissions of two-stroke engines are in general higher than the ones of four-stroke engines of the same Tier level. This can be explained by the combustion process, as two-strokes are usually slow-speed engines. For both engine types, the estimated means were the lowest for Tier III, followed by Tier I and then Tier II. Notably, the highest work-specific emissions were measured in ships capable of meeting Tier III standards but constructed before 2021.

The layout of Fig. 2 is the same as that for Fig. 1. However, Fig. 2 shows the distribution of averages per ship, representing the distribution of emission factors in the fleet without considering the number of port calls (valid measurements). It has to be pointed out that different numbers of measurements are available for the different ships. Since, however, for the vast majority less than ten measurements were available, no correction for the sample size has been carried out.

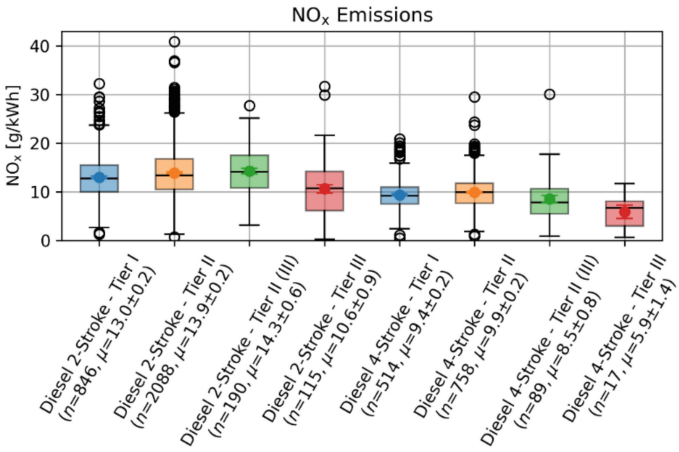


Fig. 2. Distribution of NO_x emission factors per engine type and Tier-level (vessels)

In broad terms, the findings discussed for Fig. 1 also apply here. The NO_x emission factors for two-strokes are larger than for four-strokes, with most vessels classified as Tier II, followed by Tier I, II (III), and Tier III. For two-stroke engines, the mean emission factors increase in the order Tier III – Tier I – Tier II – II (III). The group of II (III) vessels performs better if only four-stroke engines are considered. The average work-specific emissions do not differ significantly to Fig. 1 for two-stroke engines. The emission factors of four-stroke engines are slightly lower if individual vessels are studied rather than measurements. In both cases the data range narrows down, likely because extreme values of individual vessels tend to average out.

Due to the uncertainty of the measurement method, a reasonable number of measurements per vessel is needed to obtain a representative emission factor. It is generally accepted in the literature that the Central Limit Theorem (CLT) applies when there are

thirty or more samples. For NO_x measurements this means that the sample mean of these ships can be approximated by a normal distribution. This allows to determine confidence intervals of the work-specific emission factors based on the sample variance. Figure 3 shows the estimated emission factors for a number of ships plotted against the rated speeds of their main engines. The markers are downward/upward pointing triangles indicating the engine's cycle to be two- or four-stroke, respectively. The Tier levels of the vessels are color-coded, and the same colours indicate the applicable limits set out in MARPOL. The Tier III-limit increased by the NTE-limit was plotted to Fig. 3 as well. For the group of vessels which are Tier III-capable but were constructed before January 1st, 2021, the Tier II-limits were assumed. Note that 90% confidence intervals are not shown for Tier III ships. The reason is that for this category no vessel with a sufficient number of valid measurements was present in the data. Therefore, the limit of thirty samples, which applies to ships of all other categories, was not used for Tier III where the threshold was set to four measurements. The absence of an errorbar should in no way lead to the – incorrect – interpretation that the emission factors of the Tier III ships are more reliable.

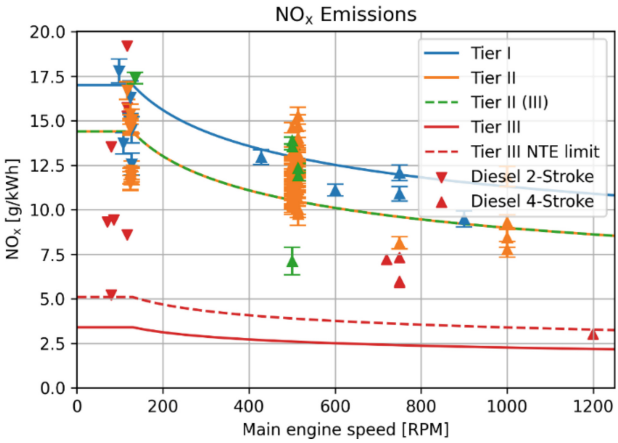


Fig. 3. Comparison of mean work-specific NO_x emissions

The data in Fig. 3 show a clear separation between two- and four-stroke diesel-engines. All two-strokes are slow-speed engines with rated speeds of 135 RPM or lower. The four-strokes cover a wide range of engine speeds with a cluster around 500 RPM. The calculated mean emission factors of almost all Tier I vessels lie below the applicable limit with high confidence. In contrast, most data points of Tier II ships exceed the line. However, since the Tier limits apply to weighted averages across multiple engine load points rather than to individual load points, and an NTE-limit only exists for Tier III, this does not indicate non-compliance in any way. The situation of the ships that are Tier III-capable but older than 2021 is similar to Tier II with one outlier towards low NO_x emissions. The latter represents the NO_x emissions of a fully cellular containership equipped with a dual-fuel LNG-engine.

As has been mentioned above, the emission factors of Tier III ships are based on fewer samples per ship and are therefore only indicative. Furthermore, the errorbars could not be determined properly and were skipped. The low samples sizes partially explain the scatter in the Tier III data. Emission factors for Tier III vessels tend to be lower than the ones of the other categories. However, the maximum value in Fig. 3 origins from a containership for which ten measurements were available. Only two data points lie in the vicinity of the NTE NO_x-limit.

4 Conclusion

Although due to the uncertainty of the measurement procedure no conclusion on compliance can be made, the overall trend confirms what has been discussed in the literature. In particular, higher emission factors were determined for Tier II ships than could be expected compared to Tier I. For Tier III ships, still more data is needed to make a robust assessment of their performance. Based on the data available in this study, the average emissions factors are lower, but the effect is less pronounced than the strict limit would indicate.

Regarding the (equivalent) sulphur content in the fuel, 99.3% of the valid measurements gave values lower than the fuel sulphur cap of 1.0 g/kg-fuel that applies in the North Sea ECA. A share of 68.6% yielded sulphur contents even lower than 0.3 g/kg-fuel. As of today, it is allowed to use both open and closed loop scrubbers in the Port of Rotterdam [21]. In 18 100 out of 23 372 valid measurements (77.4%), the passing ship was not equipped with a scrubber of any type. Referring to unique vessels in the dataset, 4 491 of 5 438 (82.6%) had no scrubber installed. It is therefore concluded that in the majority of cases compliant fuel has been fuelled to the main engines to reach low SO_x emissions.

References

1. International Maritime Organization: International Convention for the Prevention of Pollution from Ships, 1973 (MARPOL). International Maritime Organization (2024)
2. International Maritime Organization: Amendments to the Technical Code on Control of Emissions of Nitrogen Oxides from Marine Diesel Engines. International Maritime Organization (2008)
3. Geilenkirchen, G. et al.: Geraamde ontwikkelingen in nationale emissies van luchtverontreinigende stoffen 2023. Planbureau voor de Leefomgeving (2023)
4. Van Dinther, D., Duyzer, J.H., De Bie, S., Moerman, M.M., Lollinga, J.P., Maarschalkerweerd, T.V.P.: Measurements of Emission Factors of Nitrogen Oxides of Seagoing Vessels in the Port of Rotterdam. TNO (2022)
5. Knudsen, A., Lallana, A.L., Ledermann, L.: NOx Emissions from Ships in Danish Waters - Assessment of Current Emission Levels and Potential Enforcement Models. Explicit ApS for the Danish Environmental Protection Agency (2022)
6. Mellqvist, J., Conde, V.: Results from Exploratory Project on NOx Emissions from Ocean Going Vessels (OGV) Using Remote Sniffer Measurements. Chalmers University of Technology (2023)

7. Van Roy, W. et al.: International maritime regulation decreases sulfur dioxide but increases nitrogen oxide emissions in the North and Baltic Sea. Commun. Earth Environ. **4**, 391 (2023). https://doi.org/10.1038/s43247-023-01050-7
8. Riess, T.C.V.W., Boersma, K.F., Prummel, A., Van Stratum, B.J.H., De Laat, J., Van Vliet, J.: Estimating NO x emissions of individual ships from TROPOMI NO 2 plumes. Remote Sens. Environ. **324**, 114734 (2025). https://doi.org/10.1016/j.rse.2025.114734
9. International Maritime Organization: Air Pollution Prevention: Assessment of Low-Load Performance of IMO NOX Tier III Technologies. International Maritime Organization (2023)
10. International Maritime Organization: Any Other Business: Projects and Scientific Outcomes of NOX Ship Emission Measurement Campaigns. International Maritime Organization (2023)
11. Vermeulen, R.J., Verbeek, R., Van Dinther, D.: Real Sailing NOx Emissions of Sea-Going Ships with Tier III Certified Engines. TNO (2024)
12. Zhou, F. et al. Monitoring Compliance with Fuel Sulfur Content Regulations of Sailing Ships by Unmanned Aerial Vehicle (UAV) Measurements of Ship Emissions in Open Water, (2020)
13. Mellqvist, J., Conde, V.: Surveillance of Sulfur Fuel Content in Ships at the Great Belt Bridge 2019. Chalmers University of Technology (2020)
14. Mellqvist, J., Conde, V.: Surveillance of Sulfur Fuel Content in Ships at the Great Belt Bridge 2020. Chalmers University of Technology (2020)
15. Clarksons Research. World Fleet Register [Data base]. Clarkson Research Services (2026). Retrieved July-September 2026, from clarksons.net
16. Grigoriadis, A., Mamarikas, S., Ntziachristos, L., Majamäki, E., Jalkanen, J.-P.: Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations. The Scipper Project (2021)
17. Fridell, E., Verbeek, R., Matthias, V., Mellqvist, J.: Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations. The Scipper Project (2023)
18. Interim Guidelines for Voluntary Ship CO_2 Emission Indexing for Use in Trials (2005)
19. Faber, J., et al.: Fourth IMO GHG Study 2020. Planbureau voor de Leefomgeving (2020)
20. Beecken, J. et al.: Performance assessment of state-of-the-art and novel methods for remote compliance monitoring of sulfur emissions from shipping. Atmos. Meas. Tech. **16**, 5883–5895 (2023). https://doi.org/10.5194/amt-16-5883-2023
21. Port information guide (2025). https://www.portofrotterdam.com/sites/default/files/2025-01/port-information-guide.pdf.

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Accelerating Zero-Emission Urban Logistics Through User-Centric eLCV Innovation: The Shift2Zero Project

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Abstract. Urban logistics is at a critical crossroads, with decarbonisation urgently needed to meet European Union climate targets. The Shift2Zero project aims to accelerate the uptake of electric light commercial vehicles (eLCVs) by delivering six user-driven, mission-specific N1 eLCV concepts designed for diverse logistics scenarios. Building on proven IVECO e-Daily and Alkè ATX platforms, the project integrates energy-efficient technologies and leverages modularity, geofencing, and ergonomic design to meet evolving urban needs.

The project's impact is significant: through co-development with logistics operators, fleet managers, and policymakers, Shift2Zero aims to reduce CO_2 emissions by 1–3% at project level, decrease operational costs by 10%, and enhance safety, thus increase eLCV adoption by tackling operational and economic barriers. Each single Shift2Zero vehicle aims at replacing 3 traditional N1 vehicles. Innovative features such as multi-temperature cargo bodies, swappable transshipment units, and dual-use passenger/goods vehicles enable scalable, future-proof solutions.

Validation takes place via four pilots and one macro-pilot across six European cities, covering varied urban conditions to ensure transferability. Shift2Zero delivers not just vehicles, but a replicable model for sustainable urban transport. By aligning technical innovation with real-world logistics challenges paves the way for resilient, zero-emission urban mobility, positioning Europe at the forefront of green logistics transformation.

Keywords: eLCV · modularity · geofencing · ergonomic · dual-use

1 Introduction

In urban areas across Europe, the shift towards zero-emission logistics is not just a policy preference, but a growing and crucial necessity. Nonetheless, despite the growing variety and reduced costs of electric-Light Commercial Vehicles (e-LCVs), their adoption lags, particularly in contrast to markets like China [1]. This gap highlights an urgent need for better-tailored e-LCV solutions, in line with the mission they aim to cover, and regarding future market and societal needs.

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At the vehicle level, current market dynamics reveal a gap between existing vehicles, the evolving needs of urban logistics, and the envisioned climate targets. This discrepancy is highlighted by the fact that, in 2023, more than 1.2 M new LCV registrations were diesel-powered, while only 108.200 were battery-electric, indicating a significant gap in the adoption of eLCVs. This slow uptake can be an opportunity for the entrance of new players, focusing on purpose-built e-LCVs as an alternative to the traditional manufacturers' approach, which has historically emphasized versatility to achieve economies of scale [2]. The latter often involves using the same platforms across vehicle segments, which can result in the adoption of vehicles that are not optimally designed for specific urban logistics operations, sometimes being oversized, less efficient, or not meeting the highest safety standards. Recognizing these issues, traditional Original Equipment Manufacturers (OEMs) are beginning to adapt their strategies to better meet the specific needs of urban logistics. Similarly, while custom-made OEMs offer vehicles tailored to specific missions, challenges such as higher production costs and limited market uptake must be addressed.

This situation emphasizes the need for a tighter product-market fit, as most logistics companies today lean towards conventional vehicle designs when transitioning to zero-emission fleets. As an example, in Europe, the best-selling commercial van models in 2022 included the Ford Transit, Fiat Ducato, Citroën Jumper, Peugeot Boxer, and the Mercedes-Benz Sprinter, all diesel-powered and part of the heavy segment of the N1 class [3]. These models have been favoured for their reliability, durability, and cargo capacity, demonstrating a continued preference for traditional designs even as the market shifts towards greener options. However, exploring novel vehicle concepts such as modularity and swappability – both at the vehicle level and across different OEMS – could unlock efficiencies in load factor, energy consumption, and operational flexibility [4]. At the operational level, these innovations have the potential to reduce both fleet and vehicle sizes, allowing operators to make use of the same vehicles for a wide range of goods while being able to adapt to fluctuating demands without having to extend their fleet size or resort to subcontractors.

Therefore, it is imperative for OEMs to enhance their e-LCV solutions regarding end-user requirements, safety, and affordability, while also considering the upcoming EU-wide emission targets and their requirements on non-exhaust particle emissions (Euro 7). These efforts are crucial to address the large contribution of urban logistics to transport-related emissions, currently representing more than a quarter of its total [5]. The forthcoming years are expected to witness a significant increase in the delivery and collection of goods in urban and suburban areas, along with the demand for transport, via Heavy Duty Vehicles (HDVs) and LCVs. Freight vehicle activity is forecasted to grow by an average of 36% between 2020 and 2030, potentially leading to a 32% increase in GHG emissions from these vehicles if current practices continue [6].

The introduction of Urban Vehicle Access Regulations (UVARs), such as Low-Emission Zones (LEZs), is a clear response to the urgent need for cleaner urban air and reduced GHG emissions. Cities like Brussels exemplify this approach, as they are gradually expanding and increasing their emission standards for logistics vehicles: since January 1, 2026, all Euro 5 diesel and Euro 2 petrol vehicles, including light commercial vehicles, are no longer allowed to circulate in the Brussels Region [7]. Taking a different

approach, cities like Bergen are planning to try out the extension of mobility data standards, initially addressing shared mobility regulation, towards logistics vehicles. Such innovative ways of regulating city access bring the potential to facilitate the operations of urban freight vehicles within restricted zones while ensuring the safety of Vulnerable Road Users (VRUs). Data standardisation across the transport of people and goods will facilitate integrated planning approaches. Besides, the Physical Internet (PI) vision will help companies address stricter UVARs and low/zero emission vehicle standards, avoiding pollution and congestion cost-effectively. PI may support trade-offs between the accessibility of goods and services, quality of life and environmental aspects, achieving a reduction of distance for the same volumes delivered [8].

On the demand side, the recent spike in online shopping and fresh product delivery, alongside their related delivery requirements, has led to a shift in the demand for fast last-mile transport. This surge in e-commerce has resulted in an unprecedented rate of Business-to-Consumer (B2C) deliveries, especially groceries, parcels, and ready-to-eat meals [9]. Adding pressure on urban logistics systems, e-commerce logistics requires a rapid and strategic response to mitigate environmental impacts while meeting consumer needs efficiently. Requirements on the cold value chain need to be covered with novel functions that could allow mixed transport of goods, including frozen, fresh, tempered, and dry goods, to avoid logistics providers using different vehicles for different missions. Besides, e-commerce is also one of the strongest contributors to the reverse logistics market, requiring the return of products from consumer to seller.

This shifting demand and its associated environmental impact stress the necessity for innovative logistics solutions, from both multi-purpose and design-for-purpose OEMs. Last Mile Logistics (LML), identified as the least efficient and most complex part of the supply chain [10], represents significant opportunities for improvements at the vehicle and operations levels. For this reason, aligning, fine-tuning, and demonstrating innovative concepts within real-life operations, proving that new e-LCV models are not only aligned with the new market demands/mission-driven but also economically viable, scalable, and affordable, demands commitment from the whole supply chain.

2 Methodology

The methodological framework builds on the six novel N1 e-LCV concepts developed in the project, each designed to address the concrete needs, constraints, and challenges of end users and logistics stakeholders. To ensure a user- and mission-centred design process, a structured methodology identifies operational requirements and translates them into technical specifications for vehicle development. Through interviews, co-creation workshops, surveys, and holistic experience-based methods, the approach captures expectations, pain points, and preferences across diverse logistics missions. These insights directly inform the design of purpose-built solutions, including modular multi-temperature cargo bodies, energy-efficient systems, improved cabin ergonomics, safety enhancements, and interoperable transshipment features, ensuring that the vehicles meet current and future urban logistics needs. The resulting concepts are simulated and optimised for realistic delivery scenarios and then validated in real-world pilots, generating solid evidence to assess technical, environmental, economic, and societal impacts while supporting future adoption and scalability.

2.1 Multi-temperature Controlled, Dynamically Optimised and Energy-Efficient Cargo Body

The concept focuses on integrating movable panel systems with a multi-temperature modular cargo body, enabling dynamic optimization of temperature distribution in the inner compartments and adapting to fast-changing demands. The thermal management system will rely on a main pack of eutectic evaporators regulating the lower-temperature chamber, along with a controlled airflow system that transfers cold air to adjacent, higher-temperature chambers. Smart sensors integrated into the cargo body and linked to the vehicle's thermal management system will ensure and monitor this functionality. FEM simulations, including CFD and thermal analyses, will optimize and validate the design, assessing factors such as access-door positioning and temperature distribution. These features enhance efficiency by optimizing cargo space and maximizing capacity. The multi-temperature control body also increases flexibility, allowing the transport of goods at +18 °C, +4 °C, and frozen conditions in a single vehicle, ensuring optimal storage throughout the process. Altogether, these innovations strengthen operational versatility and facilitate handling a wide range of goods.

2.2 Optimised Thermal Comfort and Safe Ergonomics in N1 Vehicles' Cabin

The project aims to improve cabin features in both vehicles, addressing user needs and mission requirements related to thermal comfort, safety, and ergonomics. For thermal comfort, an advanced radiation-heating concept using IR Heating Panels will be integrated. This lightweight, reliable solution converts electric energy directly into radiant heat, ensuring optimal comfort. With a thickness of only 150 μm, the power film is highly flexible and enables rapid heat-up within seconds. These radiant heaters are versatile and can be strategically placed throughout the cabin, positioned near passengers for maximum efficiency.

To manage thermal comfort settings, a display-based HMI will be included, integrating the existing HVAC system and IR panels. Default comfort settings will be automatically determined by the thermal management strategy, while passengers can easily adjust temperature through intuitive buttons such as "Too COLD" or "Too HOT." The control strategy will dynamically adapt heating based on user input, with the display providing clear feedback on intensity.

2.3 eLCVs with Holistic Energy Management for Cold Value Chain Deliveries Acting as Energy Sources for Optimised Charging Operations

Holistic smart energy management redefines how energy is used and optimised during deliveries, particularly in cold value chains. Integrating energy-saving technologies is essential to boosting efficiency and reducing environmental impact. This innovation combines vehicle control strategies, regenerative braking, and advanced tyre technologies to lower emissions, and is tested in a pilot on bi-directional charging.

Intelligent powertrain control maximises recuperation and optimises drive cycles to improve overall efficiency. Advanced brake and tyre Digital Twins will be developed

to analyse and reduce non-exhaust emissions from component wear — a critical factor in stop-intensive urban missions. Low-rolling-resistance compounds and optimised tread designs further minimise friction losses, enhancing energy efficiency and reducing particle emissions.

Bi-directional charging enables eLCVs to operate as energy providers, feeding surplus power back to the grid during low-demand periods or supplying energy to delivery or cargo e-bikes. This increases grid stability while creating potential revenue streams for fleet operators.

2.4 Modular Swappable Concept Enabling Seamless Standardised Transshipments across and in Multi-OEM Fleets

The swappable concept streamlines package movement across the logistics chain, fostering interaction, standardisation, and synchro-modality while helping fleets adapt to increasing access restrictions such as LEZs, ZEZs, and infrastructure changes. Modular cargo bodies with standard-dimension swappable units support varied cargo types and vehicle architectures, enabling efficient transshipment between eHDVs, eLCVs, and smaller vehicles to improve distribution efficiency, reduce costs, and optimise fleet use while supporting demand management and regulatory compliance. Transshipment at terminals, between vehicles, or at micro-hubs is carried out with full cargo security, using standardised OEM-neutral swap boxes that enhance collaborative logistics. Their traceability, foldability, and compact design facilitate integration into smaller vehicles, minimise empty returns and idle time, and reduce emissions. Overall, the concept shortens transit times, cuts delays, and boosts supply-chain performance and customer satisfaction.

2.5 Geofenced N1 Right-Sized Vehicles for Safe Driving in Restricted Urban Areas

This enables authorities to manage dynamic functions such as curbside allocation and geofencing-triggered actions, including speed limitation, access control, and data exchange. Vehicle-to-infrastructure connectivity is strengthened via IoT architectures and cloud-based platforms that support real-time tracking and operational supervision. The innovation also incorporates mechanisms for validating delivery permissions and enforcing load restrictions, extending geofencing functionality beyond conventional speed control. Drivers receive visual HMI alerts when nearing geofenced zones, allowing controlled deceleration and safer manoeuvring. To improve pedestrian and occupant protection, structural components (front bumper, bonnet, and interior door trim) are re-engineered using 3D-printed prototypes subjected to impact-performance validation. Bio-sustainable materials are employed to reduce CO_2 emissions while maintaining high energy-absorption efficiency and ensuring lateral-impact resistance without compromising cabin integrity.

2.6 Dynamically Optimised Space in Modular 4-Seater Vehicles for Dual Transport of Goods and People

A novel dual-transport concept is proposed (cargo hitching), enabling innovative use of 4-seater vehicles. The solution allows simultaneous transport of up to four people in the double cab and goods in the rear cabin, prioritizing safety and passenger comfort in line with the existing model. The prototype will include advanced IoT systems to ensure secure rental and operation. Foldable seats provide strong versatility, expanding cargo capacity while keeping strict separation from passengers. When seats are folded, the protective partition can move forward, enlarging the rear cargo area. The vehicle adapts to changing needs, serving as a delivery unit during off-peak hours and a passenger transporter during peak times, supporting integrated and shared transport models. Its sustainable design consolidates functions into one modular vehicle, reducing cost, time, and emissions while maintaining high load and towing capability. Additionally, a foldable swap box can be included for optimized storage, fitting into the upper rail system when empty to maximize space without compromising cargo safety.

3 Results

The main expected results and innovations at the end of the project are structured in six groups:

- Full list of technical and operational requirements for innovative e-LCVs, from all relevant stakeholders (logistics suppliers, urban policy makers, freight receivers, wider society).
- 6 innovative N1 e-LCV concepts ready for qualification, homologation, and large-scale production, integrated in 4 physical prototypes of 2 N1 platforms.
- Vehicle control strategies integrating optimised tyre designs and regenerative braking system.
- Validated and scalable concepts of integration of people and freight vehicle operations in dense urban areas using eLCVs.
- Development of policy guidelines for scaling up, ensuring widespread adoption of innovative logistics concepts.
- Validated business cases and route to market roadmap.

Each pilot tests the vehicle concepts in different combinations, exploring potential synergies to address evolving user requirements. To ensure broad relevance and scalability, various end users and stakeholders are directly involved. Public authorities with policy and decision-making roles represent cities with established or expanding low- or zero-emission zones, serving as references for other EU cities aiming to decarbonize logistics.

Real-life testing of the prototypes and concepts will be conducted in four pilots and one macro-pilot across diverse urban and suburban contexts in Northern, Western, Central, and Southern Europe, demonstrating six new vehicle concepts in scalable zero-emission operations.

The following Fig. 1 presents the Shift2Zero innovation matrix, which compiles all innovations and the corresponding urban and suburban contexts for each prototype.



Fig. 1. Major innovations per vehicle and pilot in Shift2Zero project.

4 Discussion and Conclusions

One of Shift2Zero's strengths is placing end-users at the core of its innovation process. By involving logistics operators, fleet managers, policy makers, and industry stakeholders from the start, the project ensures that its new vehicle concepts meet current and future supply and demand needs for the commercial delivery of goods.

With these innovations, Shift2Zero aims to address both the supply (operational and industrial requirements) and the shifting demand (increased e-commerce and fresh product delivery):

- Multi-temperature controlled, optimised and energy-efficient cargo body: efficient eutectic evaporators and airflow integration allow mixed transport of fresh, temperature-sensitive, and dry goods, reducing fleet size and emissions.
- Optimised thermal comfort and safe ergonomics in vehicles' cabin: integration of advanced lightweight radiant heating panels that warm up within seconds and can be placed strategically near passengers for maximum efficiency.
- Holistic energy management: combining regenerative braking, advanced tyre technology, and bi-directional charging for greater efficiency and sustainability.
- Modular swappable transshipment units: standardised cargo modules improve operational flexibility, reducing handling and boosting efficiency.
- Geofenced N1 vehicles for urban safety: implementing open-standard logistics solutions for geofencing, curbside reservations, and pedestrian and passenger safety improvements.
- Dual-use modular vehicles for goods and passenger transport: flexible seating and IoT-powered safety measures enable efficient transport of both people and cargo.

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References

1. Alsauskas, O. et al.: Trends in Electric Light-Duty Vehicles: Global EV Outlook 2023 – Catching up with Climate Ambition. International Energy Agency, Paris (2023)
2. Frank, S., Hans, M., Heid, B., Jautelat, S., Schaufuss, P.: Built for Purpose: EV Adoption in Light Commercial Vehicles. McKinsey & Company, Industrials & Electronics Practice (2023)
3. Best-selling European light commercial vehicles 2023. https://www.truck1.eu/blog/european-lcvs-2023-t787. Accessed 15 Mar 2025
4. Marthaler, L., Dobbs, H., Magallón, I.: The Urbanized Vision for Modular Commercial Vehicles for Future Urban Logistics. Position Paper. Bax & Company, Urbanizer Project (2023)
5. Punte, S., Tavasszy, L., Baeyens, A., Liesa, F.: A Framework and Process for the Development of a Roadmap Towards Zero-Emissions Logistics 2050. ALICE – Alliance for Logistics Innovation through Collaboration in Europe (2019)
6. Deloison, T. et al.: The Future of the Last-Mile Ecosystem: Transition Roadmaps for Public- and Private-Sector Players. World Economic Forum, Geneva (2020)
7. City of Brussels: Low Emission Zone: New Ban since 2026. Brucity Administrative Centre, Brussels (2026)
8. Ballot, E. et al.: Roadmap to the Physical Internet. ALICE – Alliance for Logistics Innovation through Collaboration in Europe (2020)
9. E-commerce statistics for individuals. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=E-commerce_statistics_for_individuals. Accessed 20 Mar 2025
10. Bosona, T.: Urban freight last mile logistics—challenges and opportunities to improve sustainability: a literature review. Sustainability. **12**(21), 8769 (2020)

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Assessing the Potential for CO_2 and Pollutant Emission Reduction via Redistribution of Port-Induced Road Traffic: A Case Study of the Port of Rotterdam

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Abstract. Public authorities face the challenge of air quality management in complex territories and need tools to disentangle the contributions of heterogeneous sources of emissions. Transportation is a major source of nitrogen oxides and accounts for about 30% of global carbon emissions. This becomes even more relevant in territories where transportation significantly serves other purposes than just people mobility. Port cities are among these territories where transportation is key to ensure goods displacement, and more complexity arises when goods transport interacts with people mobility. This paper aims to model and analyse port-induced road traffic emissions, and to explore reduction strategies by optimizing the temporal distribution of traffic induced by freight transport. A mesoscopic emission model incorporating road characteristics, traffic flow, and vehicle fleet data, was used to estimate the contribution of each emitter on each road segment of the studied area. Real traffic count data from the Port of Rotterdam were used to compare a reference scenario (current traffic patterns) with a scenario shifting container-shipment traffic to off-peak hours. Results indicate that while annual CO_2 emission reduction is modest (~1%), this approach noticeably reduces (~30%) peak-time pollutant peaks and traffic congestion, improving air quality and operational efficiency during the busiest hours.

Keywords: Port logistics · Emission modelling · Road traffic regulation · Emission reduction measures

1 Introduction

Air pollution is a major environmental and public health challenge. Millions of premature deaths each year are linked to ambient and household pollution, with fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NOx) contributing strongly to respiratory and cardiovascular diseases. Air pollution also reduces ecosystem services and crop yields and complicates climate mitigation because many pollutants share sources with greenhouse gases. Transport is a key contributor, and decarbonising the sector remains technically and institutionally difficult, with uneven progress in electrification and low-carbon fuels.

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Port cities illustrate the complexity of the urban transport–air quality nexus. Maritime activity, harbour operations and related hinterland freight flows concentrate emission sources—oceangoing vessels, auxiliary engines, cargo-handling equipment, heavy-duty trucks traffic—within coastal metropolitan areas, producing heterogeneous pollution patterns and local hotspots of NOx, sulfur dioxide (SO_2) and particulate matter [1]. The co-location of freight and passenger mobility complicates exposure attribution and mitigation design, since measures in one sector (e.g., shore power) may have limited effects on roadside concentrations if truck traffic remains high [2].

Effective policy therefore requires source-aware, high-resolution tools linking activity data, traffic dynamics and emission processes [3]. Traditional emission inventory models (e.g., EMEP/EEA methods) provide consistent national and regional estimates but usually operate at coarse spatial or temporal scales, limiting their usefulness for identifying road-link-level contributions within cities. Receptor-based approaches and dense monitoring networks can identify source signatures, but they are costly and not always easily connected to activity-based policies. Mesoscopic emission models address this gap by combining traffic flow representations, road-segment attributes and fleet composition to estimate emissions at finer spatial and temporal resolution [4, 5]. When integrated with traffic counts and sectoral activity models, these frameworks support road-link-level source apportionment and scenario testing of operational strategies.

Building on these motivations, this study develops and applies a mesoscopic emission modelling framework to quantify the contribution of port-induced road traffic to local NOx and CO_2 emissions, and to evaluate the air-quality and congestion impacts of temporal redistribution policies for goods movements. Using real traffic counts from the Port of Rotterdam as a case study, we compare a reference scenario that reproduces current daily traffic patterns with an alternative in which a share of container-shipment truck trips is shifted to off-peak hours. The approach combines link-level traffic flows, fleet and emission factors, and scenario-based adjustments to departure time distributions; it is designed to be operationally transparent and readily adoptable by municipal and port authorities for decision support.

2 Methodology

To accurately simulate the temporal shift of port-related road operations, it is essential to rely on a modelling framework capable of representing both the current and prospective state of the transport system. Such a framework must capture three interrelated dimensions: the temporal and spatial distribution of traffic volumes, the resulting emissions produced along each road segment, and the composition of the vehicle fleet that conditions emission intensities.

Estimation of Hourly Traffic Flow per Road Segment. Accurate estimation of road traffic volumes at a fine spatial and temporal resolution is a prerequisite for reliable emission modelling. In this study, we applied a data-driven flow estimation approach developed at IFPEN, which enables hourly traffic predictions on any road-link of a given network, even when direct measurements are unavailable.

Let $\mathbf{L}$ denote the set of road links (segments). For each link $l \in \mathrm{L}$, we ingest:

(i) X_l^{static}: *static* features from Geographic Information System (GIS) layers, including geometry and length L_l, functional class, number of lanes, curvature, slope ∇l, signage and junction types, and posted speed limit.

(ii) X_l^{dyn}: *dynamic* features such as historical speed patterns, real-time probe speeds (FCD), counting stations (where present), and temporal descriptors (hour-of-day, day-type, season).

All features are harmonised to an hourly time base $h \in \{1, \ldots, 24\}$ for the target day. For each road link l and hour h, a supervised deep learning model $\boldsymbol{F}_\theta\left(X_l^{static}, X_l^{dyn}\right)$ predicts the total flow $Q_{l,h}$(veh/h) from static and dynamic features, following a spatio-temporal approach for network-wide flow profile estimation [6, 7]. The reference dataset of traffic flow measurements used for training the supervised model contains traffic counts from French major urban and peri-urban areas. The vehicle flow is aggregated across all vehicle classes. The model produces hourly flows on all links, with uncertainty estimates derived from validation residuals.

To ensure network-wide consistency, a correction model enforces flow continuity across nodes. This is formulated as an optimization problem solved with an interior-point method, with constraints on connectivity and congestion states. Measurement-equipped links are given higher weights in the objective function, so that available counts anchor the estimation. The final output is a temporally resolved traffic flow estimate for each link, at an hourly resolution, consistent both with local data and with global network continuity.

The traffic flow prediction model, grounded in an artificial intelligence framework, offers both flexibility and computational efficiency, enabling rapid calibration against real-world measurements when such data are available. As demonstrated in the results section, the model can be fine-tuned to align closely with observed traffic counts in the study area, thereby improving the accuracy and contextual relevance of the predictions.

Estimation of Traffic Emissions per Road Segment. Once traffic flows are estimated, emissions are computed using an enhanced mesoscopic model. Traditional macroscopic approaches (e.g., COPERT, HBEFA) rely solely on average speed and tend to underrepresent the effects of congestion, slope, and road characteristics. In contrast, the proposed model incorporates additional input dimensions: infrastructure type (e.g., urban arterial, motorway), slope classes, posted speed limits, and average speed. These descriptors are linked to emission factors derived from a large microscopic emissions database.

The calibration database is based on trajectories from the *Geco air* platform, which aggregates over 100 million km of real driving data collected at 1 Hz resolution from GPS-enabled smartphones. Each trajectory includes detailed speed, acceleration, and altitude profiles, which are then coupled with vehicle-specific models to estimate emissions of CO_2, NOx, hydrocarbons, CO, particulate matter, and noise. Emission factors are not limited to median driving styles: the model also provides 25^{th} and 75^{th} percentile values, reflecting gentle and aggressive driving conditions, respectively.

To reduce computational complexity, the calibration dataset was binned by infrastructure type, slope, average speed, and speed limit. Within each bin, representative trajectories corresponding to the median and extreme quartiles were retained, producing

a compact yet representative training set. A supervised learning model was then fitted to link the input variables to emission factors [8, 9].

For each vehicle category and pollutant, the mesoscopic model thus predicts average emission factors and their variability for any road segment. Combined with hourly traffic flows, this yields temporally and spatially resolved emission inventories. Crucially, the approach captures the sensitivity of emissions to congestion and road attributes, providing results that are both computationally tractable and closer to real-world dynamics than factor-based averages.

Model of the Vehicle Fleet Composition. Finally, realistic emission estimates require a representation of the circulating vehicle fleet. Fleet composition is specified at the level of four broad categories: light vehicles (LV), light commercial vehicles (LCV), heavy-duty vehicles (HDV), and two-wheelers (2WD). For each category, the distribution across fuel types (diesel, gasoline, electric, hybrid) and Euro standards is derived from national statistics (CITEPA, SDES) and International Energy Agency (IEA) scenarios. Importantly, road fleet shares are corrected to reflect actual usage, since vehicles differ in mileage intensity. For instance, while motorcycles are numerous in stock, heavy-duty vehicles dominate road presence in terms of vehicle-kilometres travelled. This correction ensures that the computed emission shares reflect real exposure conditions rather than ownership statistics.

3 Results

We applied the proposed road traffic emission modelling framework to the area of the Port of Rotterdam to assess both its sensitivity and its extrapolation capability to territories outside the training domain. This application provides a stringent test of the model's generalisation performance.

Port of Rotterdam Measurement Data. The Port of Rotterdam dataset comprises 409,571 traffic measurements collected from 40 sensors distributed across the port area (see Fig. 1). Sensor coverage is heterogeneous: blue sensors record aggregate vehicle counts, cyan sensors provide counts disaggregated into three vehicle classes, and green sensors differentiate up to five classes. These data were systematically processed to extract hourly vehicle counts, average speeds, and, where possible, vehicle category information, which served as inputs for model calibration and validation.

Traffic Flow Calibration. Traffic flow estimations were first compared against available ground-truth measurements, and the model was subsequently calibrated to improve accuracy for this specific use case. In the baseline modelling approach, historical traffic speed information from HERE Maps is used to estimate traffic flows, which are subsequently converted into emission estimates. In the case of the Port of Rotterdam, however, traffic count measurements were available, allowing for a two-step calibration procedure. First, whenever a sensor provided speed data, the corresponding HERE speed on the associated road segment was replaced with the observed sensor speed. Second, for links equipped with traffic counters, sensor-based vehicle counts were incorporated to fine-tune the AI-based flow estimation model.



Fig. 1. Location of the sensors providing the measurement data. Blue sensors record aggregated vehicle counts, cyan sensors provide counts disaggregated into three vehicle classes, and green sensors differentiate up to five classes.

To reduce the risk of overfitting, the calibration did not attempt to exactly reproduce the measured flows at each sensor location. Instead, fitting errors were smoothed across the network, ensuring that adjustments improved global consistency rather than producing local biases. A summary of the calibration results is provided in Fig. 2.

Calibration is particularly important in this scenario due to the specific traffic characteristics of the A15 highway, which crosses the southern part of the Port of Rotterdam. On regular working days, this corridor is predominantly used by port employees and heavy-duty vehicles, resulting in atypical traffic dynamics. Consequently, despite being a two- to three-lane highway, the measured traffic volumes remain relatively low compared to similar road infrastructures. This fine-tuning strategy proved effective in enhancing the accuracy of the model while preserving its generalisation capacity. The procedure is transferable and can be replicated in other port or urban areas where traffic sensors provide flow and speed data.

Vehicle Fleet Composition Calibration. The traffic sensors deployed around the Port of Rotterdam provide vehicle counts with varying levels of disaggregation. Three sensor types are distinguished: (i) *blue sensors*, which record undifferentiated counts for all vehicles; (ii) *cyan sensors*, which classify vehicles into three length-based categories ($l \leq 5.60$ m; 5.60 m $< l \leq 12.20$ m; $l > 12.20$ m); and (iii) *green sensors*, which offer a finer classification into five length intervals (1.85 m $< l \leq 2.40$ m; 2.40 m $< l \leq 5.60$ m; 5.60 m $< l \leq 11.50$ m; 11.50 m $< l \leq 12.20$ m; $l > 12.20$ m).

Data pre-processing was required to ensure consistency. Approximately 0.8% of the raw data were discarded due to sparsity, incoherence, or missing values. In addition, sensors that did not provide vehicle-type distinctions were excluded, representing 71.1% of the initial dataset. After filtering, only 17 of the 40 sensors remained, corresponding exclusively to the green category with five vehicle classes. This resulted in a curated dataset of 80,680 measurements, equivalent to 19.7% of the original records.

For compatibility with the emission modelling framework, which is based on four broad vehicle categories—heavy goods vehicles (HGV), light commercial vehicles

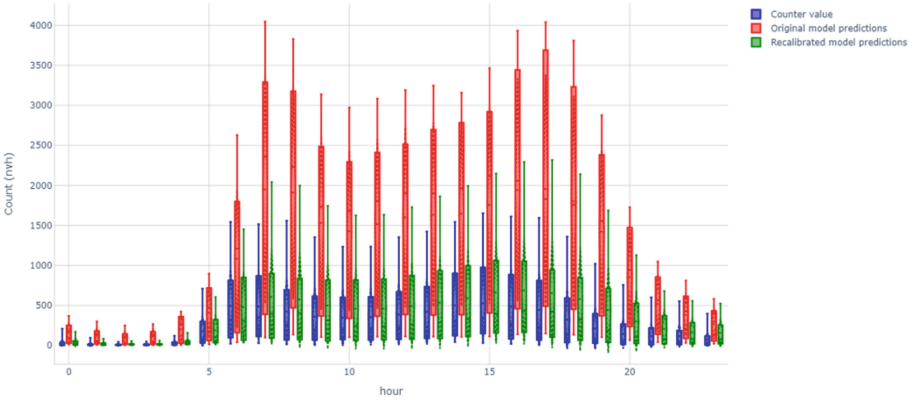


Fig. 2. Average hourly traffic flow at sensor locations as a function of the hour of the day. The blue boxplots indicate the measured data. The red boxplots indicate the model estimation before calibration. The green boxplots indicate the model estimation after calibration.

(LCV), light vehicles (LV), and two-wheelers (2 W)—the two longest sensor classes were merged and treated as HGV. This mapping is consistent with empirical evidence showing a strong correlation between vehicle length, gross vehicle weight, and typical usage (e.g. long-haul trucks and articulated lorries fall within the longest length categories, whereas shorter segments capture vans and passenger cars). As a result, the aggregated fleet composition derived from the sensor data is 40.2% HGV, 6.5% LCV, 53.0% LV, and 0.3% 2 W. This adjusted distribution provides a realistic representation of the active road fleet in the port area, while ensuring methodological consistency with the emission models.

Analysis of the Container-Shipment Traffic Volume Shifting Scenario. As part of a policy aimed at reducing peak-time emissions, we simulate a traffic volume-shifting scenario. In this scenario, we assume that the average hourly traffic flow in the port area can be regulated by redistributing heavy-duty-vehicles missions throughout the day in such a way that it remains uniform throughout the daytime period (06:00–18:00) and accounts for 60% of the total daily flow, while the off-peak flow is also uniform and represents the remaining 40% of daily traffic.

This traffic redistribution results in modest but measurable impacts on annual emissions, yielding a 1% reduction in CO_2 and a 1.1% reduction in NO_n compared to the nominal scenario. This reduction is modest because in our simulation we do not alter the total traffic volume in the two scenarios and at the annual aggregation level only the effect of reduced congestion during most congested hours, as measured by the sensors, is visible on the total emissions. However, more interestingly, the effects on the hourly distribution of emissions reveal that a decrease in daytime traffic flow leads to a more significant reduction in emissions, whereas an increase in off-peak traffic flow produces a corresponding rise in emissions (see Fig. 3, road traffic emissions are indicated in dark blue).

Consequently, peak-time emissions are mitigated by about 30%, and emissions are more evenly distributed across the 24-h period. This effect is particularly relevant for

local pollutants such as NO_n, for which peak-shaving measures can have a substantial impact on air quality and public health in areas surrounding ports.

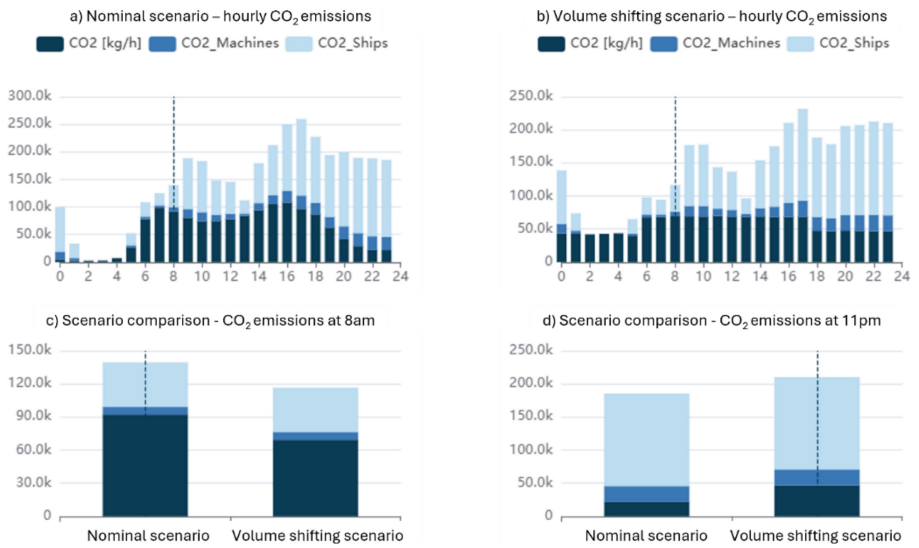


Fig. 3. Evaluation of CO_2 emissions in the two analysed scenarios. The dark blue bars indicate emissions caused by road traffic, the denim blue bars indicate emissions caused by container-handling machines, the light blue bars indicate emissions caused by berthed vessels. Subfigures a) and b) show the hourly CO_2 emissions for the two scenarios. Subfigures c) and d) show a zoom of the carbon emissions for a peak-time and an off-peak hour, respectively.

4 Conclusion

In conclusion, this study highlights the role traffic distribution strategies can play in reducing road-traffic emissions from port freight transport, a major source of port-induced hinterland emissions. By calibrating the traffic and emission model with real sensor data, we compared the current traffic scenario with an alternative "optimal" configuration in which traffic was evenly distributed between peak and off-peak hours. The results show that the maximum achievable annual reduction through traffic spreading is about 1% for CO_2, with a similarly marginal effect for NO_n. At the hourly scale, however, peak-time emissions decrease by about 30%. While this demonstrates the technical feasibility of regulating traffic flows and its potential to reduce population exposure to local pollutants such as nitrogen oxides, it also highlights the limited capacity of this strategy to deliver significant progress toward ambitious decarbonization targets. If substantial progress toward sustainability is required, greater emphasis should be placed on transformative measures, particularly replacing conventional fuels with cleaner alternatives such as electrification or hydrogen-based propulsion. These strategies are more likely to align port operations with long-term environmental goals.

This work also represents a step within the MAGPIE project. With emission calculations transitioning to the HESP tool developed by the Port of Rotterdam Authority with BigMile, future analyses will benefit from improved data and greater transparency in tracking transport-related emissions, ensuring continuity and enabling more comprehensive insights into heavy-duty vehicle emissions.

Acknowledgments. The MAGPIE project is funded by the European Commission as part of Horizon 2020 under grant agreement number 101036594.

References

1. Tokaya, J.P., et al.: The impact of shipping on the air quality in European port cities with a detailed analysis for Rotterdam. Atmos. Environ. X. **23**, 100278 (2024). https://doi.org/10.1016/j.aeaoa.2024.100278
2. Acciaro, M., Hein, C., Dalhuisen, M., Flikkema, M.: Sustainable and greenhouse-gas-neutral initiatives within European ports: insights from the MAGPIE project. In: Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRA Conference (2024). https://doi.org/10.1007/978-3-031-89444-2_58
3. Rodriguez-Rey, D., et al.: A coupled macroscopic traffic and pollutant emission modelling system for Barcelona. Transp. Res. Part D: Transp. Environ. **92**, 102725 (2021). https://doi.org/10.1016/j.trd.2021.102725
4. Dib, A., Balac, M., Sciarretta, A.: Deep learning approach to predict microscopic pollutant emissions from mesoscopic traffic simulations. Transp. Res. Part D: Transp. Environ. **146**, 104791 (2025). https://doi.org/10.1016/j.trd.2025.104791
5. Öztürk, A.T., et al.: A mesoscopic model of vehicular emissions informed by direct measurements and mobility science. Sustain. Cities Soc., 106421 (2025). https://doi.org/10.1016/j.scs.2025.106421
6. Laraki, M., De Nunzio, G., Othman, B.: A large-scale and data-based road traffic flow estimation method leveraging topography information and population statistics. In: Proceedings of the 2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC) (2022). https://doi.org/10.1109/ITSC55140.2022.9921799
7. Hammoumi, A., De Nunzio, G., Charléty, J., Chataignon, A.: TrafficFlowNet: a deep-learning spatio-temporal model for network-wide traffic flow profiles estimation. In: Proceedings of the IEEE 9th Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (2025). https://doi.org/10.1109/MT-ITS68460.2025.11223525
8. De Nunzio, G., Laraki, M., Thibault, L.: Road traffic dynamic pollutant emissions estimation: from macroscopic road information to microscopic environmental impact. Atmos. **12**(1), 53 (2021). https://doi.org/10.3390/atmos12010053
9. Bussod, S., Sabiron, G.: Deep learning-based method for an assessment of road traffic pollutant estimation from predicted driving behaviors. In: Proceedings of the 2024 International Conference on Machine Learning and Applications (ICMLA), Miami, FL, USA, pp. 658–663 (2024). https://doi.org/10.1109/ICMLA61862.2024.00095

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Optimizing Battery Size and Charging Infrastructure for Public Ferry Fleet Electrification

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Abstract. Ferry electrification plays a crucial role in reducing greenhouse gas and air emissions from transport, particularly in coastal and archipelagic countries. Current approaches typically emphasize battery electric range for continuous daily operation with night charging to match diesel ferry performance. This study develops a mixed-integer linear programming model to minimize the total cost of ownership for a battery electric ferry fleet while determining optimal battery sizes, charging locations, and charging power capacities. The study evaluates two scenarios for the public ferry fleet in Gothenburg, Sweden, which comprises six ferries operating across 19 docks: fixed routes with current schedules and flexible route assignments that maintain the overall schedule. Results show that routing different ferries specifically for opportunity charging can reduce the required charging infrastructure power by 30%, required installed battery capacity by more than 10% and the total system cost by 10%. This cost reduction makes electrification more competitive than equivalent diesel-powered vessels. Fleet electrification provides around 95% reduction in GWP relative to the fossil option. Our optimization framework demonstrates that strategic placement of charging stations, power allocation at each location, and coordinated charging strategies enable significant system cost reduction.

Keywords: Ferry electrification · Waterborne · Optimization · Chargers · Life cycle assessment

1 Introduction

Electrification of the public ferries is gaining momentum [1] and is a promising solution to reduce environmental impacts associated with emission of greenhouse gas and other air pollutants, including carbon dioxide, methane, nitrous oxide, nitrogen oxides, sulphur oxides, and particulate matter [2, 3]. Ferries are ideally suited for electrification owing to their distinctive operational characteristics, such as regular, shorter trips and comparatively longer docking intervals that facilitate charging [4, 5]. Operators pose concern regarding the adoption of fully electric ferries over hybrid ferries due to technical challenges such as increased weight, charging durations, range limitations, battery replacement, hotel load, and safety concerns [6, 7].

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Previous studies (e.g. [8, 9]) have shown that opportunity charging and route-specific charging strategies (i.e., charging while the ferry is at a dock when passengers embark and debark) can reduce battery size and overcome range limitations [8]. Reducing the size of batteries can reduce the draught, in turn reducing hull resistance, and thus less power and energy is required for the same operation speed. However, this needs the installation of multiple charging infrastructures at different locations, which comes with additional cost depending on the required charging power. The high-power requirements pose a significant challenge to grid infrastructure. Another challenge with frequent charging is that it can reduce the battery life, which will result in several replacements. By using a low depth of discharge (DoD), battery life can be optimized [10].

With proper strategies, infrastructure installed for opportunity charging can be used by multiple ferries; this will allow better utilization of the chargers and also simultaneously reduce the battery size for the ferries operating as a fleet. The system approach considering the ferry fleet has not been examined in earlier studies and can assist the full electrification of ferries operating in different cities. This study presents a novel contribution by developing an optimization model based on mixed-integer linear programming to determine the optimal opportunity charging location and charging power and optimal battery size for reducing the overall system cost for the public ferry fleet. The main aim of the study is to assess the economic viability of full electrification of the public ferries operating in Gothenburg. This case study is motivated by the emphasis on electrification as a key strategy for decarbonizing the transport industry in Sweden and specifically included in the climate targets for the Göteborg region [11].

The model includes several design aspects, including a battery degradation model, depth of discharge, weather factor, energy demand change based on weight and speed profile, heat demand in various seasons, auxiliary energy demand, charging and discharging rates, required battery replacements, other powertrain components including inverters, heat pumps, and electric motors, investment costs, spot electricity price, and grid fees. In addition, the cost is compared with the diesel and biodiesel.

2 Method

A mixed-integer linear programming model is developed in the study, which integrates the energy consumption of electric ferries based on route detail with a charging optimization model that minimizes total cost of ownership (TCO). The objective function TCO is based on both the investment, operational, and replacement costs, including batteries (sizing and depth of discharge), number of chargers, charging power, battery life, and state of charge. The model is built on Python, and optimization is performed using Gurobi optimizer. We fit the optimization model on the operation of a public fleet of six ferries operating on 5 different routes connecting various archipelago islands with the mainland (having a total of 19 different docks where ferries stop). The operation is different and depends on the time of day, which gives time for opportunity charging.

The analysis is performed for two different scenarios: 1) battery size, charging power, and charging location optimized for the fixed schedule and fixed routes for the vessels as they are today, and 2) the overall schedule is maintained; however, the vessels would operate on a flexible route, thereby giving sufficient time for charging between routes. In

the second scenario, the overall schedule is not compromised, but the ferries are timed to operate on different routes, ensuring sufficient charging time rather than on the same route. The optimization model schematic is shown in Fig. 1, where decision variables are determined by the model to meet propeller energy demand, heat demand, and auxiliary demand that is required to operate in the given schedule, distance, speed, and time. The interrelations between parameter, decision variable, and different costs are represented by mathematical equations in the model and is detailed below.

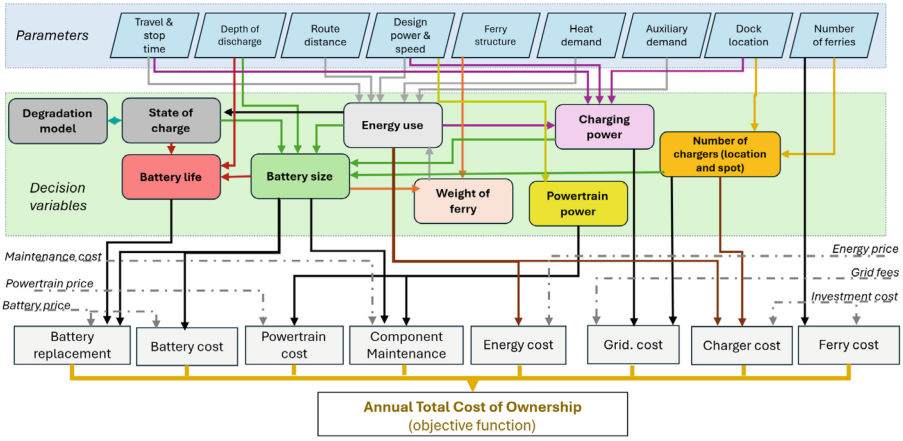


Fig. 1. The optimization model with objective function, decision variables and parameters.

2.1 Battery Size and Charging Optimization

Optimization model of battery size for ferries, as well as location and capacity for charging infrastructures

- Input data: Schedule of each ferry at each time schedule(i,t). schedule(i,t) = 0 represents the ferry is operating on the sea and schedule(i,t) = 1 ~ 19 means the ferry is stopping at the corresponding dock.
- This objective function of this optimization model is to minimize the TCO, that including the CAPEX (battery, chargers, ferry, inverter, electric motor, and heat pump), battery replacement cost, electricity cost (spot and grid) and OPEX.
- The decision variables include the battery size for six different ferries C_bat(i), the location and charger capacity of charging infrastructures among 19 passing stations B_station(j) * C_station(j); charging power for each ferry for each time P_char(i,t), the state of charge of battery for each ferry after each time SOC(i,t).
- The following constraints are included in the model,

  – Maximum charger capacity for each station (5 MW).
  – Maximum battery size for each ferry (ferry weight constraint) of 4 MWh.

  - Minimum state of charge (SOC) of 25% with additional 15% weather factor.
  - Maximum SOC: 90%.

- The state of discharge are calculated as in Eq. 1.

$$SOC(i, t+1) - SOC(i, t) = E_{charging}(i, t) - E_{consumption}(i, t) \tag{1}$$

- The charging power constraint of battery at each station (Eq. 2):

$$0 \leq \mathrm{P_char}(i, t) \leq \mathrm{B_station(j)} * \mathrm{C_station(j)}, \text{if schedule(i, t)} = \mathrm{j} \tag{2}$$

- The charging energy is calculated as (Eq. 3):

$$E_{charging}(i, t) = \eta_{bat.charge} * \eta_{inverter} * T_{charge}(i, t) * \mathrm{P_char}(i, t) \tag{3}$$

The charging and discharging cycles are limited considering degradation (Eq. 4):

$$\sum_{t=1}^{T} E_{charging}(i, t) \leq C_{bat}(i) * \mathrm{Max_{cycle}} * \mathrm{DOD} \tag{4}$$

In addition, McCormick linearization is used in two cases in the model to make the objective fully linear, the first one in assigning the spot of charger along with selection of charger power. Second one is used of the NPC multiplier based on number of replacement and battery size.

2.2 Energy Consumption Module

The energy consumption for the route: The energy consumption for each travel includes the propulsion energy, and constant energy consumption of auxiliary engine and heat pump (Eq. 5).

$$E_{consumption}(i, t) = E_{prop}(i, t)/\eta_{motor} + E_{aux}(i, t) + E_{hp}(i, t) \tag{5}$$

Propulsion energy for each travel is calculated based on travel time and ferry weight correction. The propulsion energy considers three stages of operation, including acceleration, cruise, and braking. Pushing power is needed for 1 min after each stop. Assume that 1 min for acceleration and braking stages, and the remaining travel time is for cruise (Eq. 6).

$$E_{prop}(i, t) = \left(P_{acc} + P_{brake} + P_{push} + P_{cruise} * \left(T_{stop}(i, t) - 2\right)\right)/60 \tag{6}$$

The propulsion energy should be corrected considering different ferry weights / drought and is recalculated based on admiralty law. However, this non-linear correction is difficult to solve via MILP, so linearization is required. This method uses discrete parameters and linear fittings to linearize the relationship between battery size and specific energy consumption per minute.

2.3 Life Cycle Assessment

Life cycle assessment is performed for the fleet considering cradle to grave, including the life cycle stages of ferries and the fuel life cycle. The life cycle of ferries involves the construction of superstructure, as well as the production of powertrain components, including batteries. It is assumed that the ferry is built in Europe, and it is operated in Sweden. The functional unit is annual operation. Replacement of the components, including batteries, is also considered where components have a shorter life than the complete ferry. The well-to-wake is divided into well-to-tank (material and energy extraction, energy carrier production and distribution) and tank-to-wake (impact from the use phase of the ferry). All the underlying life cycle inventories are assumed from our previous study [8] and Swedish mix is considered for charging. The focus of the study is only global warming potential for a 100-year perspective and is based on IPCC AR6 [12].

2.4 Input Data

The major input data for this optimization model is presented in Table 1.

Table 1. Input parameters for the optimization model

Parameters	Value [unit]	Parameters	Value [unit]
CAPEX of ferry	6 000 000 EUR	Battery charging efficiency	95%
CAPEX of charger	500 EUR/kW	Inverter efficiency	95%
CAPEX of battery pack	400 EUR/kWh	Electric motor efficiency	95%
CAPEX of inverter	100 EUR/kW	Battery maximum SOC	90%
CAPEX of electric motor	120 EUR/kW	Battery minimum SOC	35%
CAPEX of heat pump	750 EUR/kW	Battery maximum capacity	5000 kWh
OPEX of ferry	1%	Charger maximum power	5000 kW
OPEX of charger	1%	Auxiliary engine power	60 kW
OPEX of battery	0.5%	Heat pump power	300 kW
OPEX of inverter	1%	Inverter power	150 kW
OPEX of electric motor	1%	Electric motor power	450 kW
OPEX of heat pump	1%	Electricity price (spot)	0.05 EUR/kWh
Ferry lifetime	40 years	Discount rate	5%
Charger lifetime	20 years	Other component lifetime	20 years

3 Results

Optimization is performed for the two scenarios: 1) in the first case, the optimization of battery size, charging power, and charging location is done with a fixed schedule and fixed routes for the vessels as it is today, and 2) the overall schedule is maintained;

however, the vessels won't have fixed route. Each vessel operates on a flexible route so longer stops of a vessel are modified thereby giving sufficient time for charging different ferries. Table 2 shows the battery sizes for each ferry, the charger power, and the charger locations required for the battery electric ferry fleet (BEFF).

Table 2. Optimal battery size for ferry and charger for each station. No chargers needed in other docks.

Battery size (kWh)			Charger size (kW)		
Ferry Label	Scenario-1	Scenario-2	Dock Label	Scenario-1	Scenario-2
Ferry #1	2830	2650	Dock #1 (3 spots)	5000 + 0 + 0	3590 + 150 + 150
Ferry #2	2180	2210	Dock #4	150	150
Ferry #3	2460	3030	Dock #7	150	150
Ferry #4	3150	2431	Dock #10	150	150
Ferry #5	3080	2110	Dock #14	1500	240
Ferry #6	4890	3100	Dock #16	150	150
			Dock #17	150	150

It can be noted that compared to scenario 1, scenario 2 needs significantly less charging power in the docks, especially in dock 1 (the main dock in the mainland) and dock 14 (also in the mainland). This is because scenario 2 allows more time for charging. In cost optimization, this reduces investment cost in charging infrastructure but also the cost associated with the grid for high-power charging. However, in this case the batteries for the first three ferries are higher; this can be explained by the fact that the lower charging power is not enough to fully charge the batteries for selected stops. Hence, the ferries need to start some schedules without reaching maximum SOC. However, ferries #1, #2, and #3 need smaller batteries, as the stop time is sufficient for the charging for the next trip.

Dock #1 has the highest installed size of charging infrastructure with one charger with a combined power of 5000 kW, since this dock serves as the major dock for all ferries. All ferries operate round trips from this dock to other docks, so ferries have more opportunities to charge their batteries when stopping at this dock. Regarding the ferry battery capacity, depending on scenarios, the battery capacity varies. In scenario 1, Ferry #6 needs a larger battery capacity of around 4900 kWh, reaching the maximum allowed capacity due to ferry weight constraints. This is because these ferries need to travel for long periods continuously but stop for only 2–8 min, so it requires a larger battery to maintain the operation. In contrast, Ferry #2 and Ferry #3 have more stopping time between operations at 30–250 min, so a relatively smaller battery is sufficient to maintain their daily operations. In scenario 2, when the routes are optimized, the ferries with more stop time are exchanged for shorter periods, and hence the routes are optimized to have a lower total cost. Therefore, the optimal cost represents a trade-off between optimal charging power and optimal battery size.

The state of charge for each ferry as in scenario 1 is shown in Fig. 2. It can be noted that most of the ferries have critical bottlenecks during the later part of the daily

operation, which includes the peak time operation around 16:00 to 19:00. In the morning, even if ferries start with a full charge from night charging, the peak morning hours also leave less time for the opportunity charging.

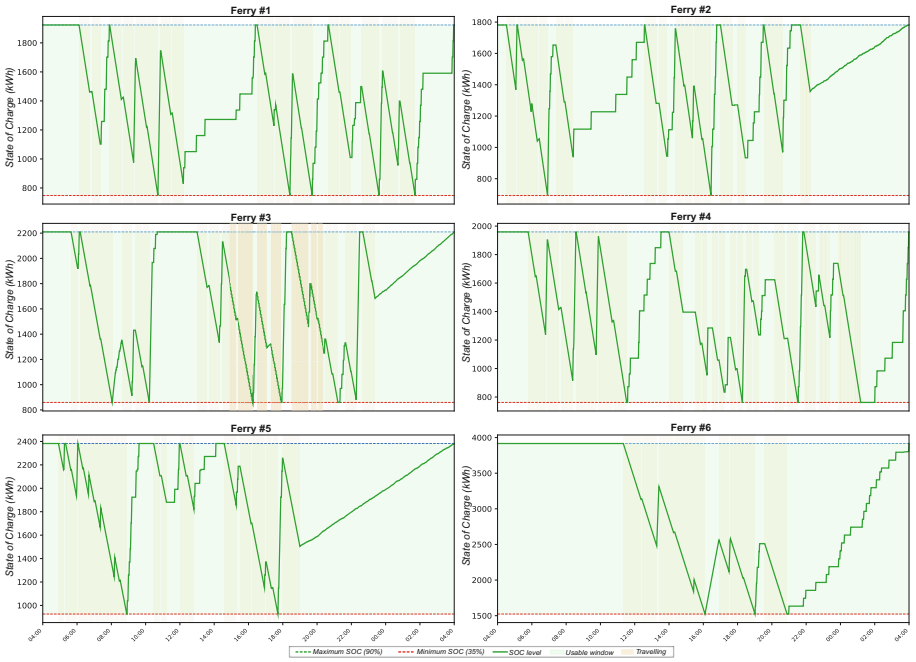


Fig. 2. State of charge of each ferry under scenario 1 showing discharging and charging of the batteries within usable window.

Figure 3 shows the total cost of ownership as calculated in the cost optimization model and also the global warming potential calculated using life cycle assessment. It can be noted that bio-diesel scenario has the highest cost (Fig. 3A) due to high fuel cost. Scenario 1 has higher cost compared to scenario 2, this difference is mainly due to the need for high charging power. This is because the utilization rates for the charging infrastructure are lower when installed charging power is high, as it only caters for the same operation fleet. The installed battery size is also 10% lower for scenario 2. The TCO is also compared with the equivalent diesel cases. In scenario 2, the TCO is lower than fossil diesel (marine gas oil (MGO)) due to lower operational cost. It may be noted that the results are based on the electricity price in Sweden. The daily and seasonal variation in the electricity price is not considered in the study.

Figure 3B shows the GWP100 results, and the results show that both BEFF options provide more than 95% reduction in GWP relative to the fossil option, whereas the biodiesel offers only around 65% reduction. For fossil diesel, the major contributor is the tank-to-wake phase when the diesel is burned, accounting for 80% of the global warming impact. For HVO, the largest contribution comes from the energy-intensive fuel production phase (WTT). It accounts for 90% of its impact. For BEFF, the major

contribution comes from electricity generation (WTT), which accounts for around 65% of the total impact, followed by the battery packs (including initial acquisition and replacements). There are only small differences in GWP among various BEFF options. This shows that even if overall battery sizes are larger for scenario 2, its impact of GWP is minimal.

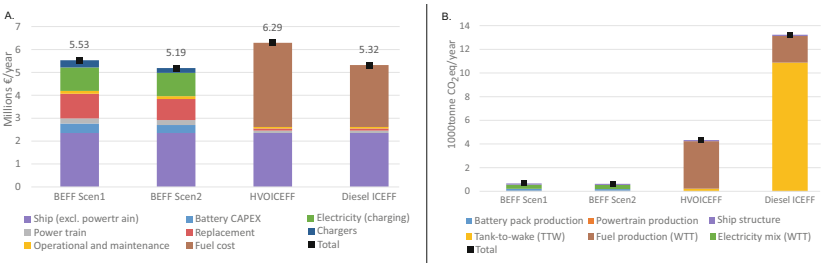


Fig. 3. Total cost of ownership (TCO) results for the battery electric ferry and Global warming potential of case study ferry fleet. A) TCO comparison of total ferry fleet; B) GWP comparison of total ferry fleet.

4 Conclusion

This study presents a comprehensive optimization framework for the full electrification of public ferry fleets, demonstrating both technical feasibility and environmental benefits while highlighting economic considerations. The mixed-integer linear programming model successfully integrates multiple critical factors, including battery sizing, charging infrastructure placement, operational schedules, battery degradation, and total cost of ownership, to provide actionable insights for ferry fleet electrification. Shared charging infrastructure and scheduling flexibility across multiple ferries improve utilization rates and reduce overall system costs, making electrification more economically viable for public transport operators. The case study of Gothenburg's six-ferry fleet reveals that adjusting routes increasing opportunity charging (Scenario 2) offers significant advantages over fixed routing (Scenario 1). This reduces total required charging power and installed battery sizes and thereby reduces the total electrification cost by around 10%. This finding has important implications for cities and regions planning ferry fleet transitions.

References

1. DNV AS: Energy Transition Outlook 2023: Maritime Forecast to 2050. DNV AS (2023)
2. Kanchiralla, F.M., Brynolf, S., Malmgren, E., Hansson, J., Grahn, M.: Life-cycle assessment and costing of fuels and propulsion systems in future fossil-free shipping. Environ. Sci. Technol. **56**(17), 12517–12531 (2022)
3. Kanchiralla, F.M., Brynolf, S., Mjelde, A.: Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations. Energy Environ. Sci. **17**(17), 6393–6418 (2024)

4. Siemens Energy AG: Decarbonizing Marine Transport: A Study on the Electrification of the European Ferry Fleet. Siemens Energy AG, Munich (2022)
5. Kanchiralla, F.M., Brynolf, S., Olsson, T., Ellis, J., Hansson, J., Grahn, M.: How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. Appl. Energy. **350**, 121773 (2023)
6. Sæther, S.R., Moe, E.: A green maritime shift: lessons from the electrification of ferries in Norway. Energy Res. Soc. Sci. **81**, 102282 (2021)
7. Papanikolaou, A.D.: Review of the design and technology challenges of zero-emission, battery-driven fast marine vehicles. J. Mar. Sci. Eng. **8**(11), 941 (2020)
8. Kanchiralla, F.M., Grunditz, E., Nordelöf, A., Brynolf, S., Wikner, E.: Environmental and economic assessment of electric ferries with different lithium-ion battery technologies. Appl. Energy. **396**, 126274 (2025)
9. Oyediran, D., Thakur, J., Khalid, M., Baskar, A.G.: Electrification of marinas in Stockholm: optimizing charging infrastructure for electric boats. Energy. **305**, 132311 (2024)
10. Wikner, E., Björklund, E., Fridner, J., Brandell, D., Thiringer, T.: How the utilised SOC window in commercial li-ion pouch cells influence battery ageing. J. Power Sources Adv. **8**, 100054 (2021)
11. City of Gothenburg: 2030 Climate Neutrality Commitments. City of Gothenburg, Gothenburg (2024)
12. IPCC: Assessment Report 6: Climate Change 2022: Mitigation of Climate Change. IPCC (2022)

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Scaling Up the Charging Infrastructure for Electric Aircraft While Retaining Airport Flexibility: A Comparative Analysis of Several Technical Concepts

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Abstract. Airport infrastructure should be designed to meet the requirements of future aviation technologies, including battery electric aircraft. But, since electric aircraft and other propulsion technologies are still under development, technical performance characteristics and future market evolution pathways of different aviation solutions are uncertain. This creates risk for airports, which discourages large up-front capital investments in supporting infrastructure. This investment bias may reduce the ability of airport charging capacity to scale quickly, which could become a hindrance to the development of electric aviation. The current research explores low-risk investment strategies for airports seeking to prepare for the introduction and growth of electric aviation. Previous research identified several technical concepts for charging battery-powered electric aircraft, the relative advantages of which depend on the demands for aircraft charging, and hence on the number and timing of electric flights at an airport. The current work explores how these charging technical concepts may be scaled up as charging demand increases. Operational performance is considered from the standpoint of two contrasting airport scenarios: a single airport managing its own electrification transition (ownership model) and a system of heterogeneous airports managing the transition as a group (leasing model).

Keywords: Airport charging infrastructure · electric aircraft charging · mobile energy storage · flexibility at airports · electric aviation

1 Introduction

Electric aviation is expected to play a significant role in decarbonising air transport. While long-haul flights will likely use sustainable aviation fuels and/or hydrogen propulsion systems, battery-electric aircraft (BEA) are considered an option for short-haul applications [1]. Several studies have shown the potential for electric aircraft in decarbonizing Swedish regional aviation over the long term [2–4]. It has been noted that the performance characteristics of electric aircraft may even encourage new commercial short-haul routes and the development or expansion of new regional airport hubs [5]. This is particularly significant for smaller airports that support regional economic development beyond their own operations [6].

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While the ultimate market share of electric aviation is unknown, experience from road transport suggests significant potential: coordinated policy support has proven effective, and improvements in cost and performance may yield positive spillovers to the much smaller aviation sector [7]. Road transport electrification also highlights the role of charging infrastructure in accelerating adoption [8].

Much electric aviation research focuses on the BEA design and operation (e.g., routes). Airport charging infrastructure studies focus on the long-run, steady-state charging needs, rather than on transition pathways [9–12]. This research fills a gap in exploring the scaling of airport charging infrastructure as electric aviation grows.

The current study builds on previous work [13], in which technical advantages and disadvantages of four technical concepts for electric aircraft are evaluated against the conditions expected at different types of airports. This effort extends the previous work on end-state airport charging configurations to considerations of scaling pathways. The research questions are:

1. How do different technical concepts (TCs) for electric aircraft charging scale as the number of electric flights at an airport increase over time?
2. For a given airport, which TCs are most robust to electric aviation scaling?
3. As electric flight scales, what are the opportunities (e.g., for sharing charging equipment) for groups of cooperating airports that would not be available if similar airports acted independently?

This analysis considers only the technical performance (electrical energy and power) of different charging options. Other considerations, such as technical complexity, economic cost, equipment lifetimes, and non-electrical impacts on airport operations, while important, lie outside the scope of this study. Without published data on high-power BEA charging at airports, empirical validation is currently not possible.

2 Context and Concept Descriptions

This section summarizes the four technical concepts (TCs) used in the analysis and the stylised assumptions applied across scenarios. Figure 1 illustrates four charging TCs:

- **TC1**: Fixed chargers connected directly to the airport grid.
- **TC2**: Fixed chargers with dedicated battery energy storage systems (BESS) sized to charge one BEA.
- **TC3**: Mobile chargers that connect to the airport grid at the aircraft stand.
- **TC4**: Mobile chargers as in TC3, with onboard/mobile BESS as in TC2.

The mobile concepts, TC3 and TC4, are electrically equivalent to their fixed counterparts, TC1 and TC2, respectively, but provide greater operational flexibility (i.e., aircraft stand access) to the airport operator at the expense of greater technical complexity. They may also be more easily deployed from one airport to another as charging needs evolve over time. However, the mobile concepts require space to maneuver at the aircraft stand, which could present a logistical challenge for space-constrained airports. These and other non-electrical impacts on airport operations are not considered within this analysis.

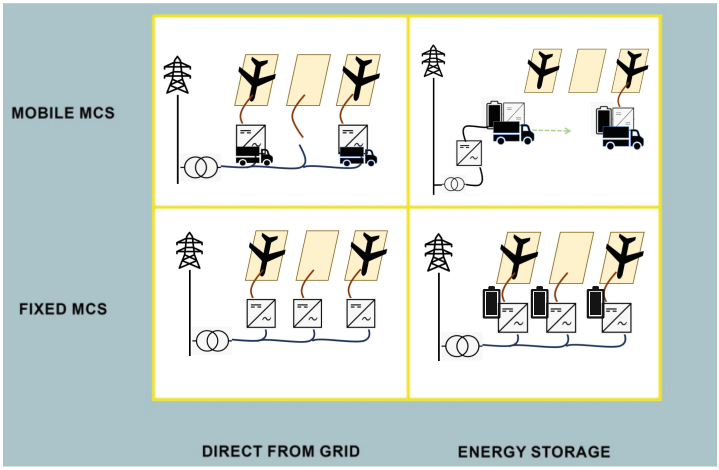


Fig. 1. Four airport charging technical concepts with TC numbers as referred to in the text.

To illustrate the interplay between aircraft charging demand, grid (power) capacity, and battery (energy) capacity on airport operations, a simple system dynamics spreadsheet model was developed by the authors to simulate airport power operations over a 24-h period in response to a user input schedule of BEA charging events. Operating In half-hourly time intervals, the model tracks aircraft charging demands; BESS charging, discharging, and state of charge (SOC), if applicable; and power drawn from the electrical grid for both aircraft and BESS re-charging. Concepts TC1/TC3 are modelled as an airport with no BESS; TC2/TC4 are modelled as an airport that charges BEA via BESS, with the grid used to recharge the BESS. Hybrid solutions are also modelled, prioritizing direct grid charging and supplementing with BESS, subject to battery energy capacity and recharging power constraints.

As the model is designed for illustrative purposes, it assumes a set of simplified aircraft and charging technical characteristics. All battery units, both onboard the aircraft and in the BESS, have working capacities of 1 MWh, and they are both charged and discharged at a constant rate of 2 MW (i.e., 2C) to support a 30-min aircraft turnaround. Always operating at its maximum power flow of 2 MW, the battery is effectively prohibited from simultaneous charging and discharging. These assumptions differ slightly from the assumptions in [13], which assumes more realistic charging power profiles that depend upon the aircraft state of charge (SOC), for example.

We use this simplified model to evaluate the electrical performance of airports with three different grid capacities (2 MW, 5 MW, and 15 MW) under a variety of demand profiles for charging electric aircraft (i.e., electric aircraft turnaround schedules). These grid capacities are chosen as representative of grid-constrained, semi-constrained and non-constrained operating environments; and they span the range of grid connections one could expect to find at Swedish airports. A pseudo-stochastic ensemble of electric aircraft arrival schedules was simulated at each airport, varying in both number of flights and arrival intervals, of which a small selection of scenarios that illustrate the relevant

operational considerations for airports is presented in the results section. Both the number of daily BEA charging events (i.e., demand for electric energy) and the number of simultaneous BEA charging events (i.e., demand for electric power) are important parameters in each simulation.

We also consider the operation of a collection of airports. This might represent an industry consortium of airports, a set of airports operated by a single commercial entity, or a third-party equipment leasing company serving the charging equipment needs of their customer airports.

3 Results and Comparative Analysis

3.1 Scaling of Technical Concepts

Average Daily Charging Limits. The number of charging events (electric aircraft turnarounds) that can be supported each day is limited by grid (power) capacity for all four TCs. For example, when a simulated charging event uses 2 MW of power for 30 min, an airport with available grid capacity of 2 MW is limited to charging a maximum of 48 electric aircraft per day on a continuous basis, regardless of the availability of airport battery (energy) capacity. Sufficient BESS capacity allows an airport to exceed this aircraft throughput limit temporarily, but the need to recharge the batteries from the grid creates the steady-state limit.

Peak Charging Limits. Charging multiple aircraft simultaneously requires additional increments of 2 MW of grid (power) capacity for each additional aircraft in TC1/TV3, and 1 MWh of BESS (energy) capacity per simultaneous aircraft in TC2/TC4. Charging depleted BESS units from available grid capacity before they can be reused for another aircraft places additional timing constraints on TC2/TC4 scenarios.

As the demand for additional electric aircraft charging grows beyond the available grid capacity, the only mitigating options with TC1/TC3 are to reschedule charging events or to upgrade grid capacity to accommodate higher power consumption. The deleterious effects of rescheduling aircraft landing and turnaround schedules on airport operations are not evaluated in this analysis, as it is not considered an attractive scaling strategy.

By contrast, simultaneous charging in TC2/TC4 is limited not by grid power capacity, but by total BESS energy capacity. BESS-mediated concepts are still dependent on the grid capacity for recharging the BESS units, though. While a BESS is recharging, it is unavailable for charging an aircraft, and the recharging time depends on the state of charge (SOC) of the BESS and available grid power. Figure 2 illustrates the effects this can have on an airport charging schedule. Using the simplified spreadsheet model described above, the authors simulate the charging operations of a hypothetical airport with 5 BESS units to implement battery-mediated electric aircraft charging (i.e., TC2/TC4) and a 5 MW grid connection to recharge the BESS batteries. In this simulated day, at 6:00 and again at 17:30 this airport is able to support simultaneous charging of five aircraft (10 MW charging power). With only 5 MW of grid power, this airport would only be able to charge two aircraft in each half-hour block (or 5 per hour) using TC1/TC3 without batteries. Note, however, that no charging is available in the half hour

immediately following a peak charging event, as all BESS units need to be recharged from the grid.

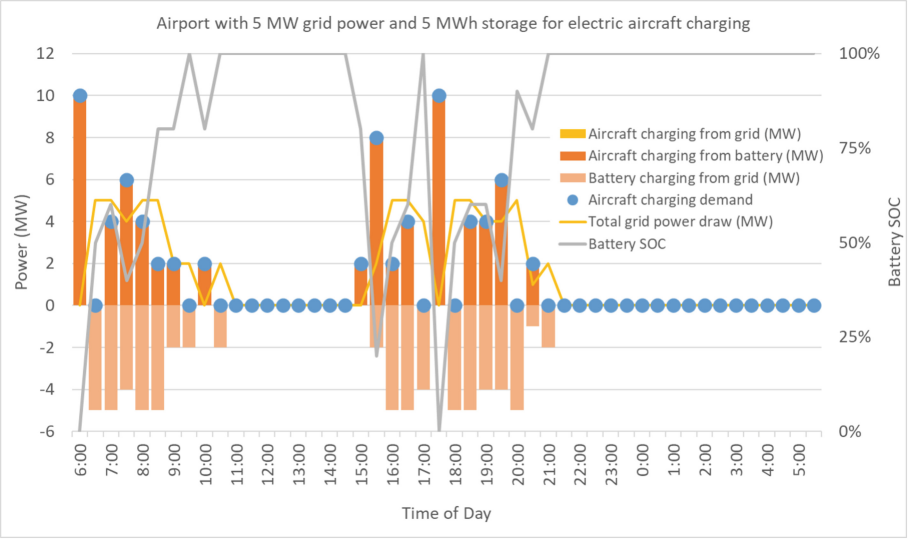


Fig. 2. One simulated day of an airport with 5 MW grid capacity for charging, using five chargers with 1 MWh each of energy storage each (TC2/TC4) to charge up to five electric aircraft at a time (10 MW charging power).

The simulated results can be generalized: over any time window $[t_1, t_2]$, the number of BEA that can be charged depends on BESS energy capacity and grid power availability:

$$N_c(t_1, t_2) \leq \frac{E_B + \int_{t_1+t_c}^{t_2-t_c} P_G \, dt}{E_c}, \quad t_2 - t_1 \geq 2t_c \tag{1}$$

Here, $N_c(t_1, t_2)$is the number of aircraft charged between times $t_1$and t_2, $E_B$is the total energy capacity of the BESS units, $E_c$is the capacity required to charge an aircraft, $P_G$is the grid power available for charging, and $t_c$is the time to charge.

The simulation data illustrated in Fig. 2 and characterized in Eq. 1 demonstrate that the relevant driver of charging capacity for BESS-mediated charging is not power (i.e., multiple aircraft charging events within the same 30-min time step of the model), but energy (i.e., cumulative charging events within a rolling time window of consecutive model time steps) over a period of time whose temporal extent is related to grid power capacity. The model showed that the 2 MW airport with five TC2/TC4 chargers could charge up to five electric aircraft (with any schedule distribution) within a three-hour rolling window, whereas TC1/TC3 could charge up to six aircraft in three hours, albeit only one at a time.

3.2 Matching Technical Concepts to Airports

TC1 offers the simplest technological charging solution if the available grid power can support enough chargers. In the early stages of deployment, even an airport with the smallest grid capacity simulated (2 MW) could likely support the small electric flight volumes that would occur. But, as electric flight volumes grow, increasing the likelihood that multiple electric aircraft would need to be charged simultaneously, TC1 may not scale as well as other concepts. We consider airports with three different grid capacities, corresponding to their ability to charge multiple electric aircraft directly from the grid.

2 MW Airport. For a severely grid-constrained airport, TC1/TC3 does not scale. If the airport anticipates significant demand growth, it will likely need one of the BESS-supported concepts, TC2/TC4, to handle times of peak demand. It may be more efficient in the long term, though, to upgrade its grid. After the grid constraint is removed, the airport could revert to the scalable TC1/TC3 option, but this leaves the airport with potentially stranded TC2/TC4 equipment. This airport will therefore need to develop a charging equipment transition plan, which may involve the use of mobile equipment (i.e., mobile BESS units) that can be repurposed after they are no longer needed for aircraft charging.

5 MW Airport. An airport with a moderate grid capacity (5 MW) may be able to postpone equipment decisions longer than smaller airports. TC1/TC3 options will scale up to charging two electric aircraft simultaneously, and it may never need more capacity than that. BESS charging options would enable scaling to considerably higher peaks, as long as the daily average power consumption remained below the grid limit.

A hybrid charging concept offers some interesting advantages for an airport with a medium-capacity grid and growing volumes of electric flights. While TC1/TC3 with two chargers would support two aircraft charging every half hour indefinitely, the model shows that TC2/TC4 with two chargers would only be able to charge two aircraft every hour. Adding a third charger with an additional 1 MWh battery would allow this airport to charge three aircraft at once, but only 6 aircraft in each 90-min period, which is the same throughput as TC1/TC3 with only two chargers. Thus, the addition of battery charging at this airport adds complexity (and cost) but questionable operational benefit.

Instead, the simulation model shows that a hybrid solution consisting of 2 fixed chargers (concept TC1) and a third charger with a 1 MWh BESS (TC2 or TC4), would allow this airport to charge up to three aircraft simultaneously, and 7 aircraft in 90 min. If the third charger and BESS were mounted on a mobile platform, this hybrid solution would offer additional operational flexibility for the airport, while still taking advantage of the simplicity of TC1 for two of its chargers. Beyond three, any additional chargers would need to be TC2/TC4 due to the grid constraint.

In general, combining both grid-connected and battery-mediated aircraft chargers allows for a different number of charging events than shown in Eq. 1. With the same variable definitions, we have:

$$N_c(t_1, t_2) \leq \frac{E_B + \int_{t_1}^{t_2} P_G \, dt}{E_c}, \quad t_2 - t_1 \geq t_c \tag{2}$$

15 MW Airport. An airport with 15 MW of grid power available for charging could support up to 7 simultaneous charging events continuously. Scaling from one charger to

multiple chargers using the TC1/TC3 concept requires the least amount of technological complexity and provides a convenient upgrade pathway in this case.

3.3 Opportunities for Groups of Airports

Although the model does not indicate de-commissioning of chargers as demand grows, it does suggest an opportunity for redeploying dedicated BESS as grid power capacity is upgraded. Storage needs increase while charging power demand exceeds grid capacity, then fall after grid capacity is enlarged. Coordinated plans for deployment of charging equipment, BESS, and grid expansion among heterogeneous airports can, therefore, enable redeployment of mobile BESS units from recently upgraded airports to those that are still grid-constrained, reducing the risk of stranded assets.

4 Conclusions

Previous research concluded that no single charging concept is best for all airports [13]. This research extends that principle to a single airport as electric flight scales over time and to groups of airports.

The simulations indicate that grid-connected charging scales readily up to the grid limit, whereas adding battery-mediated charging can increase peak aircraft throughput but remains constrained by the grid over longer periods.

For an airport with sufficient grid capacity, grid-connected charging (TC1) is a simple solution. For airports with grid constraints and an expectation of high volumes of electric flights, grid power capacity expansion is necessary. For airports with moderate grid capacities and/or uncertain electric aviation expectations, integrated BESS offers a scalable growth strategy that can postpone investment decisions and reduce risk.

Growth of electric aviation may provide a specific opportunity for smaller, regional airports with limited grid capacities, ample space, and modest expected volumes of electric flights. Such airports might be able to use a single charging concept (TC1, or TC2 if direct charging is infeasible) from the time when electric flight is first introduced until the market reaches maturity, minimizing upgrade costs stranded-asset risk. This could provide a rare economic competitive advantage for smaller airports, compared with larger airports, under market uncertainty.

Since the growth of electrified aviation requires collaboration across a network of airports, there may be network benefits from collaborative BEA charging strategies as well. Increasing grid capacity infrastructure can take years but is probably on the same time scale as the aviation electrification transformation. For an airport with future grid upgrade plans, adding mobile BESS units to support BEA charging gives it the option to relocate those assets to other airports after grid capacity is increased. This can lower costs for associated airports and encourage expansion of the electrified airport network.

References

1. IPCC: Climate change 2022: mitigation of climate change. In: Working Group III Contribution to the Sixth Assessment Report. See Chapter 10 (Transport). Cambridge University Press, Cambridge, U.K (2022)

2. Jüriado, R., Wigler, K., Wargsjö, A., Spångberg, L., Eliasson, J.: Vi ser himlen runt hörnet: Slutrapport för regeringsuppdraget om det statliga stödet till forskning och innovation på elflygsområdet (report 2022/8755). Trafikverket, Borlänge, Sweden (2022)
3. Trafikverket: Upphandling av. fossilfritt flyg: En förstudie om möjligheten att avtala om fossilfri flygtrafik under allmän trafikplikt (report 2020/82259). Trafikverket, Borlänge, Sweden (2020)
4. Sager, A., Alfredsson, H., Esbjörnsson, M., Holmberg, P.-E.: Internationell forskning och finansiering för elflyg: Omvärldsanalys (report 2022:74). RISE, Sweden (2022)
5. Salomonsson, J., Jussila Hammes, J.: Det kommersiella elflyget–verklighet eller dröm: En litteraturstudie över elflygets utsikter (report 1039). Swedish Road and Transport Research Institute (VTI), Linköping, Sweden (2020)
6. Kotowska, J., Torój, A.: Regional airports and regional development: spatial difference-in-difference evidence from Poland, pp. 1–22. Spatial Economic Analysis (2025)
7. Fadhil, I., Shen, C.: Global Electric Vehicle Market Monitor for Light-Duty Vehicles in Key Markets, 2025 H1. International Council on Clean Transportation, Washington, DC, USA (2025)
8. Muratori, M., Alexander, M., Arent, D., Bazilian, M., Cazzola, P., Dede, E., et al.: The rise of electric vehicles—2020 status and future expectations. Prog. Energy. **3**(2), 022002 (2021)
9. Trainelli, L., Salucci, F., Riboldi, C.E.D., Rolando, A., Bigoni, F.: Optimal sizing and operation of airport infrastructures in support of electric-powered aviation. Aerospace. **8**, 40 (2021)
10. Doctor, F., Budd, T., Williams, P.D., Prescott, M., Iqbal, R.: Modelling the effect of electric aircraft on airport operations and infrastructure. Technol. Forecast. Soc. **177**, 121553 (2022)
11. Thomas, K. et al.: Resurseffektiva energisystemlösningar för flygplatser med hög andel elflyg (RES-flyg). Energimyndigheten, Eskilstuna, Sweden (2023)
12. Alfredsson, H. et al.: Air-Charge: Feasibility Study on System Demonstrator for High-Power Charging of Battery-Electric Aircraft (Report 2024:88). RISE Research Institutes of Sweden (2024)
13. Käck, S. et al.: Technical concepts of airport infrastructure for charging battery-electric aircraft. In: Proceedings of the 12th Swedish Aerospace Congress (FT2025). Linköping University Electronic Press, Linköping, Sweden (2025)

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Vehicle Fleet Modelling Methodology and Prospective Impact on Local Air Quality: A Practical Application in France

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Abstract. Robust air-quality policy starts with knowing exactly which vehicles will be on each road tomorrow. We present a bottom-up fleet-projection algorithm that blends France's official registration data (2011–2024) with International Energy Agency outlooks to 2040. The model disaggregates national scenarios to municipality and department scale, preserves age, powertrain and mileage-decay profiles, and reproduces local fleet composition.

The algorithm feeds Planet'Air, an innovative decision-support platform, which chains emission factors and dispersion models to convert fleet changes into pollutant flows and, ultimately, atmospheric concentrations. Comparing the Sustainable Development Scenario with the Stated Policies baseline shows that accelerated electrification can markedly lower tailpipe nitrogen oxides (NOx) in major cities by 2040.

By isolating the fleet module, this paper concentrates on data fusion, spatial downscaling and projection validation, and uses Planet'Air only to illustrate the added value of fine-grained fleets. The service is immediately usable by municipalities that need geographically resolved evidence before committing to low-emission zones, charging infrastructure or procurement rules, and it can be refreshed yearly as new registrations appear. The approach is transferable to any country with basic registration statistics and comparable scenario assumptions, enabling rapid policy benchmarking.

Keywords: vehicle fleet · air quality · NOx · policy scenarios

1 Introduction

Urban air pollution remains one of the most pressing environmental health challenges of the 21st century, responsible for substantial premature mortality linked to nitrogen oxides (NOx), fine particulate matter ($PM_{2.5}$), and ozone precursors. Road transport is a major contributor, accounting in European cities for up to 40–50% of NOx emissions and a significant fraction of primary $PM_{2.5}$. Reducing emissions from the on-road fleet is therefore a core pillar of municipal and national air-quality policy.

A vast body of research has examined fleet turnover modelling, vehicle survival curves, and technology diffusion. Classical top-down approaches rely on national statistics and scrappage models calibrated on historic survival rates to predict future fleet

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composition. More recent dynamic models integrate new registrations and retirements, often in system-of-equations or cohort-based frameworks, to estimate both fleet size and total vehicle-kilometres travelled. These approaches are well established at the national level, supported by comprehensive datasets, and underpin major scenario frameworks such as those produced by international agencies [1].

Because policy levers (LEZ calendars, charging rollout, procurement) are decided locally, municipal-scale fleet composition is the operative variable for credible emission inventories.

However, national-level scenarios often fail to capture the heterogeneity of local fleets. Municipalities deviate from national averages: city centres tend to host more electrified or newer fleets, while peri-urban and rural areas retain a higher proportion of conventional vehicles. Applying uniform national shares across all regions therefore introduces structural biases in bottom-up emission inventories and distorts estimates of local air-quality gains from interventions such as low-emission zones or scrappage incentives.

Existing models either (i) focus on national averages without local disaggregation, or (ii) do not harmonise historical registration datasets with forward-looking scenarios. No current framework integrates both dimensions into a unified, reproducible municipal-resolution projection chain.

Achieving accurate emission modelling requires granular knowledge of the fleet including size, fuel mix, age structure, emission standard (EURO class), and usage patterns. Coarse or outdated fleet data may lead to large discrepancies: emissions might be underestimated if older diesel vehicles are undercounted or overestimated if electrification is underrepresented. In France, the study presented in [2] demonstrates that spatial heterogeneity in fleet composition (age, share of diesel, renewal rates) is significant at departmental scale, underscoring the need for territory-aware fleet modelling.

To overcome these challenges, this work fuses historical registration data from *Service de la Donnée et des Études Statistiques* (SDES) (2011–2024) with forward-looking scenario projections, reconciling differences to ensure continuity. It then disaggregates national trajectories down to the municipal level by leveraging recent local registration patterns, thereby capturing regional specificities without losing global consistency. The contributions of this paper are: 1) **Data fusion & harmonization**: blending SDES historical records and scenario trajectories into continuous, coherent forecasts. 2) **Spatial downscaling**: allocating national trends to municipalities based on local registration distributions, preserving heterogeneity. 3) **Policy relevance**: embedding the approach in the Planet'Air decision-support platform, to convert fleet projections into spatially resolved emission and concentration maps for decision makers.

This paper focuses on the fleet-projection module, emission modelling and atmospheric dispersion tools are considered out of the scope of this paper. By offering a transparent, annually refreshable methodology, this work supports robust policy benchmarking and equips local authorities with tools grounded in both global trajectories and local reality.

2 Vehicle Fleet Modelling Literature Review

Accurate modelling of the vehicle fleet is essential for analysing emission dynamics and evaluating transport and air-quality policies. Authors in [3] presented a framework for reconstructing both the static fleet (registered vehicles) and the dynamic fleet in circulation (weighted by kilometres travelled), calibrated with fuel sales for consistency with energy balances. This was refined in [4], who showed that divergences of up to 20–30% can arise between models due to differences in assumptions on dieselisation, vehicle age, or EURO standards. Building further, [5] demonstrated that fleet characteristics vary significantly across territories, with strong contrasts in diesel shares and renewal rates. Together, these studies establish robust foundations but stop short of a harmonised reconciliation between historical inventories and prospective scenarios and of systematic territorial projections.

The present work addresses both by fusing national and local data into a reproducible projection framework. At the national level, previous works from CITEPA [6] are considered the official reference for emission inventories, providing comprehensive coverage and international consistency. However, its reliance on national averages limits its application to municipal-scale policies, such as low-emission zones (LEZs). Our approach complements CITEPA by downscaling national trajectories to municipalities while preserving alignment with national totals. Internationally, [7] developed a stock-flow model for Norway that simulates car fleet renewal under different policy scenarios, and more recently [8] designed the SALAMA model for Finland. While both models provide rigorous national-level projections, they focus primarily on dynamic renewal and fuel shares without harmonising historical and prospective datasets, addressing regulatory classifications, or offering spatial disaggregation.

In contrast, the present work ensures continuity between observed and projected trends, reconstructs EURO classes from Crit'Air labels, and downscales national scenarios to municipalities within a decision-support framework.

3 Data Sources

This study relies on two complementary datasets: (1) historical vehicle registrations from the SDES, and (2) long-term scenario projections from the International Energy Agency (IEA). Their integration forms the foundation of the fleet-projection model developed in this work.

3.1 SDES Vehicle Registration Data

The SDES provides open statistical data on the French vehicle fleet, compiled from the national registration system (*Système d'Immatriculation des Véhicules*, SIV). Covering 2011–2024, the dataset reports annual counts of registered vehicles by administrative level (municipal, regional, national), vehicle category (passenger cars, light commercial, heavy-duty), and energy type (diesel, petrol, hybrid, plug-in hybrid, electric). Where available, it also includes Crit'Air classifications.

At the municipal level, the SDES details the distribution of vehicles by fuel and Crit'Air class. At the regional level, it provides additional information such as age profiles and user status (private, corporate, leasing). Nationally, the data offer aggregated summaries of fleet composition and environmental characteristics. Vehicle location is determined by the address on the registration certificate; for leased vehicles, the lessee's address is used.

The SDES offers comparable information for all major road vehicle categories but excludes two-wheeled vehicles and license-free cars, which are therefore not represented. Overall, the SDES is a robust and spatially detailed source for analyzing the historical evolution of the French fleet and its environmental composition. However, as it contains no forward-looking projections, it must be complemented with scenario data, such as those from the IEA, for future forecasting.

3.2 IEA Scenario Data

To construct projections, this study uses data from the IEA. These scenarios are widely recognised for analysing the impacts of transport and energy policies on technology adoption, emissions, and climate objectives.

From 2025, two scenarios are considered: 1) STEPS (Stated Policies Scenario): follows current and planned policies. It acts as a baseline and leads to about +2.6 °C warming by 2100. 2) SDS (Sustainable Development Scenario): a more ambitious path aligned with the Paris Agreement. It involves faster clean technology adoption and stricter measures, aiming for net-zero emissions by 2050 in advanced economies and limiting warming to +1.7 °C. These scenarios provide national trajectories, serving as references for long-term planning. In this study, the SDS is used as the reference scenario, consistent with European climate targets. Integrated with SDES historical data, the IEA projections generate harmonized time series (2011–2040) that link observed trends with policy-driven futures.

3.3 Inconsistencies Between Data Sources

Although both the SDES and IEA datasets describe the composition of the French vehicle fleet, their formats and classification systems differ, preventing direct integration. The IEA scenarios (STEPS and SDS) provide national-level projections of vehicle stocks. For harmonization, these types are regrouped into the broader categories used by SDES. In contrast, the SDES database, derived from national registration records, classifies vehicles primarily by administrative categories and Crit'Air labels. To ensure compatibility with the downstream emission-estimation workflow, SDES data are converted from Crit'Air to EURO standards.

4 Method: Bottom-Up Projection Workflow

We project municipal fleets by (i) reconstructing EURO classes from SDES, (ii) harmonising national totals to scenario paths, and (iii) downscaling to regions and municipalities under strict closure constraints.

The methodological framework follows a sequential, multi-scale process designed to ensure both temporal continuity and spatial coherence between national, regional, and municipal levels. It integrates four key stages:

1) **EURO pre-treatment:** Conversion of SDES data classified by Crit'Air vignette into EURO emission standards, based on fuel type, Crit'air category, and first registration year.
2) **National harmonization:** Application of IEA scenario trends (STEPS or SDS) to the SDES 2024 baseline to produce continuous national trajectories by vehicle type and fuel. Computationally, this establishes the definitive top-down constraint for the model, defined as the adjusted future predictions. This national-level trajectory is derived by applying a non-linear trend fitting algorithm to IEA fleet data, capturing the expected curved trajectories of vehicle phase-outs or adoptions. These raw extrapolations are subsequently adjusted on the historical SDES data to ensure a seamless and calibrated transition from the baseline year into the projection period.
3) **Regional disaggregation:** Projection of the fleet at the regional level using historical SDES data. Baseline growth expectations for each region are established by calculating the Compound Annual Growth Rate (CAGR) from the historical period. To ensure spatial coherence, these regional projections undergo a proportional adjustment, forcing the sum of the regional fleets to maintain strict mathematical consistency with the national top-down constraint.
4) **Municipal allocation:** Distribution of regional forecasts across communes using SDES-derived historical shares. To prevent local forecasting errors from compounding, the algorithm enforces a bottom-up reconciliation step: it calculates the unadjusted sum of all commune-level projections for a given year and computes an annual adjustment factor. This continuous factor is multiplied across the bottom-up commune data, forcing the aggregate local projections to perfectly align with the overarching regional and national constraints. Finally, reconstructed EURO distributions are applied to obtain the detailed municipal-level projections by vehicle type, fuel, and EURO class.

This structured approach ensures that local projections remain consistent with national trajectories while capturing regional and municipal heterogeneity. The resulting dataset supports policy analysis, air-quality modelling, and scenario evaluation at multiple spatial scales.

The example (Fig. 1) shows methodology applied for heavy-duty vehicles (PL) under the SDS scenario, operates across three spatial levels: (1) National (2) Regional and (3) Municipal.

At the national level, we observe a monotonic decline in the total number of heavy-duty vehicles (PL) under SDS. At the regional level, metropolitan areas broadly follow this downward trajectory, whereas Mayotte (overseas department) continues to grow, which shows that the workflow captures local particularities rather than forcing uniform trends. At the municipal level (here: Le Havre), the IEA-constrained prospective paths impose a notable decrease in total PL across scenarios; this even induces a trend reversal for EURO 6 diesel PL, which rise strongly between 2015 and 2025 but then decline thereafter. Caveat: at municipal scale, volumes can become very small; consequently,

statistical artefacts may affect the balance between vehicle subsets, and results should be interpreted with appropriate caution.

Taken together, these three levels illustrate how the pipeline preserves local particularities (via recent growth profiles and municipal weighting) while enforcing national and regional closure, hence avoiding artificial gains or losses during downscaling.



Fig. 1. Example of Heavy-Duty Vehicle (PL) Fleet Projection under the SDS Scenario across National (a), Regional (b), and Municipal Levels (c)

5 Prospective Scenario: Application to Lyon, France Within Planet' Air

Planet'Air is the software-as-a-service formalisation of the full end-to-end workflow for urban air-quality analysis. Interested reader can refer to [9, 10].

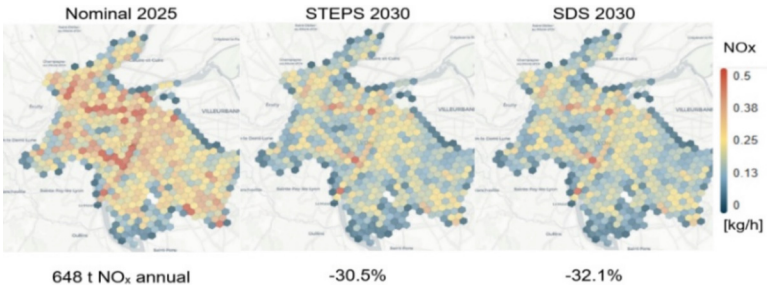


Fig. 2. NOx emissions aggregated for the Nominal 2025, STEPS 2030 and SDS 2030 scenarios. Annual totals indicate a ~30% reduction in annual NOx emissions.

It chains together (i) traffic activity estimation, (ii) vehicle fleet projections, (iii) emission modelling and (iv) dispersion computation, to deliver decision-ready indicators such as high-resolution concentration maps and virtual air-quality sensors.

The fleet-projection module presented in this paper is one of the main inputs to this chain, conditioning emission factors and pollutant flows that feed into dispersion and exposure assessment. We compare Nominal 2025, STEPS 2030 and SDS 2030 (definitions provided in Sect. 3). Projected fleets feed the emission chain and dispersion in Planet'Air. Figure 2 shows NOx emission and Fig. 3 displays concentration maps.

Results show that both 2030 scenarios deliver reductions of around 30% in annual NOx emissions compared to the nominal case. When propagated through the dispersion model, these emission reductions translate into decreases of 27–29% in mean NOx concentrations across the city. This alignment demonstrates the internal consistency of the chain, from fleet assumptions to concentration outcomes.

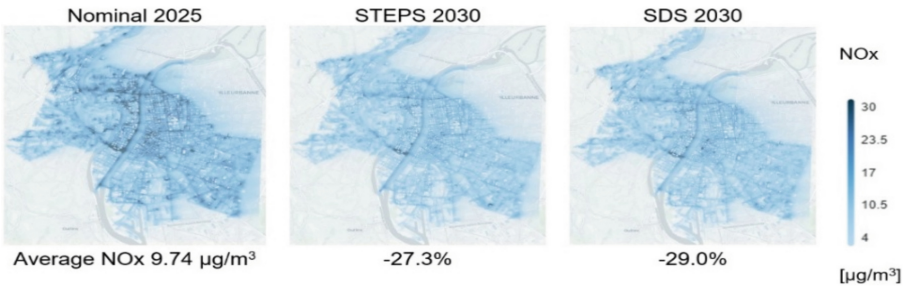


Fig. 3. NOx concentrations for the Nominal 2025, STEPS 2030 and SDS 2030 scenarios. Reductions in emissions are mirrored by decreases in average exposure (-27% to -29%).

Spatial concentration maps highlight two important findings: (i) despite the reduction in average levels, hotspots persist along major traffic axes even in the ambitious SDS scenario, and (ii) improvements are more homogeneous in residential areas compared to traffic corridors. This suggests that while fleet renewal policies can substantially improve average air quality, complementary measures such as modal shift, traffic management, or stricter low-emission zones remain essential to reduce exposure near roadways. Overall, this application demonstrates how Planet'Air integrates fleet projections with the broader modelling, offering municipalities a practical digital twin to benchmark policy options and anticipate the air-quality benefits of fleet renewal strategies.

6 Conclusions

We have presented methodology to project French municipal vehicle fleets by combining historical SDES data with national scenario trajectories and propagating reconstructed EURO mixes to local scale. The workflow guarantees consistency across national, regional, and municipal levels, while preserving observed heterogeneity in age structures and fuel types. When coupled with dispersion modelling in Planet' Air, these projections deliver decision-ready indicators: in the Lyon case study, both STEPS 2030 and SDS

2030 reduced annual NOx emissions by about 30% compared to Nominal 2025, with comparable decreases in population-weighted concentrations.

However, the survival and mileage of recent powertrains are not yet well established; used-vehicle trade (imports/exports) and non-exhaust particulate emissions are also imperfectly captured. The reconstruction of EURO classes from Crit'Air and age could be improved with additional data sources such as technical inspections. At the municipal level, SDES registrations provide only aggregated counts by fuel and Crit'Air, without mileage or usage profiles, which limits the robustness of local projections. This limitation is particularly acute for heavy-duty vehicles, whose registrations do not always reflect the actual circulating stock. A possible improvement is to constrain their distribution at national or regional level, and to account explicitly for freight attraction poles, which shape the territorial structure of heavy-duty traffic.

Future work will therefore focus on three directions: (i) strengthening validation with administrative datasets such as inspections or insurance records, (ii) incorporating policy-sensitive elasticities (e.g. LEZ schedules, charging rollout) to explore alternative municipal pathways, and (iii) quantifying uncertainty envelopes by perturbing survival, activity, and scenario assumptions. Finally, the workflow has been fully implemented and exposed through web services, ensuring integration within Planet'Air's SaaS environment and facilitating direct reuse by partner cities and consultancies. Overall, the proposed approach provides municipalities with a transparent and reproducible tool that links global scenarios to local realities.

References

1. International Energy Agency: Electric Vehicles — Tracking Clean Energy Progress. IEA Transport Outlook Dataset. International Energy Agency (2024)
2. André, M., Allemand, A.: Parc automobile routier territorialisé. Research Report, Inventaire National Spatialisé project. IFSTTAR, Marne-la-Vallée (2020)
3. André, M., Roche, A.L., Bourcier, L.: Statistiques de parcs et trafic pour le calcul des émissions de polluants des transports routiers pour la France. Technical report. IFSTTAR-LTE, Bron (2013)
4. André, M., Carteret, M., Pasquier, A.: Traffic and vehicle fleet statistics for the calculation of air pollutant emissions from road transports in France. In: André, M., Samaras, Z., Jacob, B. (eds.) Research for Innovative Transports Sets – Vol. 1: Energy and Environment, pp. 417–433. ISTE Wiley, London (2016)
5. André, M., et al.: Methodology for characterizing vehicle fleet composition and its territorial variability, needed for assessing low emission zones. Transp. Res. Procedia. **25**, 3290–3302 (2017)
6. CITEPA: Rapport OMINEA – 14ème édition. Organisation et méthodes des inventaires nationaux des émissions atmosphériques en France. Technical Report, Paris (2017)
7. Fridstrøm, L.: A stock–flow cohort model of the national car fleet. Eur. Transp. Res. Rev. **8**(4), 22 (2016)
8. Viri, V., et al.: Modelling car fleet renewal in Finland with the SALAMA model. Res. Transp. Econ. **90**, 101063 (2021)
9. Sabiron, G., et al.: From road traffic to virtual air quality sensors: PLANET'AIR – an integrated mesoscopic modelling framework. In: Transport and Pollution Conference. Rueil-Malmaison, France (2025)

10. Bussod, S., Sabiron, G.: Deep learning-based method for an assessment of road traffic pollutant estimation from predicted driving behaviors. In: Proceedings of the International Conference on Machine Learning and Applications (ICMLA), pp. 658–663 (2024)

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Stakeholder-Based Analysis of Emission Calculation and Reduction Strategies in Inland Waterway Transport on the Danube

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Abstract. To meet EU climate targets, inland waterway transport must significantly reduce emissions. However, little is known about how shipping operators currently assess their emissions or which specific actions they are planning or implementing. This study investigates how CO_2 emissions are measured, which actions are being taken by operators, and which strategies are seen as necessary to achieve climate neutrality by 2050. Six semi-structured interviews with Danube shipping companies and operators, along with a focus group involving eight sector experts, explored current emission accounting practices, planned or ongoing CO_2 reduction measures, and perspectives on long-term decarbonization. Operators typically calculate emissions using aggregated fuel consumption and tonne-kilometres on a monthly or annual basis. Detailed, route- or vessel-specific calculations are considered too complex for routine use. Measures already in place focus on cost-effective fuel savings, such as optimized routing, improved propulsion systems, and gradual integration of alternative fuels. Broader adoption of low-emission technologies is rare due to regulatory uncertainty, insufficient incentives, and infrastructural gaps. Experts emphasized that achieving climate neutrality by 2050 will require a transition to alternative fuels - particularly biofuels and methanol - while hydrogen and electric propulsion remain only longer-term options. Land-based power during berthing was viewed positively, whereas market-based instruments such as emissions trading were met with mixed reactions.

Keywords: climate targets · inland waterway transport · CO_2 emissions · climate neutrality · emission reduction

1 Introduction

The transport sector accounts for about one quarter of the European Union's total greenhouse gas (GHG) emissions and is the only major sector in which emissions have increased since 1990 [1]. Achieving the EU's climate neutrality target by 2050 therefore requires a fundamental transformation of mobility systems, including cleaner technologies, alternative fuels and reduced demand where possible [2, 3]. In this context, both the European Union and the Central Commission for the Navigation of the Rhine (CCNR) aim for zero-emission inland vessel by 2050 [4].

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Various strategies to reduce emissions in shipping have been discussed in the literature, including technical and operational measures, environmentally friendly fuels and alternative energy sources [5]. However, research focusing specifically on inland waterway transport remain limited [6]. Existing studies examine options such as battery-electric propulsion, alternative fuels (e.g., hydrogen, methanol, or biofuels), improved ship designs, modern diesel engines, and energy-efficient onboard technologies [7, 8].

Given the limited research on the decarbonisation of inland shipping, this paper applies a qualitative approach to better understand current and planned measures for monitoring and reducing greenhouse gas emissions. The study addresses the following research questions:

RQ1: How do ship operators and shipping companies currently measure and analyse their greenhouse gas emissions?
RQ2: What key strategies and actions are currently being implemented by ship operators and shipping companies to reduce emissions?
RQ3: Which emission reduction measures are necessary or most effective in inland shipping to achieve climate neutrality by 2050?

To answer these research questions the following section outlines the qualitative methodology employed to examine current and planned measures for greenhouse gas emissions monitoring and reduction in inland shipping.

2 Methodology

The qualitative methodology consisted of two complementary components, each designed to capture different perspectives on emissions monitoring and reduction in inland shipping. The following sections describe the in-depth interviews with shipping companies and operators and the expert focus group discussion.

2.1 In-Depth Interviews

The study draws on in-depth interviews with six representatives of inland shipping companies in the Danube region, including managers, technical specialists, and staff responsible for sustainability issues. This approach was chosen because it allows for the integration of both practical experience and individual perspectives, providing a deeper understanding of current practices in the sector. The interviews followed a semi-structured guideline designed to ensure comparability across cases while leaving room for respondents to elaborate on their own views [9]. It was structured into two core topics: (1) measuring and calculating greenhouse gas emissions, and (2) strategies for reducing greenhouse gas emissions. The interviews were carried out virtually using MS Teams. With the consent of participants, all conversations were recorded and transcribed. For the analysis, the transcripts were coded using MAXQDA, which allows the export of coded and summarized data into MS Excel. This dataset then served as the basis for the qualitative content analysis following [10].

2.2 Focus Group Discussion

In addition to the interviews, a focus group was conducted to critically reflect on identified emission reduction measures and to discuss their practical feasibility from different professional perspectives. Focus groups are particularly suitable for this purpose, as they allow experts from various fields to exchange experiences, challenge assumptions, and jointly develop new insights [11]. The eight participants were carefully selected to ensure a balanced mix of expertise from inland shipping, shipbuilding, logistics, administration and research. This group size falls within the commonly recommended range of six to ten participants for focus group research, which is considered appropriate to balance diversity of viewpoints with the possibility for each participant to actively engage in the discussion [12].

The discussion, which took place on 2 July 2024 at the so-called DigiSpace at the University of Applied Sciences Upper Austria in Steyr, lasted approximately three hours and was moderated to encourage structured yet open dialogue. The session was video-recorded, transcribed, and analysed (with MAXQDA) following qualitative content analysis according to [10]. This methodological approach made it possible to systematically capture the group's perspectives and to identify central themes and practical considerations for the decarbonisation of inland navigation.

3 Results and Discussion

This chapter commences with the presentation of results from the expert interviews, organized according to the main thematic blocks of the interview guide. It concludes with an integrative synthesis of the focus group findings on the various reduction measures discussed.

3.1 Results from Expert Interviews

The following sections summarize the insights from the six expert interviews, structured around key themes: how companies currently measure and calculate emissions, the strategies they implement to reduce them, the incentives and frameworks influencing their decisions, and their perspectives on achieving climate neutrality by 2050.

Emissions Measurement and Calculation
Three companies track emissions, primarily using fuel consumption and tonne-kilometres. Company 1 and 2 calculate CO_2 monthly or annually, while voyage-specific data are considered impractical due to operational complexity (Company 1). Company 2 uses long-term averages to smooth fluctuations. Company 4 is digitalizing its fleet, providing real-time data and calculating a "C-value" with engine manufacturers, but retrofitting older engines causes measurement issues. Companies 3, 5, and 6 do not systematically measure emissions, citing low client demand, limited regulation, and uncertain investment incentives. Company 3 is testing a database with fuel flow meters but notes high technical and personnel costs.

Emission Reduction
Reductions are primarily pursued when economically beneficial. Company 1 complies with Stage V engines and exhaust after-treatment, driven by regulation rather than voluntary CO_2 targets. Company 3 modernizes its fleet but sees ecological investments constrained by competition and labor shortages. Company 4 optimizes rudder and propeller systems and explores e-fuels. Company 5 is gradually converting a vessel to diesel-electric, considers hydrogen for the long term, but focuses currently on routing and speed optimization due to political uncertainty and vessel lifespan. Company 6 has no capacity for emission-reduction investments. When asked about the measurement and documentation of achieved or planned reductions, only Company 4 reported systematic monitoring. Consumption data are collected annually, with a reduction target of 20% (currently 8–10% achieved). Low-water conditions remain a major limiting factor and reliance on diesel limits potential further reductions.

Incentives and Framework Conditions
Companies call for clear European frameworks and international coordination (Company 2). Direct subsidies are seen as market-distorting; fair competition and functional infrastructure are preferred (Company 1). Existing incentives are insufficient for large-scale investments (Company 4, 5), and Company 3 stresses that additional funding is crucial for sector survival. Programs in Germany facilitate modernization, while Slovakia lacks comparable support. Overall, firms highlight the need for policy clarity, investment security, and competitive conditions.

Path to Climate Neutrality
The 2050 zero-emission target is widely regarded as unrealistic. Company 2 cites long lead times, missing international strategy, and low customer willingness to pay. Company 1 notes the lack of mature zero-emission technologies for large vessels and mentions overhead lines as a potential, yet untested, solution. Companies 3 and 4 see potential in alternative fuels and shore power but cannot define a clear pathway. In summary, achieving climate neutrality seems to be constrained by technological, economic, and regulatory barriers under current conditions.

Building on these insights from the interviews, the following section presents the results of the focus group, which discussed and critically evaluated potential measures for reducing greenhouse gas emissions in inland shipping.

3.2 Results from the Focus Group

Within the focus group, which took place on 2 July 2024, various measures for reducing greenhouse gas emissions in inland shipping were discussed. To structure the analysis, the discussion was categorized not only by thematic content but also along two overarching evaluative dimensions: positive and negative assessments by the experts. The aim was to obtain an initial impression of how the measures are perceived in terms of feasibility, effectiveness, and practicality. While some measures, such as shore power and the use of HVO100, received predominantly positive feedback, others were met exclusively with criticism, particularly the Energy Efficiency Index, lightweight construction, and the adjustment of port fees and navigation charges. These were considered ineffective for

supporting the decarbonization of inland shipping. The following section summarizes the key findings.

Alternative Fuels and Propulsion Technologies
The focus group session began with participants being asked to indicate, on a flip chart, which alternative fuel or energy source they considered most promising for the future of inland shipping. The results show that biofuels and methanol were seen as the most promising options, rated as either very likely or likely by the majority of participants. In contrast, ammonia and LNG/CNG were largely considered either very unlikely or unlikely. Hydrogen and batteries received more mixed assessments, suggesting differing levels of experience or uncertainty regarding their technological development. Following the rating exercise, a detailed discussion addressed practical experiences, regulatory developments, technical feasibility, and fuel availability.

Biofuels/HVO100
HVO100 was viewed by five participants as a promising short- to medium-term option. Its main advantage lies in compatibility with existing engines, tanks, and pipelines, allowing flexible blending with diesel. Expert 5 noted, however, that costs remain high and issues of taxation and labelling are unresolved. The expert also suggested reserving HVO100 for sectors with limited alternatives, such as shipping and aviation.

Methanol
Methanol was discussed as a longer-term option. Compared to hydrogen, it is easier to handle and store but requires about twice the storage volume of diesel. Experts 5 and 8 highlighted the resulting space challenges on existing vessels. Two applications are currently under consideration: dual fuel engines and fuel cells. According to Expert 8, the absence of standardized fuel quality and regulatory gaps - such as the lack of harmonized safety rules - remain key barriers. All experts regarded broad market uptake within the next decade as unlikely.

Hydrogen (H_2)
Hydrogen was generally seen as a long-term option. Its low energy density makes storage and logistics complex, requiring either cryogenic cooling or high-pressure tanks. Expert 5 highlighted these conditions, along with the absence of international infrastructure, as major barriers to cost-effective deployment. The latest National Hydrogen Strategy progress report likewise makes no reference to inland shipping, focusing instead on pilot projects in buses and industry [13]. Expert 3 noted that operating costs would remain well above diesel, while Expert 5 pointed to incomplete ES-TRIN standards and the lack of a suitable regulatory framework, leaving both combustion and fuel cell pathways with significant gaps.

Batteries/Electrification
Batteries were considered of limited current relevance. Experts 3, 5, and 8 pointed to range and space constraints, particularly in long-distance navigation. Options discussed included exchangeable battery modules and, more radically, overhead line electrification. Both were seen as technically feasible but requiring extensive infrastructure.

Future advances, such as solid-state cells, were regarded more positively, though their applicability remains uncertain.

Ammonia (NH_3) and LNG/CNG
From the outset, the direct use of ammonia and LNG/CNG in inland navigation was considered unrealistic by all discussants for reducing greenhouse gas emissions, and these options were therefore not pursued further in the discussion.

Use of Shore Power
Shore power was widely assessed as positive. Experts 1, 5, and 6 underlined benefits for crews and emission reduction. While Austria already provides standardized connections, Expert 1 stressed that significant infrastructure gaps remain in other Danube countries. At the time of the focus group, a free pilot system was being tested in Austria, while questions regarding operatorship and billing systems remained unresolved. Expert 5 suggested a simple card-based payment model.

Integration of Inland Shipping into the EU Emissions Trading System
Integration into the EU ETS was judged useful by Expert 3 for steering emissions reductions, provided a uniform European approach is ensured. Experts 3, 4, and 5 emphasized equal treatment with other transport modes, while Expert 4 warned that exemptions in some states could create competitive disadvantages.

Emission-Based Port Fees
Emission-based port fees were seen as ineffective. Expert 6 highlighted the imbalance between minimal port fee savings (€240 in Rotterdam) and retrofit costs (€600,000). Expert 1 and 3 warned that centrally regulated fees could distort competition.

EU Energy Efficiency Index (EEI) Methodology
The transfer of the maritime EEDI to inland shipping was strongly rejected by Experts 3, 6, 7, and 8. They stressed that energy use depends on highly variable external conditions, making a uniform index meaningless. Hydrodynamic optimizations also reduce cargo capacity, and many riparian states are non-EU members, limiting regulatory scope (Expert 8). Experts 6 and 7 further noted that diverse operating conditions and the lack of data make uniform benchmarks impractical.

Other Measures
The focus group also discussed supplementary measures that could reduce emissions but not achieve zero-emission inland shipping. Expert 8 saw optimization potential in propellers and crew training, noting that anticipatory navigation can improve efficiency, whereas improper practices (e.g., leaving the anchor partially deployed) increase resistance. Lightweight construction, however, was deemed unsuitable: retrofitting existing vessels was ruled out, and aluminium—though lighter than steel—offers lower strength, higher costs, and greater damage risks. Frequent repairs and limited shipyard capabilities further undermine its feasibility in freight shipping (Expert 5 and 8).

4 Conclusion

This study highlights the complex challenges faced by the inland waterway transport sector on its pathway toward climate neutrality. While operators acknowledge the importance of reducing emissions, current monitoring practices remain relatively limited. Emissions are typically calculated using aggregated indicators such as fuel consumption and tonne-kilometres, while voyage- or vessel-specific monitoring is rarely applied. Measures implemented so far mainly focus on incremental efficiency improvements, including propulsion optimisation, routing adjustments, and fuel savings, and are often driven by economic considerations. Investments in alternative propulsion technologies remain rare, reflecting regulatory uncertainty, limited incentives, and infrastructural constraints.

The expert focus group further indicated that a transition to alternative fuels will likely be necessary if the sector is to align with European climate targets. Biofuels and methanol were considered the most feasible options in the near to medium term, while hydrogen and electrification were generally seen as longer-term solutions due to remaining technical and economic barriers. Shore power was widely regarded as a practical measure, although its broader use depends on further infrastructure development along the Danube. In contrast, policy tools such as emission-based port fees or the transfer of maritime efficiency indices were seen as largely ineffective or impractical.

Overall, the findings reveal a clear gap between the ambitions of European climate policy and the current realities of inland navigation in the Danube region. Bridging this gap will require coordinated action from both policymakers and industry stakeholders. For policymakers, this includes providing stable and long-term regulatory frameworks, strengthening financial support schemes for low- and zero-emission vessel technologies, and accelerating the development of infrastructure for alternative fuels and shore power along the Danube corridor. For operators, improving the transparency and accuracy of emission monitoring, testing alternative fuels in pilot projects, and increasing collaboration across the sector could represent important first steps toward a more systematic decarbonisation pathway.

The results should also be interpreted in light of certain limitations. The study relies on a relatively small sample of interviews and a qualitative focus group discussion. While this approach allows for in-depth insights into the perspectives of practitioners, the findings cannot be considered statistically representative for the entire sector. Nevertheless, they provide valuable exploratory insights into current practices, barriers, and possible transition pathways in the Danube region.

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References

1. European Environment Agency Homepage. https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility?activeTab=07e50b68-8bf2-4641-ba6b-eda1afd544be. Accessed 16 Mar 2026

2. European Commission Homepage. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12438-Sustainable-and-Smart-Mobility-Strategy_en. Accessed 16 Mar 2026
3. Haasza, T., et al.: Perspectives on decarbonizing the transport sector in the EU-28. Energ. Strat. Rev. **20**, 124–132 (2018). https://doi.org/10.1016/j.esr.2017.12.007
4. Pauli, G., Boyer, B.: Regulation for the decarbonisation of IWT in Europe. In: Proceedings of PIANC Smart Rivers, vol. 264, pp. 1398–1408. Springer, Singapore (2022)
5. Xing, H., Spence, S., Chen, H.: A comprehensive review on countermeasures for CO2 emissions from ships. Renew. Sust. Energ. Rev. **134** (2020). https://doi.org/10.1016/j.rser.2020.110222
6. Raftis, C.C., Vanelslander, T., van Hassel, E.: A global analysis of emissions, decarbonization, and alternative fuels in inland navigation - a systematic literature review. Sustainability. **15**(19) (2023). https://doi.org/10.3390/su151914173
7. Perčić, M., Vladimir, N., Fan, A.: Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. Renew. Sust. Energ. Rev. **148** (2021). https://doi.org/10.1016/j.rser.2021.111363
8. Hörandner, L., Duldner-Borca, B., Beil, D., Putz-Egger, L.-M.: measurement techniques, calculation methods, and reduction measures for greenhouse gas emissions in inland navigation - a preliminary study. Sustainability. **16**(7) (2024). https://doi.org/10.3390/su16073007
9. Ruslin, M., Saepudin, R., Muhammed, S.A., Firdiansyah, A., Hijrah, S.: Semi-structured interview: a methodological reflection on the development of a qualitative research instrument in educational studies. J. Res. Method Educ. **12**, 22–29 (2022)
10. Mayring, P.: Qualitative Content Analysis: Theoretical Foundations, Basic Procedures and Software Solutions. Springer, Dordrecht (2014)
11. Borucki, I., Kleinen-von Königslöw, K., Marschall, S., Zerback, T.: Handbuch Politische Kommunikation. Springer VS, Wiesbaden (2022)
12. Freitas, H., Oliveira, M., Jenkins, M., Popjoy, O.: The Focus Group, A Qualitative Research Method. ISRC 010298 (1998)
13. BMK und BMAW Homepage. https://www.parlament.gv.at/gegenstand/XXVII/III/1208. Accessed 16 Mar 2026

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Building Readiness and Foresight for Zero-Emission Mobility Solutions in the metaCCAZE Project Through Status Quo Mapping – The Limassol Living Lab

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Abstract. The Horizon Europe metaCCAZE project aims to accelerate deployment of innovative zero-emission mobility solutions across ten European living labs: four Trailblazer (Amsterdam, Munich, Limassol, and Tampere) and six Follower living labs (Athens, Krakow, Gozo-Malta, Milan, Miskolc, and Poissy-Paris). To inform tailored implementation, the project develops Status Quo Mapping methodology to systematically establish living-labs readiness according to current conditions, capacities, and specific needs. The framework integrates three components: the Capability Map, analysing existing mobility plans, smart services, resources, innovation outcomes from related initiatives and alignment with Sustainable Urban Mobility Plans and Climate City Contracts; the Empathy Map, capturing stakeholder needs, priorities, and perceived barriers through structured ecosystem dialogues and co-creation workshops; and the Data Map, cataloguing available datasets with attention to maturity, quality, consistency, coverage, and suitability for monitoring and evaluation. This holistic approach aligns established local contextualization with broader project objectives, guiding the co-design of diverse use cases from autonomous e-shuttles and dynamic curbside management to Artifical Intelligence-based on-demand services and tradable mobility credits while identifying shared challenges in operational reliability, accessibility, regulation, and financial sustainability across varied urban mobility landscapes. The resulting insights provide robust foundations for prototyping, evaluation, cross-city knowledge transfer, and long-term scaling of sustainable mobility innovations.

Keywords: Status Quo Mapping · Climate Neutrality · Resource mapping · metaCCAZE · Zero-emission Mobility

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1 Introduction

Europe's urban mobility landscape is evolving rapidly in response to the escalating climate crisis, energy transitions, and increasing demand for smart and inclusive transport solutions. The metaCCAZE [1] project, funded under 2ZERO [2], CCAM [3] and Cities Mission partnerships [4], contributes to these ambitions by accelerating the uptake of shared, connected and zero-emission mobility services for passengers and freight. To guide the cities in achieving their Climate City Contract (CCC) [5], Sustainable Urban Mobility Plans (SUMP) [6] targets, metaCCAZE brings together ten living labs (LL), including four Trailblazer cities (T-LL) - Amsterdam, Munich, Limassol, and Tampere and six Follower cities (F-LL) - Athens, Krakow, Gozo-Malta, Milan, Miskolc, and Poissy (Paris). They are implementing a broad spectrum of twelve Use cases (UCs), ranging from autonomous shuttles, dynamic curbside management, multimodal hubs, to AI-optimised on-demand services and energy-integrated transport systems. In the metaCCAZE project, a UC represents an innovative zero-emission mobility or freight solution addressing specific local challenges within each LL. To ensure these solutions are grounded in local realities, the project's Status Quo Mapping (SQM) methodology is applied, structured around three complementary pillars: Capability, Empathy, and Data Map. The following sections present the methodology and application to four UCs in Limassol, Cyprus, a designated EU Mission city.

2 Methodology

While several approaches exist for co-design, stakeholder engagement, and urban mobility planning, there is currently a lack of integrated frameworks that combine policy alignment, stakeholder needs, and data readiness into a unified diagnostic tool for early-stage mobility innovation. The SQM methodology builds upon established approaches. In particular, it draws on the Living Lab paradigm [7, 8], promoting co-creation and experimentation in real-world environments involving multiple stakeholders. Co-design methodologies support the iterative development of solutions based on needs and constraints. In parallel, data-driven frameworks have been increasingly used to define and monitor urban mobility interventions through measurable indicators and cross-city benchmarking [9]. The methodology serves as a diagnostic and strategic tool supporting the LLs to establish a baseline of their institutional, social, and technical ecosystem within which each UC must operate. Assessment has been performed through structured, yet flexible framework composed of three foundational components: the Capability Map, the Empathy Map, and the Data Map, each of them detailed below. By identifying critical gaps, it informs complementary tasks of social embracement activities (behavioural surveys across LLs, designed for citizens, stakeholders, and service providers) and supports the realistic selection of Key Performance Indicators (KPI's) for the Standardised Impact Evaluation Framework (SIEF). For context, SIEF serves as the core methodology for assessing the impact of zero-emission shared mobility (ZESM) solutions demonstrated in the metaCCAZE project. The outcomes of these components were consolidated and compared to create a comprehensive Status Quo Map for each LLs UC. Through SQM, metaCCAZE ensures that innovation is not only aspirational but also actionable, guided by evidence, anchored in policy, validated by users, and supported by measurable data.

2.1 Capability Map

The Capability Map aims to assess each LLs' preparedness through a standardized template compiled collaboratively and its technical support partner successfully capturing key dimensions including: city profile and mobility context (e.g. size, demographics, economic and geographic characteristics, and modal split), alignment with SUMP or similar strategies (scope, targets, and KPIs), and Climate City Contract (CCC) actions related to urban mobility (e.g. public transport upgrades, micro-mobility, electrification). It also includes preliminary UC descriptions and anticipated challenges (e.g. governance, operational, and behavioural barriers), relevant past studies or pilots, existing smart mobility services (e.g. traveller information systems, ticketing platforms, bike-sharing schemes, including their coverage and integration challenges), and local communication and stakeholder engagement channels.

Table 1. Synthesis of the Capability Map of Limassol LL

Dimension	LI-UC01 (On-demand buses)	LI-UC02 (Shared -bikes)	LI-UC03 (Multi-Modal Hub)	LI-UC04 (Transport and Energy platform)
Policy Alignment (SUMP/CCC)	Strong	Strong	Strong	Moderate (future-oriented)
Objective	Reduce car dependency, flexible PT	Promote active mobility	Improve multimodality	Optimize energy–transport integration
Existing Services	Bus system, traveller info	Bike-sharing pilots	PT network	Charging infrastructure
Experience from Projects	CIVITAS, SUMPORT	CIVITAS	Limited	Limited
Key Barriers	User adoption, service design	Terrain, infrastructure gaps	Governance coordination	Data integration, grid complexity
Enabling Factors	AI routing, existing demand	Digital platform, docking expansion	Strategic location	IoT platform, CCC alignment

To ensure comparability across cities, common template and definitions were applied across all LL. Key elements such as modal split were harmonized using official SUMP documents, transport studies, and municipal data. The synthesis (Table 1) followed an iterative and co-creative process. LL partners compiled and interpreted local inputs based on contextual knowledge, while technical partners ensured consistency in structure and terminology. Cross-review at project level enabled alignment and facilitated structured comparison across cities. Rather than applying a numerical scoring system, the analysis focused on identifying patterns of alignment, strengths, and barriers in relation to policy

objectives and implementation conditions. The resulting information was consolidated into a unified analytical format, establishing a comparable baseline across LLs and enabling the identification of strategic leverage points, common challenges, and context-specific conditions influencing the feasibility of zero-emission mobility solutions.

2.2 Empathy Map

The Empathy Map (summarised in Table 2), operationalized through ecosystem dialogues, supports early stakeholder engagement capturing behavioural and emotional dimensions.

Table 2. Synthesis of the Empathy Map of Limassol LL

Dimension	LI-UC01 (On-demand buses)	LI-UC02 (Shared -bikes)	LI-UC03 (Multi-Modal Hub)	LI-UC04 (Transport and Energy platform)
Stakeholders	Students, families, operators	Citizens, commuters	Authorities, PT users	Authorities, energy providers
Key Needs	Reliable, safe, easy booking	Accessible bikes, better coverage	Seamless transfers, info systems	Real-time coordination, efficiency
Barriers	Safety concerns, usability	Terrain, station placement	Institutional coordination	Data sharing, system integration
Behavioural Insights	Car dependency	Low cycling culture	Need for convenience	Trust in digital systems
Key Insight	Integration with existing apps needed	Localised planning critical	Strong governance needed	Backend intelligence is key

Using an adapted canvas, each LL gathered insights through a combination of informational presentations, interactive discussions, and live polling tools (e.g. Mentimeter), focusing on mobility challenges, perceptions of proposed services, and conditions for adoption. Responses were consolidated and categorised into: identified needs (e.g. reliable cost-effective alternatives to private cars, improved mobility infrastructure, real-time information and journey planning), barriers, concerns (e.g. digital literacy gaps, institutional complexity, behavioural patterns such as car dependency), stakeholder feedback (e.g. attractiveness, usability, integration), and pains and gains (e.g. commuting stress versus quality-of-life improvements, data limitations versus opportunities for system integration). Stakeholders were selected based on their role within the local mobility ecosystem and including public authorities, transport operators, technology providers, research institutions, and user groups. For example, in Limassol, engagement combined a physical stakeholder event, targeted interviews, and an online questionnaire conducted at different stages, ensuring inclusion of both institutional and user perspectives. To

enhance robustness and mitigate bias, insights were triangulated across formats and aggregated into standardized thematic categories, enabling comparability across cities. This mapping ensures co-creation from the outset and provides each LL with a structured qualitative knowledge base that informs Use Case design and Business Innovation and Governance Models (BIGMs), while identifying social acceptance factors, contextual risks, and institutional enablers.

2.3 Data Map

The Data Map (summarised in Table 3) focuses on assessing availability and suitability of data required to support the implementation and evaluation of UCs, leveraging existing data infrastructure, secondary sources, and outputs of previous co-creation activities. Each LL completed a standardized Excel template capturing key attributes of datasets, including availability, type, source, update frequency, spatial and temporal coverage, quality, format, and access restrictions. Data was collected across three levels: (i) baseline city-wide datasets, (ii) UC-specific datasets, and (iii) additional contextual datasets (e.g. environmental indicators, travel behaviour). The collected data was analysed using a structured qualitative assessment based on four key dimensions: availability, quality, coverage, and accessibility. Based on these criteria, datasets were categorized into indicative readiness levels (e.g. high, medium, low), reflecting their suitability for monitoring and evaluation purposes. While no formal numerical scoring was applied, a consistent interpretation framework ensured comparability across cities.

Table 3. Synthesis of the Data Map of Limassol LL

Dimension	LI-UC01 (On-demand buses)	LI-UC02 (Shared -bikes)	LI-UC03 (Multi-Modal Hub)	LI-UC04 (Transport and Energy platform)
Data Availability	High (70%)	High (75%)	High (75%)	Medium (60%)
Data Sources	EMEL, PT systems	Nextbike	Municipality	Energy + transport systems
Data Type	Ridership, routes	Usage, GPS	PT + infrastructure	Energy + mobility
Key Gaps	Real-time integration	Demand forecasting	Hub performance data	EV charging + grid data
Readiness Level	High	High	Medium	Medium–Low
Workarounds	Surveys, logs	Usage analytics	Proxy indicators	User logs, simulations

This analysis enabled the identification of data gaps and differences in data maturity across Living Labs, supporting the realistic selection of Key KPIs within the SIEF, and informing complementary data collection strategies where needed.

3 Results

The SQM methodology has been applied for the analysis of 10 cities and their varied UCs. Results from Limassol describes its readiness to meet its ambitious climate-neutrality targets, formalised through its 2019 SUMP [10] and 2024 CCC [4]. UC01 and UC02 show strong alignment with overarching policy objectives such as reducing car dependency and promoting active and shared mobility through measures including zonal and temporal restrictions, expansion of bike sharing, and electrification strategies. Both UCs introduce forward-looking elements, such as AI-based routing and transport energy optimisation, not yet embedded in current frameworks. UC01 demonstrates an inclusive design approach, initially targeting students and expanding to employees and tourists, extending mobility services also to underserved and low-density areas. UC03 introduces a spatial dimension developing a multimodal passenger hub.

The **Capability Map** validated its alignment with existing plans while identifying governance complexities, particularly the need for inter-ministerial coordination on land use. In contrast, UC04 highlights gaps between current policy frameworks and emerging needs such as dynamic grid management and vehicle-to-grid (V2G) services, which are not reflected in SUMP but align with CCC objectives. This demonstrates the Capability Map's dual role in validating alignment and identifying opportunities for policy evolution. The analysis reveals differing maturity levels across UCs. UC01 and UC02 benefit from prior EU-funded projects such as CIVITAS DESTINATIONS and SUMPORT, which provide a strong foundation through existing cycling infrastructure, EV uptake, and charging networks, enhancing feasibility and institutional continuity. Conversely, UC03 and UC04 face complex governance and infrastructural challenges, requiring inter-ministerial agreements and targeted investments (e.g. fast-charging infrastructure). The methodology highlights the value of mapping existing services and stakeholder ecosystems: systems such as the real-time Bus Traveller Information System and Bus Fleet Management System, initially linked to UC01, emerge as enabling assets for UC03 and UC04 by supporting backend coordination and user experience. Similarly, challenges in the bike reservation system, such as limited free-flow availability, insufficient docking stations, and fragmented responsibilities, are addressed by including expansion of docking infrastructure, integration of free-flow systems, and stronger collaboration between universities and NextBike.

The **Empathy Map** proved essential in capturing behavioural, emotional, and contextual drivers. For UC01, feedback highlighted concerns around safety, journey time, and app usability, suggesting integration with platforms such as Google Maps to improve uptake. For UC02, stakeholders emphasized terrain-appropriate infrastructure and strategic station placement, underscoring the need for context-specific planning. System-level insights also emerged: UC03 stakeholders stressed the importance of real-time dashboard-based public transport data, while UC04 highlighted need for improved inter-organisational cooperation and real-time energy and demand data. Common challenges such as bureaucratic delays and institutional fragmentation were observed across all UCs, though manifested differently, for example, land-use coordination in UC03 versus subsidy imbalances in UC01 and UC02.

The **Data Map** dives deep into Limassol's data ecosystem. Foundational datasets, including ridership, fleet composition, scheduling, and station occupancy are routinely

collected by actors such as EMEL, Nextbike, and municipal authorities, forming a reliable basis for monitoring and evaluation. However, significant gaps remain, particularly in real-time interoperability and datasets related to charging infrastructure performance and traffic signal timing. Gaps are addressed by proposing alternative data collection strategies, such as user surveys or vehicle logs, for example to estimate EV charging behaviour and peak load impacts in UC04. Social embracement tools, including surveys, interviews, and focus groups will capture both behavioural changes and perceptions of safety, usability, and acceptability across implementation phases. For instance, UC01 combines surveys and focus groups, UC02 relies on questionnaire-based monitoring of mobility habits, while UC03 and UC04 use stakeholder consultations to refine backend system requirements and data needs. Importantly, the SQM framework also enables cross-use case integration: outputs from UC01 and UC02 support the functionality of UC03, while UC04's platform-based architecture can enhance backend systems across all UCs. These insights allow cities to cluster investments, prioritise actions, and plan integration early, thereby maximising resource efficiency and policy coherence.

4 Conclusions

The SQM is an integrated framework to assess cities' readiness for innovative solutions by combining policy alignment, stakeholder perspectives, and data availability. By linking top-down strategic frameworks (e.g. SUMP and CCC) with bottom-up stakeholder insights and evaluation needs, it enables a comprehensive understanding required for successful UC implementation. The application in Limassol demonstrates its value in generating a multi-dimensional diagnosis of the local mobility ecosystem. The Capability Map validated alignment with strategic objectives while identifying governance and institutional barriers; the Empathy Map captured behavioural dynamics and user needs, grounding solutions in real-world conditions; and the Data Map assessed available datasets, highlighted key gaps, and supported KPI definition and data collection strategies. SQM also enables cross-use case integration and more efficient prioritisation of actions, while contributing to the broader metaCCAZE framework through the development of BIGMs, SIEF, and social embracement activities. However, the analysis relies primarily on qualitative inputs and reflects variability in stakeholder engagement and data availability across cities. Future research should focus on developing quantitative indicators and validating the framework during implementation phases.

References

1. metaCCAZE homepage. https://www.metaccaze-project.eu/. Last Accessed 26 Mar 2026
2. Homepage. https://www.2zeroemission.eu/. Last Accessed 26 Mar 2026
3. CCAM: Partnership. https://www.ccam.eu/. Last Accessed 26 Mar 2026
4. EU Mission: Climate-neutral and smart cities. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en. Last Accessed 26 Mar 2026
5. Net Zero Cities. https://netzerocities.eu/climate-city-contract/. Last Accessed 26 Mar 2026
6. Rupprecht Consult: Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan (SUMP). Rupprecht Consult, Cologne (2019)

7. Alonso Raposo, M., et al.: The Future of Road Transport: Implications of Automated, Connected, Low-Carbon and Shared Mobility. Publications Office of the European Union, Luxembourg (2019)
8. European Network of Living Labs (ENoLL). https://enoll.org/living-labs/#living-labs. Last Accessed 26 Mar 2026
9. Boeing, G., et al.: Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. Lancet Glob. Health. **10**, e907–e918 (2022)
10. PTV Transport Consult GmbH: Consultancy services for the development of a SUMP for the greater urban area of the city of Limassol (Final SUMP report – Summary), Karlsruhe (2019)

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Alternative Fuels for Decarbonising Freight Transport: A System Dynamics Approach

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Abstract. This system dynamics (SD) model evaluates the adoption of hydrogen, biofuels, and synthetic e-fuels to decarbonise freight transport across global corridors, supporting global climate-neutral goals. The model integrates quantitative data from international freight pilots and global datasets (e.g., IEA, IRENA) with qualitative insights from stakeholders, including fleet operators, policymakers, and researchers. It simulates fuel adoption scenarios under varying policy, infrastructure, and market conditions, focusing on vehicle fleet, energy efficiency, carbon emissions reductions, and circular economy principles (e.g., biofuel production from organic waste). Key outputs include optimal policy levers (e.g., subsidies, carbon pricing) identified through sensitivity analysis and potential emission reductions of 30% by 2035 with targeted investments. The model provides a scalable decision-support tool for policymakers and industry, addressing barriers to alternative fuel adoption.

Keywords: System dynamics modelling · Freight transport decarbonisation · Alternative fuels · Scenario analysis · Circular economy

1 Introduction

Freight transport is a key driver of economic development but also a major source of greenhouse gas emissions and energy consumption. In 2022, road freight contributed significantly to global energy-related CO_2 emissions, highlighting the urgency of decarbonising the sector [1]. With demand expected to rise due to urbanisation, industrial growth, and expanding supply chains, the environmental impact of freight transport will intensify without targeted interventions. As a result, alternative fuels such as hydrogen, biofuels, and synthetic e-fuels are increasingly being explored as pathways to climate neutrality.

The transition to low-carbon freight systems is not purely technological; it involves complex interactions between policy instruments, infrastructure availability, market dynamics, and stakeholder behaviour. Measures such as subsidies and carbon pricing can accelerate adoption, but their effectiveness depends on supporting systems and user responsiveness [2, 3]. These interactions involve feedback loops, time delays, and uncertainties, making freight decarbonisation a complex socio-technical process. Traditional modelling approaches often fail to capture such dynamics. System Dynamics

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(SD) offers a more suitable framework by modelling feedback mechanisms and temporal changes, particularly in data-constrained contexts [4–6]. However, its application to freight decarbonisation, especially in emerging economies, remains limited.

This study addresses these gaps by developing an SD model for Delhi, integrating quantitative data and stakeholder insights to assess how policy and infrastructure scenarios influence fleet composition and emissions. It contributes by providing an integrated, transparent, and policy-relevant framework for analysing freight decarbonisation.

2 Literature Review

System Dynamics (SD), introduced by Forrester [4], is widely used to analyse complex systems characterised by feedback loops, delays, and non-linear interactions. In transport research, SD has proven particularly valuable for understanding long-term policy impacts and system behaviour under uncertainty [5, 7]. Unlike traditional approaches such as traffic simulation or discrete choice models, SD enables a dynamic and integrated analysis of interactions across multiple system components [6].

A growing body of literature applies SD to freight transport and decarbonisation. Early studies, including Piattelli et al. [8], demonstrated the effectiveness of infrastructure investment in enabling modal shifts, while Han and Hayashi [9] identified rail expansion as a key strategy for emissions reduction in China. Liu et al. [10] further highlighted the limitations of regulatory measures in isolation, emphasising the importance of infrastructure development. Similarly, Choi et al. [11] and Brito Junior et al. [12] examined modal transitions in South Korea and Brazil, highlighting the long-time horizons required for policy and infrastructure interventions to yield results. At a broader scale, models such as GLADYSTE [13] have simulated global transport demand and emissions, though with limited representation of feedback mechanisms and behavioural dynamics. More recent studies incorporate stakeholder perspectives and behavioural elements. For instance, Seitz [14] emphasised stakeholder engagement, while Kumar and Singh [15] applied SD to India's freight sector, integrating alternative fuel supply and adoption variables. Advances in hybrid modelling, including machine learning integration, further demonstrate the evolving capabilities of SD approaches [16].

Despite these contributions, key limitations persist. Many studies lack transparency in model structure and assumptions, limiting replicability [17], and validation practices often remain inadequate. Additionally, policy, infrastructure, and market dynamics are frequently analysed in isolation. Addressing these gaps, this study develops an integrated SD framework that combines policy interventions, infrastructure capacity, and alternative fuel dynamics, supported by both quantitative data and stakeholder insights to enhance policy relevance in emerging economy contexts.

3 Methodology

3.1 Data Collection

This study employs a mixed-method approach combining qualitative expert insights with quantitative secondary data to capture system dynamics. Secondary datasets on fleet, emissions, and energy use align with World Bank (2023) projections [13]. Unstructured

stakeholder interviews [18] in Delhi informed key variables, including infrastructure capacity, Alternative Fuel Vehicle (AFV) adoption, fuel supply, and efficiency [19].

3.2 Model Development

The System Dynamics (SD) model was developed to simulate the evolution of Delhi's freight transport system under varying policy and infrastructure conditions. It integrates key variables, including Infrastructure Capacity, AFV Adoption Rate, Alternative Fuel Supply, Subsidies, Diesel Vehicle Fleet, AFV Fleet, Energy Efficiency, and Emission Reduction Rate. Qualitative insights were translated into model parameters and structural relationships, ensuring both empirical grounding and contextual relevance in analysing transition pathways.

Causal Loop Diagram

- *Reinforcing Loop (R1):* Subsidies boost AFV Adoption Rate, reducing Diesel Vehicle Fleet and increasing AFV Fleet, enhancing Energy Efficiency and Emission Reduction Rate, potentially justifying further subsidies.
- *Balancing Loop (B1):* Limited Infrastructure Capacity delays AFV Adoption Rate as demand grows, stabilising fleet expansion.
- *Reinforcing Loop (R2):* Increased Alternative Fuel Supply supports AFV Adoption Rate and Energy Efficiency, tempered by supply delays.
- *Balancing Loop (B3):* Technology Maturity accelerates AFV Adoption Rate, but initial low maturity slows adoption.

Infrastructure investments driven by GDP growth and public–private financing generate reinforcing dynamics within the system [20], while regulatory interventions aimed at reducing emissions influence costs and demand [12, 21]. Emissions, in turn, feed back into policy responses, forming balancing loops that shape long-term system behaviour [9].

Stock and Flow Analysis

The model adopts a stock–flow structure to represent the evolution of vehicle fleets over time. Key stocks include the Diesel Vehicle Fleet and the AFV Fleet, capturing conventional and alternative fuel vehicles. These are linked through adoption and retirement flows, which govern transition dynamics. Adoption is driven by policy incentives, infrastructure availability, and alternative fuel supply, while retirement reflects ageing fleets and regulatory pressures. Supporting variables such as Energy Efficiency are computed as weighted averages of fleet composition, and Emission Reduction Rate is estimated from differences in fuel efficiency and emissions intensity. This structure captures dynamic interactions in line with System Dynamics principles [4, 6] (Fig. 1).

Model Structure, Assumptions and Calibration

All variables are defined in consistent units, ensuring dimensional accuracy. Equations are based on established literature and calibrated using secondary data [1, 13] and expert inputs. Key parameters were estimated from 2015–2024 data and iteratively refined. The

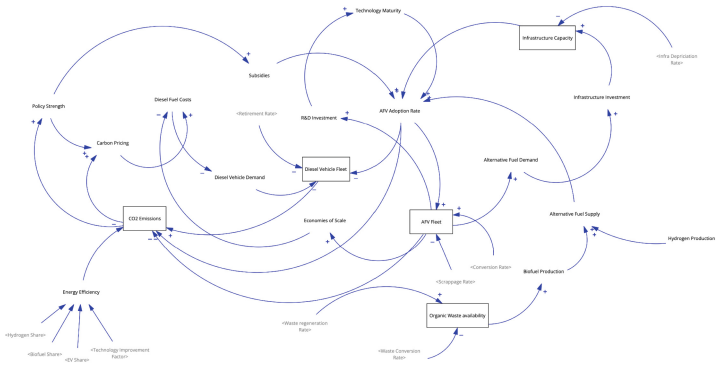


Fig. 1. Causal Loop Diagram

model assumes gradual technological change, time delays, and non-linear policy effects, consistent with prior SD studies [5, 7].

3.3 Scenario Design

A business-as-usual (BAU) scenario was established as a baseline, assuming continuation of current trends in freight demand, infrastructure development, and limited policy intervention. Three scenarios were then developed: Increased Economic Growth (8% GDP growth with moderate adoption), Policy Action (strong regulatory measures including carbon pricing and subsidies), and Increased Infrastructural Development (expanded charging and refuelling networks).Infrastructure capacity reflects both physical expansion and functional accessibility, influencing adoption by reducing operational constraints. GDP growth drives freight demand, affecting fleet size and energy use. Scenario parameters were informed by historical data and expert inputs [3, 6].

3.4 Validation

Model validation employed multiple approaches. Simulated outputs were compared with historical data (2015–2024), showing consistent trends. Dimensional checks ensured unit consistency, while behavioural validation using the BAU scenario confirmed expected system dynamics. Sensitivity analysis (±10% variation in key parameters) demonstrated model robustness, with stable results across scenarios, in line with established system dynamics validation practices [22].

4 Results and Scenario Analysis

4.1 Increased Economic Growth Scenario

This scenario assumes sustained GDP growth of 8%, driving higher freight demand alongside gradual technological adoption. The AFV Adoption Rate is set at 7%, with subsidies increasing to 900 million rupees by 2050, reflecting a market-led transition.

Results show the AFV fleet rising to 90,899 vehicles, while diesel vehicles decline from 141,037 in 2025 to 78,191. Emissions fall from 130.84 Mt. to 71.46 Mt. (45.4% reduction), with AFVs reaching a 53.76% share. Despite steady progress, decarbonisation remains limited due to infrastructure gaps, cost barriers, and behavioural inertia, highlighting the constraints of growth-driven transitions without strong policy support.

4.2 Policy Action Scenario

This scenario incorporates strong policy interventions, including a carbon tax rising to 100 rupees per tonne and subsidies reaching 1,200 million rupees by 2050. The AFV Adoption Rate increases to 12%, accelerating fleet transition. Results show a sharp rise in AFVs to 174,825 vehicles and a decline in diesel vehicles to 2,657. Emissions drop significantly from 128.90 Mt. to 10.78 Mt., achieving a 91.6% reduction, with AFVs comprising 98.50% of the fleet. While highly effective, this represents an upper-bound scenario, assuming robust enforcement, infrastructure readiness, and behavioural responsiveness that may be challenging to fully achieve in practice.

4.3 Increased Infrastructural Development Scenario

This scenario emphasises infrastructure expansion, increasing capacity by 5,000 km without additional subsidies. The AFV Adoption Rate rises to 8%, reflecting improved accessibility and reduced operational constraints. The AFV fleet grows to 117,492 vehicles, while diesel vehicles decline to 54,257 by 2050. Emissions decrease from 130.75 Mt. to 49.96 Mt., representing a 61.8% reduction, with AFVs accounting for 68.41% of the fleet. Compared to economic growth alone, infrastructure delivers stronger emissions reductions, demonstrating its enabling role. However, without complementary policy support, the transition remains partial, indicating infrastructure alone cannot drive full decarbonisation.

4.4 Comparative Analysis

Comparative results highlight distinct transition pathways across scenarios. The Policy Action scenario achieves the highest emissions reduction (91.6%), followed by Increased Infrastructural Development (61.8%) and Increased Economic Growth (45.4%). Transition dynamics differ significantly: economic growth leads to gradual adoption, with crossover around 2042, while policy action accelerates transition, reaching crossover by 2038 and rapid emissions decline between 2035–2045. Infrastructure-led transition is slower, with crossover around 2045 and steady emissions decline. These findings emphasise that while infrastructure and growth contribute, strong policy interventions are most effective in achieving rapid and deep decarbonisation (Fig. 2).

4.5 Sensitivity Analysis

Sensitivity analysis (Fig. 3), using $\pm 10\%$ parameter variation, indicates strong model stability. Variations remain minimal across key outputs, including emissions (5.92

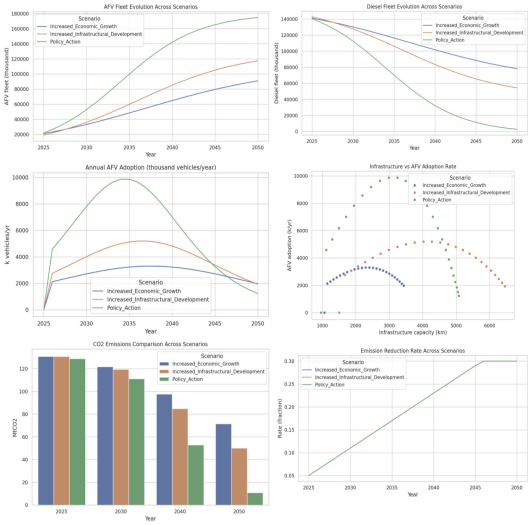


Fig. 2. Simulation results for different variable under three scenarios

$MtCO_2$), infrastructure capacity (200.264), and AFV fleet (~1,174 thousand). Energy efficiency also shows limited change, confirming robustness to parameter uncertainty and consistency of scenario trends, particularly under Policy Action.

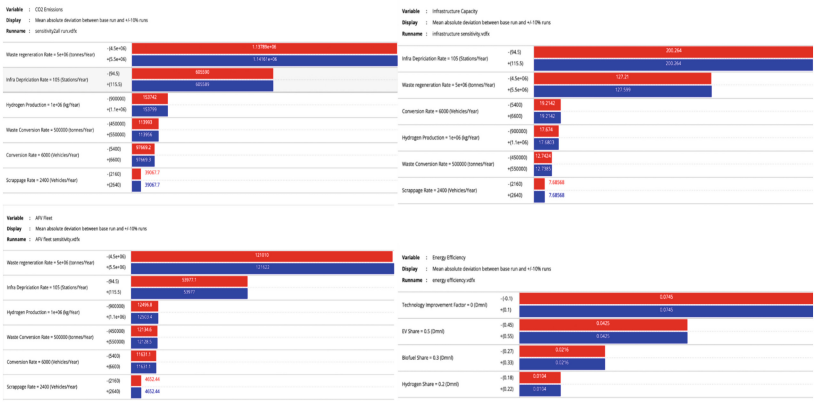


Fig. 3. Sensitivity analysis of variable in SD model

5 Discussion and Conclusion

The simulation results reveal distinct transition pathways across scenarios, highlighting the varying impacts of policy, infrastructure, and economic growth on freight decarbonisation. The Policy Action scenario achieves the highest emissions reduction (91.6%),

driven by strong fiscal and regulatory measures such as carbon pricing and subsidies, underscoring the critical role of policy intensity in accelerating AFV adoption. However, this represents an upper-bound outcome, contingent on sustained political commitment, financial resources, and institutional capacity. The increased infrastructural development scenario achieves a moderate reduction (61.8%), demonstrating that infrastructure expansion reduces adoption barriers but remains insufficient without complementary policy support. The Increased Economic Growth scenario delivers a lower reduction (45.4%), reflecting the limitations of market-driven transitions. However, the study has several limitations. The model simplifies complex socio-technical dynamics and relies on assumptions regarding technology, behaviour, and policy effectiveness. Data constraints and a limited number of stakeholder interviews may restrict representativeness, and long-term projections carry inherent uncertainty. Therefore, results should be interpreted as indicative trends rather than precise forecasts.

References

1. International Energy Agency (IEA): Global CO_2 emissions from transport (2023)
2. Johnson, D., Hensher, D.A., Nelson, J.D.: Modal shift policies for freight transport. Transp. Res. A Policy Pract. **132**, 45–60 (2020)
3. Li, S., Geerlings, H.: Decarbonising road freight transport. Energy Policy. **150**, 112134 (2021)
4. Forrester, J.W.: Industrial Dynamics. MIT Press, Cambridge (1961)
5. Shepherd, S.P.: System dynamics models in transport. Transp. Rev. **34**(6), 669–691 (2014)
6. Jonkeren, O., Jourquin, B., Rietveld, P.: Comparing system dynamics with other models. Transp. Res. Part E Logist. Transp. Rev. **126**, 52–69 (2019)
7. Thaller, C., Dahms, M., Clausen, U.: System dynamics in transport modeling. Transp. Res. Part E Logist. Transp. Rev. **97**, 1–14 (2017)
8. Piattelli, G., Lütke, D., Schade, W.: Modal shift modelling. Eur. J. Oper. Res. **139**(2), 323–338 (2002)
9. Han, J., Hayashi, Y.: CO_2 mitigation in freight transport. Transp. Policy. **15**(6), 357–367 (2008)
10. Liu, Z., Han, J., Zhang, X.: Trucking policies and modal shift. Transp. Res. Part E Logist. Transp. Rev. **103**, 27–41 (2017)
11. Choi, K., Lee, S., Kim, J.: Policy impact on modal shift. Sustainability. **11**(12), 3345 (2019)
12. Brito Junior, I., Oliveira, R.L.M., Yoshizaki, H.T.Y.: Modal shift in Brazil. J. Transp. Lit. **5**(3), 8–31 (2011)
13. Purwanto, A.J., Roda, C.: GLADYSTE model. Transp. Res. Part D: Transp. Environ. **16**(5), 375–382 (2011)
14. Seitz, C.: Stakeholder perspectives in system dynamics. Syst. Dyn. Rev. **30**(4), 245–263 (2014)
15. Kumar, A., Singh, R.K.: Freight decarbonisation in India. J. Clean. Prod. **384**, 135621 (2023)
16. Zhang, Y., Li, X., Wang, H.: System dynamics with machine learning. Transportation Research Part C: Emerging Technologies. **158**, 104424 (2024)
17. Ghisolfi, V., Chaves, G.L.D., Orlinski, C., Mattos, W.T.: System dynamics in freight decarbonisation: a review. Transp. Res. Part D: Transp. Environ. **103**, 103174 (2022)
18. Figgou, L., Pavlopoulos, V.: Unstructured interviews in social research. In: Flick, U. (ed.) The SAGE Handbook of Qualitative Data Collection, pp. 233–250. SAGE Publications, London (2015)

19. Nepveu, F.: Qualitative interviews and experience-based insights in transport research. Transp. Rev. **40**(4), 489–505 (2020)
20. Diaz, R., Marsillac, E., Ma, J.: Modelling the effects of public–private partnerships on transportation infrastructure development. J. Supply Chain Manag. **52**(3), 45–58 (2016)
21. Stelling, P.: Regulatory impacts on CO_2 emissions in transport: a European perspective. Transp. Res. A Policy Pract. **62**, 23–34 (2014)
22. Morecroft, J.D.W.: Strategic Modelling and Business Dynamics: a Feedback Systems Approach. John Wiley & Sons, Chichester (2010)

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Breaking Down the Barriers: The Evolution of Electric Truck Adoption in Transport System

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Abstract. Electrifying road freight offers substantial environmental benefits, yet logistics companies continue to face multiple barriers in implementation. Based on two interview rounds—two years apart—with 20 logistics operators, this paper examines how these barriers evolve over time. Some early challenges, such as limited charging infrastructure and driver resistance, have been partly resolved, while others persist, including uncertain total cost of ownership and risks to logistics performance. As operations scale, new barriers emerge: higher-than-expected maintenance needs, software reliability issues, energy losses during charging, and increasing coordination requirements with actors such as grid operators, insurers, and emergency services. The findings contribute to research by providing rare longitudinal evidence on how barriers to electric truck adoption shift as systems mature, highlighting the need for studies that better capture temporal dynamics and multi-actor dependencies. For practice, the results clarify which challenges can be mitigated early—through predictable routes, terminal charging, and internal training—and which require longer-term strategies, including managing TCO uncertainties, strengthening inter-organizational collaboration, and preparing for increased reliability and maintenance demands.

Keywords: Electrification · Road freight transports · Barriers · Transport system · Electric trucks

1 Introduction

Transitioning the road freight sector to a more sustainable way of goods transportation is crucial for reducing environmental impact. Electrification has emerged as a promising solution, demonstrating significant potential in mitigating this impact [1]. However, the adoption of electric trucks faces numerous barriers that challenge the current structure of transport systems [2]. These barriers include limited driving range, insufficient charging infrastructure, longer charging times compared to refuelling diesel, and higher upfront costs [2–5]. As a result, logistics companies must reconsider how they plan deliveries and determine which transport assignments are suitable for electrification.

Given that the adoption of electric trucks is still in its early stages, a certain degree of uncertainty and challenge is to be expected. As the technology matures and more actors enter the market, some of these uncertainties are likely to diminish [6]. However, many existing studies examine barriers at a single point in time, offering limited

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insight into which barriers arise during the initial transition, how they are handled, and which persist after implementation (see e.g. [3, 5]). This highlights several research gaps that the present paper addresses. Current research largely provides cross-sectional snapshots, giving little understanding of how barriers emerge, evolve, or diminish as operational experience grows. Empirical evidence is also limited regarding how logistics actors actively manage these challenges over time and which issues remain despite system maturation. From a practical perspective, this leaves logistics companies with insufficient guidance on what to expect during different phases of the transition and which adaptation strategies may support successful implementation. In response, the purpose of this paper is to deepen understanding of these barriers and their management throughout the transition to electrified road freight.

The remainder of the paper follows this structure. Section 2 presents the literature review and discusses barriers to electrification. Section 3 describes the methodology. Section 4 outlines the empirical findings. Section 5 provides the analysis and discussion. Finally, Sect. 6 presents the conclusions.

2 Literature Review – Electrification and Its Barriers

Several studies have examined the challenges—or barriers—associated with transition to electric trucks (see e.g. [2, 3, 5]). While different authors use varying terminology and categorization, there is considerable overlap in content, commonly addressed barriers include:

Technological and operational barriers: Limited range and long charging times make it difficult for electric trucks to match diesel trucks performance [2, 7]. Charging typically occurs at terminals, customer sites, or roadside stations, but infrastructure remains underdeveloped [5]. Additional concerns include reduced freight capacity due to heavy batteries and uncertainty around truck and battery lifespan [2].

Economic barriers: Electric trucks cost significantly more than diesel—up to three to four times higher [3]. While lower electricity and maintenance costs are expected due to simpler designs [2, 4, 7], these benefits are not yet fully realized. Additionally, there is strong political support for subsidizing investment costs and expanding charging infrastructure [3].

Policy and regulatory barriers**:** Shifting political agendas—such as changes in priorities—are often cited as a major concern. These shifts can affect financial support mechanisms, including incentives and subsidies, which may change or disappear rapidly [2].

Organizational barriers (inter- and intra-organizational): Major changes can lead to internal conflicts, especially if large investments are made [4]. For example, truck driver resistance is a commonly reported issue [2]. Inter-organizational challenges also arise, as the transition to electric trucks often requires deeper engagement with a broader range of actors, such as transport buyer and charge point operator [8].

3 Methodology

An interview-based paper was chosen since it can gain deeper insights into complex, non-observable phenomena [9, 10]. Two interview rounds were conducted with companies operating electric trucks. The first took place in 2022 and the second in 2024, allowing for a comparison of evolving experiences and attitudes. Two researchers held the interviews and took notes. Most questions remained consistent, with some additions in the second round based on market developments. Structured interviews were used, with identical questions posed to all respondents. Structured interviews were more suitable for this paper because the longitudinal design required a high level of consistency to enable reliable comparison across the two interview rounds. Unlike semi-structured interviews, this format minimized variation in questioning, making it easier to identify stable patterns and genuine changes in experiences over time (as suggested by [11]).

The interviews involved 18 logistics companies in the first round and 20 in the second, all operating electric trucks in regional transport flows within the same Nordic country. Most of the participating companies were the same across both rounds. While some companies were international, the questions focused solely on their operations within the same country. Some operated in a single region, while others operated across multiple regions. A convenience sample was used, as all companies were part of the same nationwide research project. This sampling approach was deemed appropriate, ensuring participation in both rounds and reflecting the limited number of companies that had invested in electric trucks at the time of the first interview. Respondents ranged from CEOs to logistics managers and transport planners, with each company selecting the individual most knowledgeable about electric trucks and their transport systems. All electric trucks had been put into operation between 2020 and 2022.

The full set of interview questions covered topics such as logistics systems, truck types, charging strategies, business models, and relationships with other actors. In total, each respondent answered more than 100 questions, some of which fall outside the scope of this paper. For the purposes of this paper, relevant questions were selected based on their alignment with the purpose of this paper. These included challenges faced, commonly cited barriers in the literature (e.g., financing, long-term viability, operational disruptions), and changes made between the two interview rounds (e.g., adjustments in transport or charging setups and the reasons behind them).

Each question was analysed inductively using content analysis to identify recurring themes and patterns, i.e. the themes needed to have been mentioned by several respondents, inspired by the thematic conceptual matrix approach outlined by Miles and Huberman [12]. The codes were inspired by different types of challenges or barriers. As a final step, the results from the inductive analysis were thematically compared with the barriers that are most reoccurring in the existing literature (also presented in the literature review of this paper).

4 Empirical Findings

4.1 Overview of the Transport and Charging Systems

Across nearly all logistics companies interviewed, installing charging infrastructure at company terminals was a common strategy. This was driven by limited public charging options early on and lower electricity costs at terminals. By the second interview round, the public charging infrastructure had been expanded, something that increased flexibility, enabling supplementary charging during, or between, assignments and serving as a backup when terminal chargers were unavailable.

In the initial phase (2020–2022), electric trucks were mainly used for short, predictable routes. As of 2024, these remain the primary use case, though many companies are now aiming for adding a shift. To support this, some companies required additional charging between shifts, which was not always feasible at the terminal. Consequently, public charging stations were used more frequently than anticipated, and driver changes were often conducted at these locations.

Operating charging infrastructure required new competencies, including knowledge of power peaks, wiring, local energy production, and storage. Some companies even created subsidiaries to manage these areas. Charger placement also posed challenges, such as avoiding collisions and dealing with non-standardized socket locations across truck models.

4.2 Main Challenges

Operational Reliability
Operational reliability was a key challenge in both interview rounds, with issues reported for trucks and charging infrastructure. A common concern was software problems at the truck-charger interface, especially in the second round, likely due to increased charger use from expanded shift schedules. These issues affected both terminal and public chargers, and some respondents even avoided certain public operators due to repeated reliability problems.

Hardware issues with trucks and chargers were generally rare and in parity to those seen with diesel vehicles. However, when they occurred, long wait times for parts or service technicians were frequently mentioned as an issue.

Another concern was the unpredictability of truck range. Many respondents, particularly in the second round, noted that weather, wind, and traffic often reduced range, sometimes leading to battery depletion and towing—causing delays and recovery challenges.

Total Cost of Ownership (TCO)
Operational reliability was a key challenge in both interview rounds, affecting both trucks and charging infrastructure. A frequent concern was software issues at the truck–charger interface, particularly in the second round, likely due to increased charger use as companies expanded shift schedules. These problems occurred at both terminal and public chargers, and some respondents even avoided certain public operators because of repeated failures. Hardware issues with trucks and chargers were generally rare and

comparable to diesel vehicles, but when they did occur, long waits for parts or service technicians were commonly reported. Unpredictable range was another major concern. Many respondents—especially in the second round—reported that weather, wind, and traffic often reduced range, occasionally leading to battery depletion and towing, which caused delays and added recovery challenges.

The Many Uncertainties
Despite years of experience with electric trucks and charging infrastructure, many logistics companies still face significant uncertainties. Four additional concerns were frequently mentioned. *High energy losses during charging were a recurring issue*, with some firms reporting losses of up to 10%, which increased costs, reduced operational range, prolonged charging times, and complicated logistics planning. Installing *chargers at terminals also introduced insurance- and safety-related obstacles*, as concerns about fire risks required additional insurance coverage, while the absence of standardized regulations meant that local authorities often made inconsistent decisions that caused delays. Nearly all respondents highlighted *long waiting times for securing additional power capacity*, with processes sometimes stretching up to a year and varying significantly between regions. Finally, as operations expanded to multi-shift schedules, companies faced *increasing difficulties in recruiting truck drivers* to meet staffing needs.

4.3 Strategies Applied

Internal Education: Interview 1 revealed resistance to electric trucks from both management and truck drivers. By the second round, truck drivers reported high satisfaction, especially with the quieter and more comfortable driving experience. Key training areas included driving techniques, charging procedures, and managing range anxiety—highlighting the importance of internal education for smoother integration. Also, transport planners were identified as needing targeted training to better understand electric truck operations. **Customer Collaboration**: Respondents stressed the need for close cooperation with transport buyers to support electrification. In some cases, long-term relationships facilitated the establishment of longer contracts (at least three years), thereby providing financial stability. Collaboration also enabled adjustments like delivery schedule changes, and in some industrial cases Even if such collaboration exist, they are still quite rare. **System Redundancy**: To manage emerging uncertainties, many companies emphasized building redundancy into transport systems—through flexible delivery schedules, varied charging locations, and robust TCO planning to handle disruptions.

5 Analysis and Discussion

5.1 Barriers That Are Partly Solved or Fully Resolved

The highest-ranked barrier in the study by [2], also noted by researchers such as [5], was the *lack of charging infrastructure*. This barrier remains only partly resolved, particularly at the international level. However, the findings indicate that initiating the development of chargers at terminals and installing some public chargers along road networks can significantly support the early stages of electrification—especially for regional and local deliveries.

Another frequently mentioned barrier (e.g. [4, 5]) is the *limited range of electric trucks*. While not all transport assignments are suitable, the findings clearly show substantial potential. This is particularly true for logistics companies with 'easy' transport assignments—those that are within range, predictable, and recurring. These findings align with the strategies presented in [3], which emphasize that predictability facilitates planning for charging and builds confidence in range, even under adverse weather conditions.

The *long charging time*, identified as a barrier by [2, 5], is only partly resolved, as it is still significantly longer than diesel refuelling. However, technological advancements are progressing, and increased power output is becoming feasible. Many respondents reported being able to charge at 300 kW, which was considered sufficient.

Truck driver resistance, noted by both [2, 3] highlighted in the first round of interviews, appears to have diminished. Thanks to experience and effective internal education, the second round of interviews revealed that truck drivers were very satisfied with electric trucks and highlighted several benefits.

5.2 Barriers That Are Still Relevant

A high TCO remains a widely recognized barrier (e.g. [2]), confirmed by this paper. Beyond cost, multiple uncertainties—such as vehicle lifespan, residual value [3, 5], volatile electricity prices, and shifting subsidies—complicate TCO calculations. Still, under favourable conditions like terminal charging and high utilization, electric trucks can achieve lower TCO. As infrastructure expands and the market matures, these uncertainties are expected to decline. It is however noteworthy, even among companies with 3–4 years of experience, TCO remains unpredictable and has only proven beneficial in select cases.

Truck weight, noted by [2, 3], continues to be a challenge for deliveries that are limited by the weight. Although this was not reflected in the findings—since transport assignments were carefully selected to suit the capabilities of electric trucks—the barrier remains.

Loss of logistics performance remains a concern, as previously noted by [3], especially with risks of fines or missed deliveries. This could be managed by improved collaboration with transport buyers (also suggested in [8]) since buyers' commission the services, their involvement is crucial to reducing environmental impact. Yet such partnerships are still rare, keeping performance risks high.

Finally, the *risk of lock-in*—where electric trucks are limited to specific types of assignments—remains relevant (identified in [6]), especially with multi-shift operations. Some companies have mitigated this by planning charging and truck driver change at public charging stations, but this approach needs further studies.

5.3 New Barriers Are Identified

Although earlier studies suggest *lower maintenance costs* for electric trucks (e.g. [2]), the findings here indicate higher costs and longer downtimes. This is mainly due to delays in spare parts, technician shortages, and limited service locations. While costs may

decrease as the market matures, this has not yet been observed among companies with 3–4 years of experience. The need *for stronger collaboration between actors*—previously noted by [3, 8]—was confirmed. Beyond transport buyers, this paper highlight cooperation with emergency services, insurers, and grid operators is essential to streamline processes and reduce regulatory inconsistencies that may hinder investment. *Software reliability*, especially at the truck-charger interface, emerged as a major issue, causing downtime and underutilization. This was reported by several respondent, that also used different software. This reflects a lack of system maturity and reinforces concerns about operational reliability, potentially discouraging stakeholder engagement. *Energy losses during charging* were a concern that affect the overall performance of electric freight systems, both in term of reliability and cost. Finally, while *truck driver shortages* are a known industry issue, the shift to multi-shift electric truck operations may intensify this challenge, making recruitment a growing barrier to electrification.

6 Conclusion and Contribution

This paper set out to deepen the understanding of the barriers to adopting electric trucks in road freight transport systems and how these barriers can be managed. Drawing on insights from 20 logistics operators who have used electric trucks for more than two years, the paper identified barriers that have been resolved (or partially resolved), those that persist, and new types of barriers that have emerged.

Barriers that have been (partly) effectively managed include the lack of charging infrastructure, limited range, and truck driver resistance. Persistent barriers include an uncertain and often unfavourable TCO and a loss of logistics performance. Newly emerging barriers include higher-than-expected maintenance costs, the need for tighter collaboration among several actors, and issues related to software reliability.

The paper shows that barriers to electric truck adoption change over time, highlighting the need for more longitudinal research that captures how challenges emerge, diminish, or persist as systems mature. The identification of new barriers—such as software issues, higher maintenance costs, and energy losses—also points to research opportunities in understanding system-level interactions and multi-actor coordination. For practitioners, the findings clarify which barriers can be addressed early through predictable routes, terminal charging, and internal training, and which require long-term strategies, such as managing TCO uncertainties, improving collaboration with transport buyers, and preparing for increased maintenance and reliability demands. Given the nature of the paper, the insights could also be used to understand potential policy interventions that could be applied to dimmish the most important barriers.

References

1. O'Connell, A., Pavlenko, N., Bieker, G., Searle, S.: A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels. International Council on Clean Transportation (2023) https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/. Last Accessed 27 Mar 2026

2. Sugihara, C., Hardman, S., Kurani, K.: Social, technological, and economic barriers to heavy-duty truck electrification. Res. Transp. Bus. Manag. **51**, 1–17 (2023)
3. Gillström, H.: Barriers and enablers: how logistics companies could tackle the transition to electrified road freight transport. Clean. Logist. Supply Chain. **13**, 1–8 (2024)
4. İmre, Ş., Çelebi, D., Koca, F.: Understanding barriers and enablers of electric vehicles in urban freight transport: addressing stakeholder needs in Turkey. Sustain. Cities Soc. **68**, 1–9 (2021)
5. Li, K., Acha, S., Sunny, N., Shah, N.: Strategic transport fleet analysis of heavy goods vehicle technology for net-zero targets. Energy Policy. **168**, 1–20 (2022)
6. Gillström, H., Björklund, M., Stahre, F., Abrahamsson, M.: Wired for change: sustainable business models in the transition towards electrified road freight transport. Clean. Logist. Supply Chain. **13**, 1–10 (2024)
7. Schiffer, M., Klein, P.S., Laporte, G., Walther, G.: Integrated planning for electric commercial vehicle fleets: a case study for retail mid-haul logistics networks. Eur. J. Oper. Res. **291**(3), 944–960 (2021)
8. Jobrant, M., Sallnäs, U., Gillström, H.: Commercial freight electrification: unravelling inter-firm coordination between logistics service providers and shippers. Int. J. Log. Res. Appl. **29**, 1–23 (2025)
9. Alshenqeeti, H.: Interviewing as a data collection method: a critical review. Engl. Linguist. Res. **3**(1), 39–45 (2014)
10. Kvale, S., Brinkmann, S.: Interviews. Learning the Craft of Qualitative Research Interviewing, 3rd edn. Sage Publications, Thousand Oaks (2009)
11. Bryman, A., Bell, E.: Business Research Methods, 4th edn. Oxford University Press, Oxford (2015)
12. Miles, M.B., Huberman, A.M.: Qualitative Data Analysis: An Expanded Sourcebook, 2nd edn. Sage Publications, Thousand Oaks (1994)

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Study on NOx Pollution Change of Railway Lines

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Abstract. The rail sector, although often seen as environmentally friendly, faces significant challenges in terms of emissions, especially for diesel locomotives. This article examines the current emissions situation in rail freight, with a particular focus on the impact of diesel engines and possible solutions. The impact of nitrogen oxides (NOx) is analysed by reviewing key studies and case studies. The primary aim of the article is to show how emissions from rail transport have changed between 2019 and 2023. Moreover, the causes of the changes. In addition, from a rail transport perspective, technical proposals are given to help railways to really reduce emissions of air pollutants from rail, since if we want to increase the share of rail transport, these solutions are essential to avoid a drastic increase in the emission of chemicals that are harmful to the environment.

Keywords: rail freight · NOx reduction · EGR system

1 Literature Review

Rail transport can play a key role in reducing air pollutants and greenhouse gas emissions, as it is one of the most environmentally friendly modes of transport. By increasing sustainability, rail can help address global climate challenges. The European Union aims to achieve full climate neutrality by 2050, which requires the development of rail infrastructure and the reduction of emissions from diesel locomotives. Currently, 56% of Europe's rail network is electrified, while the remaining 44% is still powered by diesel vehicles, which emit significant amounts of nitrogen oxide (NOx). Modernisation efforts include the introduction of technologies such as EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reduction) systems, which can significantly reduce emissions even from existing diesel locomotives. However, the introduction of new technologies and the modernisation of infrastructure impose significant financial burdens on railway companies. Maintaining and improving process efficiency in a liberalized railway market is crucial [1]. One of the most pressing issues for diesel locomotives is reducing the number of starts. Improving the starting system of long-distance diesel locomotives with supercapacitors allows for more frequent engine shutdowns without wasting fuel at

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idle [2]. This research is closely related to the consumption-based failure risk of diesel locomotives[3]. The design of the exhaust system also affects emissions, as turbulence can negatively affect combustion [4]. Operating dynamics, such as maximum acceleration and deceleration rates and idling times, are also significant factors in increased emissions [5]. Tests in South Korea have shown that real-world emissions from locomotives deviate significantly from the EPA TIER standard [6]. While a literature review has found a number of solutions, direct scientific analysis of NOx emissions is extremely rare, especially in the field of rail transport.

2 NOx Emission of Railways in Hungary

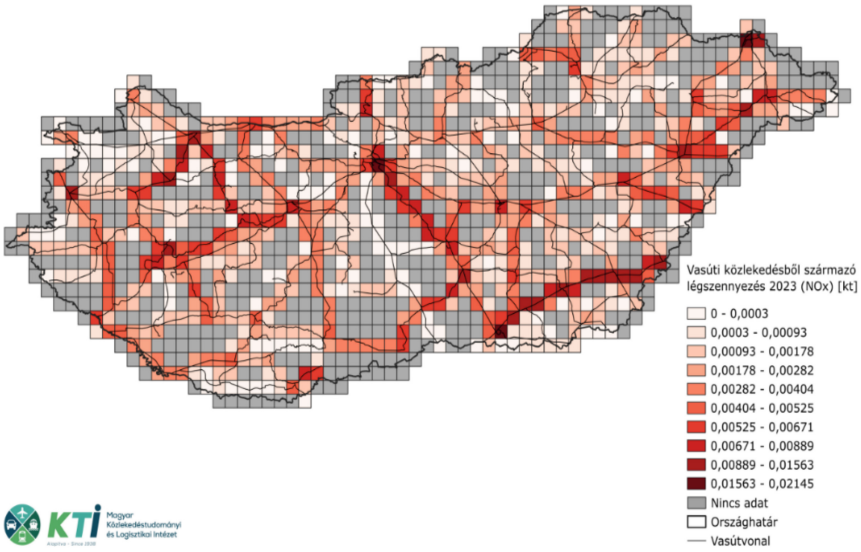


Fig. 1. NOx emission of Hungary in 2023

Large companies that require rail transport choose their partners not only on the basis of transport costs but also with regard to environmental considerations. Sustainable transport solutions, such as green logistics, are essential for maintaining competitiveness. The future development and competitiveness of rail transport depend on how service providers are able to integrate innovation and sustainability into their daily operations. We consider it important to present the distribution of emissions from rail passenger and freight transport across the Hungarian railway infrastructure network which Fig. 1 show. The annual aggregated pollutant emissions from mobile sources operated in domestic transport are laid down in Government Decree 306/2010 (XII. 23.) on the protection of air, later amended by Government Decrees 278/2014 and 133/2018. Using data collected by KTI and data provided by the respective infrastructure operators, a spatial allocation map of total emissions from mobile sources operated in rail transport in 2023 was created, broken down into 1,222 individual cells (0.1° x 0.1°) of the EMEP grid covering the entire territory of the country [7].

3 NOx Emission Changes on Hungarian Railway Lines (2019–2023)

We have conducted research on the Hungarian railway lines to find if there a change in NOx emission between 2019 and 2023, but because of the lack of data we could only set an interval for estimating the percentage change.

Table 1. NOx changes between 2019 and 2023 on different

Railway line number	Route	Emission changes between 2019 and 2023 in [%]	Number of passenger trains	Number of freight trains	Number of other trains	Electrification
2	Budapest (Rákosrendező) - Esztergom	[−130; −150]	42847	847	253	Yes
4	Esztergom-Kertváros - Almásfüzitő	[−130; −150]	3878	1148	233	No
5	Székesfehérvár - Komárom	[−250; −270]	3825	1232	375	No
8	Győr - Sopron - State border	[−20; −40]	16350	2942	1358	Yes
20	Székesfehérvár - Szombathely	[−40; −60]	51174	9382	4223	Yes
21	Szombathely - Szentgotthárd - State border	[−580; −600]	22365	2587	1085	Yes
25	Boba - Zalaegerszeg - Őrszentpéter - State border	[−20; −40]	21870	6361	2688	Yes
41	Dombóvár - Gyékényes -State border	[−80; −100]	9585	4043	1876	Yes
44	Székesfehérvár - Pusztaszabolcs	[−20; −40]	5481	36	429	No
45	Székesfehérvár - Sárbogárd	[−40; −60]	9734	50	441	No
135	Szeged - Kötegyán State border.	[−110; −130]	47518	740	544	No
1AR	Rákos - Rákos Junction	[−60; −80]	18551	2426	784	Yes
87A	Füzesabony - Eger	[−60; −80]	14400	311	277	Yes

Since Hungary has many railway lines, we will only represent those lines where significant pollution was registered, or considerable changes happened in this matter. To provide a clear methodology, we defined “extensive pollution” and significant lines as those handling more than 5,000 trains annually or where the estimated emission reduction exceeded 100%. The analysis clearly distinguishes between main lines and regional/branch lines. In addition, the correlation between the NOx pollution data and the

train numbers could only be estimated, as the timetable data are provided according to a different yearly system than the annual emissions data. For this reason, the timetable data covers only 70% of the total annual emissions, and therefore, only 70% of the timetable data were considered. Nevertheless, as the Eustat says in Hungary in 2023 541 diesel locomotive was in use, however, the national railway company (MÁV) has own 424. As a result, we know approximately 78.37% of the market in terms of vehicle numbers of emission data, making (Table 1) highly representative of the trend.

4 Proposed Solutions and Decarbonisation Pathways

To effectively reduce NOx emissions, multiple decarbonisation pathways must be evaluated, ranging from internal combustion engine upgrades to full network electrification.

4.1 Network Electrification (The Primary Goal)

As highlighted by European transport strategies, full electrification remains the ultimate goal for eliminating local railway emissions. Electrified lines produce zero direct NOx emissions. However, the capital expenditure (CAPEX) for electrifying regional lines is exceptionally high, often taking decades to realize. Therefore, transitionary technologies are required for the 44% of the network currently relying on diesel.

4.2 Use of the EGR and SCR (AdBlue) Systems

The role of the EGR valve in internal combustion engines is to reduce the emission of nitrogen oxides (NOx). The EGR valve recirculates part of the exhaust gas back into the combustion chamber where it mixes with fresh air. This allows the combustion chamber to burn at a lower temperature, resulting in less NOx formation which is shown on Fig. 2. In the case of the AU 32 (Adblue) [8], the measurements show that there are significant benefits of the Adblue system, as the NOx emissions are significantly reduced. The maximum emission drops from nearly 1400 ppm to 350 ppm when using AdBlue which is shown on Fig. 3.

4.3 Hybrid Locomotive Retrofits

As an alternative to pure diesel operation, retrofitting older shunting and mainline locomotives with hybrid drivetrains (diesel-electric with battery storage) provides high operational flexibility. For instance, in Switzerland, hybrid drivetrains were installed in Aeam 841 locomotives, significantly reducing fuel consumption. This allows locomotives to cut down local NOx emissions.

4.4 Auxiliary Shore Power Systems

A major contributor to NOx pollution is engines idling at stations and directing yards. Implementing auxiliary shore power systems allows locomotives to plug into the local electrical grid while stationery, maintaining vital onboard systems without running the main diesel engine.

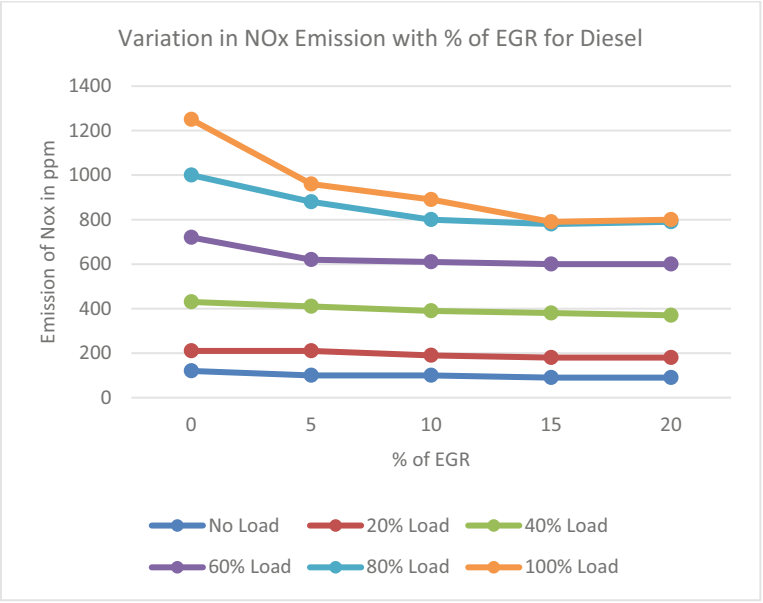


Fig. 2. EGR valve application testing

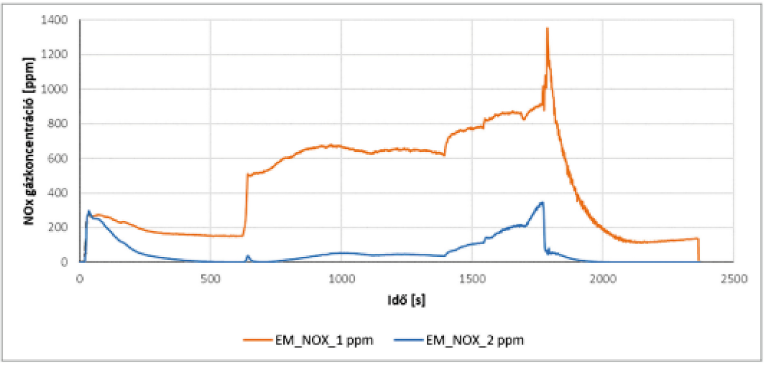


Fig. 3. Testing the use of AdBlue

5 Economic View for Locomotive Refurbishment Proposals

Hungarian Railways Company (MÁV Zrt.) in total, operates 223 diesel multiple units, mainline locomotives, or shunting locomotives with engines less than 30 years old, averaging approximately 20 years of age. Based on our approximate estimate, calculating the full cost of installing EGR at 30 million HUF (~75,900 EUR) per vehicle, significant reductions in air pollution could be achieved for the remaining 10–15 years of operation at a total cost of 6,690 million HUF (~16.92 million EUR). Out of this, the investment cost

for the 142 multiple units, which together deliver approximately 120 million passenger-km annually, amounts to 4,260 million HUF (~10.77 million EUR). According to the Handbook on the External Costs of Transport (van Essen, 2019), the air pollution of diesel-powered regional trains without EGR/SCR causes additional damage of 4.9–8.2 EUR per 1,000 passenger-km compared to trains equipped with EGR/SCR. With EGR, the estimated external cost savings of around 6 EUR per passenger-km translate into 720,000 EUR in annual environmental savings at 120 million passenger-km. Adjusted for the cumulative 16.6% euro inflation (2016–2024), a 10.1% economic growth (based on GDP elasticity of 0.8), i.e. indexed by a total of 28.4%, this corresponds to 924,800 EUR (~365.5 million HUF at the 2024 MNB average exchange rate of 395.20 HUF/EUR) in annual environmental benefit. This level of benefit suggests that, particularly for the most intensively used vehicles, the investment may also prove to be economically viable. Therefore, it would be advisable to link excise duty exemptions on railway diesel fuel to the application of EGR/SCR systems for vehicles equipped with diesel engines manufactured after 2000 but not fitted with such systems, especially in the case of railway companies with fleets of older, less favorable age distribution.

6 Conclusion

This study focuses on reducing nitrogen oxide (NOx) emissions from diesel locomotives in Hungary, presenting technological solutions (EGR/SCR systems) and their economic returns. Its main finding is that significant NOx reductions have been observed on Hungarian railway lines (2019–2023), and modernizing aging fleets is economically justified due to environmental savings. Modernizing aging fleets with EGR/SCR systems represent a highly cost-effective, transitional decarbonization pathway compared to the massive capital requirements of immediate full-scale electrification. However, realizing these environmental benefits requires overcoming several broader barriers: Regulatory Barriers: The primary recommendation is to link excise tax incentives to EGR/SCR systems, which would directly encourage the retirement or refurbishment of the heaviest polluting vehicles. Currently, a lack of cohesive tax penalization for older vehicles slows down the phase-out process. Infrastructural Barriers: Widespread adoption of SCR systems requires robust logistical support, such as building reliable AdBlue filling networks. Similarly, reducing idling emissions necessitates infrastructure investments in auxiliary shore power systems at major directing stations. Technical Barriers: Upgrading the oldest segments of the fleet poses physical challenges. Legacy locomotives (such as the M41 series) often lack the spatial capacity to safely house modern exhaust aftertreatment systems. In such cases, phased retirement or complete hybrid-re-motoring must be prioritized. By addressing these regulatory, infrastructural, and technical hurdles, rail transport can secure its position as a truly sustainable pillar of the European transport network.

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References

1. Šperka, A., Vojtek, M., Široký, J., Čamaj, J.: Improvement of the Last Mile-Specific Issues in Railway Freight Transport. Sustainability. **12**(23) (2020). https://doi.org/10.3390/su122310154
2. Malozyomov, B.V. et al.: Study of Supercapacitors Built in the Start-Up System of the Main Diesel Locomotive. Energies. **16**(9) (2023). https://doi.org/10.3390/en16093909
3. Baranovskyi, D., Bulakh, M., Michajłyszyn, A., Myamlin, S., Muradian, L.: Determination of the Risk of Failures of Locomotive Diesel Engines in Maintenance. Energies. **16**(13) (2023). https://doi.org/10.3390/en16134995
4. Benek, G., Ozsoysal, O.A.: Influences of the dead end on the flow characteristics at the exhaust manifold of a marine diesel engine. J. Therm. Eng. **7**(6), 1519–1530 (2021). https://doi.org/10.18186/thermal.991095
5. Urbański, P., Huang, Y., Gallas, D., Zhou, J.L., Merkisz, J.: Real-world assessment of the energy consumption and emissions performance of a novel diesel-electric dual-drive locomotive. Sustain. Energy Technol. Assess. **71**, 104017 (2024). https://doi.org/10.1016/j.seta.2024.104017
6. Kim, M.-K., Park, D., Kim, M., Heo, J., Park, S., Chong, H.: A Study on Characteristic Emission Factors of Exhaust Gas from Diesel Locomotives. Int. J. Environ. Res. Public. Health. **17**(11) (2020). https://doi.org/10.3390/ijerph17113788
7. Balázs, D.: Nemzetközi Közlekedéstudományi Konferencia. https://cots.sze.hu/cots22archiv. Last Accessed 12 Mar 2026
8. Akiyoshi, T., Torisaka, H., Yokota, H., Shimizu, T., Ninomiya, H., Narita, H.: Development of efficient Urea-SCR systems for EPA 2010-compliant medium duty diesel vehicles. In: SAE 2011 World Congress & Exhibition, pp. 2011-01-1309, Detroit, Michigan (2011). https://doi.org/10.4271/2011-01-1309

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From Energy Communities to Mobility Communities

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Abstract. For several years, we have seen a steady increase in both private electric vehicles (EVs) and residential PV systems. However, the mobility patterns of EV owners often do not perfectly align with the generation patterns of their PV systems. This raises a key question: How can surplus solar energy, not immediately needed for household consumption, be effectively used to charge EVs?

While stationary energy storage solutions like batteries can be installed, they are often costly and, in most cases, lack sufficient capacity. This is where the concept of mobility communities comes in. Our idea is to expand existing energy communities (ECs), enabling members to charge their EVs at other EC members' charging stations, for instance, while commuting or traveling.

This paper explores how the business model of an energy community needs to be re-structured to ensure the economic viability of newly introduced mobility communities. This study paid attention to the additional hardware and software solutions required to guarantee fair accounting among EC members. Business models built upon these technological solutions are presented.

Keywords: Energy Community · Mobility Community · Self-Consumption

1 Introduction

Three developments (relevant for this work) are currently taking place: the increase in the number of *photovoltaic systems*, the increase in the number of *electric vehicles*, as well as the implementation of *energy communities*. Let us investigate both developments in more detail: Although EVs are not new at all [7] only in recent years the number of new passenger vehicles with electric drive trains significantly increased (even though there was a small drop in 2024) [4]. This comes with some major issues: First, the number of charging stations needs to be adapted accordingly. While it can be assumed that private owners will most probably take care of installing a private charging station at their private home, public charging stations which are used especially during

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long-distance trips or when visiting points of interest (POI; e.g., shopping) need to be built. Even though slow charging might be possible with public charging stations more focus is laid on fast-charging devices (often also referred to as high-performance charging). The extension of the fast-charging network is, among others, addressed in the AFIR (Alternative Fuels Infrastructure Regulation) [3] of the European Commission. Therein, it is regulated that public accessible charging stations need to be built along the main corridors (TEN-T network) according to specific regulations, e.g., minimum power specifications and reachability requirements.

Second, the number of private photovoltaic systems (PVs) significantly increased during the last years [1]. Although some of these PVs are owned by public bodies or companies, a significant number is privately owned as well. Regardless of the owner, a coordination of PVs and EVs is necessary to gain synergies. eg., charging cars with (relatively) cheap electricity, reducing the strain on the grid.

Third is the implementation of energy communities (ECs) in Austria. Being among the first EU countries with a legal framework, an impressive number of at least 1650 ECs have been implemented [2]. The basic idea of ECs is that community members can share community-generated electricity to their own terms. A combination of PVs, ECs, and s is obvious as the operational costs of driving can be decreased even further this way. However, so far, this combination only went as far as using community-generated electricity for charging when the cars are plugged in "at home". Therefore, it is also not possible to charge your own car with electricity from your PV system when you are not at home. The obvious next step is to introduce *mobility communities* where it is possible to consume your "own" electricity even in these cases. Even though the very basic concept is quite simple (i.e., all charging-stations to be used for charging need to be part of "your" energy community) a practical implementation needs to be planned accordingly and some pitfalls and caveats need to be overcome.

The main contribution of this paper is the conceptual introduction of mobility communities which allow charging self-generated energy even when not being at home. Pre-requisits will be discussed in addition to the introduction of a basic business model how mobility communities can be operated.

The remainder of the paper is as follows: In the next section, we introduce the concept of mobility communities (MCs) in more detail. Further, we address the main prerequisites in order to establish a MC. Then, we present business models for MCs. Conclusions summarize the findings and address next necessary steps for a successful implementation.

2 Mobility Communities

The basic idea of *Mobility Communities* is to enable persons owning both, an electric vehicles (EV) and a photovoltaic sytem (PV), to charge their car with their "own" produced electricity even then when the EV is not "at home". In the following, let us discuss why we think that this concept is necessary and brings an improvement compared to the status-quo.

2.1 The Concept of Mobility Communities

With the recent and projected surge in electric vehicles, it is necessary to think about how they will be charged. Obviously, the first initiative should be to install EV chargers at home, i.e., the location where the vehicle is parked the most time. This brings some advantages: E.g., parked EVs can be used for minimizing curtailment of renewable energy resources when applying smart charging [8]. If vehicle-to-grid (V2G), i.e., bidirectional charging, is possible benefits might also be gained for the vehicle owners [6]. However, this is only possible, if cars are parked (and connected) to the grid. Therefore, the goal should be to connect vehicles as much as possible. Obviously, providing charging stations at work, facilities for leisure activities, etc. should be the overall goal. This would, however, lead to a massive surplus of charging stations compared to EVs. At the same time, EV drivers owning a PV as well would prefer to not charge at remote locations due to economic reasons and therefore this surplus of charging stations is potentially unused. At the same time, the EV charger at home is unused while the vehicle is used for commuting, shopping, etc.

Therefore, we suggest to enable charging for EV users at remote private stations under certain conditions. While the owner of a (private) EV charger is not at home, other people can connect to this device, e.g., during working hours. Obviously, it is necessary to ensure that costs imposed by the foreign vehicle are covered by the owner of this car, cf. Sect. 2.3. If the foreign owner themselves owns a PV system at home, they would prefer to charge their vehicle with their own energy, see Fig. 1. From the electrical viewpoint this can be realized via the concept of *energy communities* (EC). Therefore, mobility communities are extended energy communities where EC members can charge at other MC members' charging stations. Please note, this concept can be further extended such that not only private persons can participate but companies and their employees can be integrated as well.

2.2 Prerequisites for Mobility Communities

In order to facilitate MCs some technological as well as organisational prerequisites are necessary. It is necessary that private charging stations are easily accessible for other MC members.

- E.g., EV charger should not be installed in the closed-access garages. In addition, in many countries, it is not permitted to run charging cables across sidewalks. That is, parking on private ground next to an accessible charger for other MC members should be possible.
- While typical private EV chargers are normally relatively low-tech with respect to user authentification and authentication, more elaborated devices are necessary when non-owners should be able to use the device as well.
- Furthermore, we must accurately track the energy used by both owners and non-owners in order to provide correct billing.

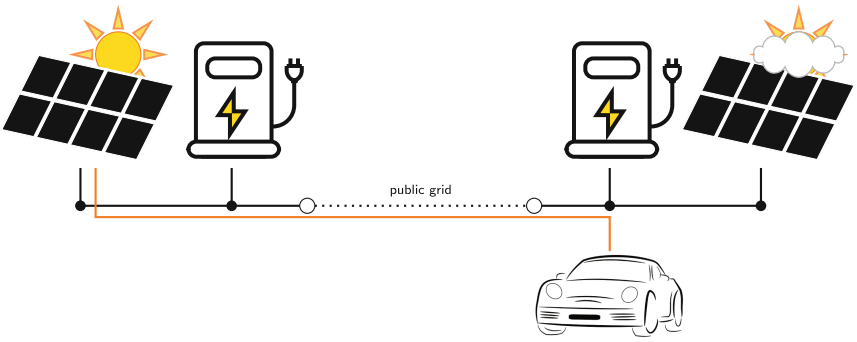


Fig. 1. Schematic diagram of a mobility community, showing a car being charged at a fellow member's station using electricity produced at the car owner's home as the PV system at the fellow's location does currently not produce energy. (source: car from pixabay.com by Ahmad Kamel)

2.3 Business Model for Mobility Communities

While different business models for energy communities already exist [5], it is necessary to come up with an economic viable model for mobility communities as otherwise the economic benefit for members would not be given. For this purpose, it is necessary to identify stakeholders in setting up MCs.

Mobility Community. According to (Austrian) law, a energy community (which is the base for an MC) needs to be a legal entity. Regardless of regulatory requirements, the MC must be treated as a whole. It is necessary, that the business model applied ensures that the MC balances the books at the end of a year. Therefore, either no costs should be covered by the MC (but directly by its members) or an income needs to be realised.

MC Member. In most cases, people will participate at MCs for one obvious reason: economic advantage. To achieve this, it is necessary to ensure that the costs imposed by participation are less than the (financial) benefits. Further, it is crucial that a correct accounting is realised when members charge at remote EV chargers.

Third-Party Service Provider (TSP). As already outlined in the prerequisites section, it is necessary that some additional technical devices are installed at MC members' homes. While it would be theoretically possible that these devices are commissioned, operated and maintained by the MC (or even the MC members) on their own, in most cases it will be more convenient when a third-party service provider provides the technological as well as organisational support. As in most cases this will be a company, coverage of costs plus surplus is necessary.

This leads to the following considerations: MCs need to be set up as ECs in the first place. Furthermore, the MC requires a TSP, who can take on one of two

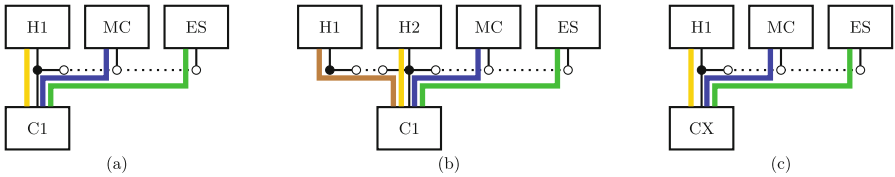


Fig. 2. Schematic representation of possible charging scenarios. H1 and H2 represent two households being member of the MC. MC stands for other households being part of the MC. ES represent an energy supplier. C1 represents the car of household H1 while CX represents a car of a non-MC member. Continuous lines represent power lines behind the meter. Dotted lines represent the public grid. In (a) three different energy flows for charging the car at home are shown. In (b) possible energy flows for charging the car at a remote location are shown. In (c), possible energy flows are shown when non-MC members charge their car at MC charging stations.

roles: a pure external service provider for management and technical services, or an integrated member of the mobility community. The latter case is especially then relevant when the TSP will not only manage and account energy flows but will also act as an energy provider (e.g., due to its own PV system). For the further context, we assume that the TSP acts only as external service provider.

In addition to "classic" EC energy flows, the following mobility related energy flows need to be considered:

- An MC member charges the car at home. Energy is provided either by the own PV system, through the MC (from other members' PV systems), or via the public grid. Accordingly, the costs incurred are either zero, the internal community price, or subject to public tariffs. See also Fig. 2a.
- An MC member charges the car at another MC member's home. Again, energy is provided either by the own PV system (but at a remote location), by the remote location's PV system, through the MC (from PV systems in the MC but not "at home" or the remote location), or via the public grid. Prices need to be adjusted accordingly. See also Fig. 2b.
- A non-MC member charges the car at a MC member's location. Obviously, it is also possible that non-MC members charge their car at charging location made accessible to the public by the MC. In this case, a similar situation is given as in the first case with respect to cash flows. The energy is either provided by the charging stations owner's PV system, by the MC, or via the public grid. Costs are adjusted accordingly. See also Fig. 2c.

The assumed prices can be generalised as follows:

$$
\begin{aligned}
p &= p_e + p_g + c_{\mathrm{TSP}}, \text{with} \\
p_e &\quad \text{price for energy} \\
p_g &\quad \text{price for grid usage} \\
c_{\mathrm{TSP}} &\quad \text{costs for management by TSP}
\end{aligned} \tag{1}
$$

Please note, that not all price components always apply. E.g., when the car is directly charged from a PV system, grid usage tariffs do not apply. The relevant price components can easily be derived from Fig. 2. In addition, p_e will be adjusted according to the source/use case. E.g., higher prices will be used for non-MC members compared to MC members. However, it is important to keep in mind that the total price p must not be higher than tariffs at public charging stations as otherwise even MC members will use the public charging stations and the benefits with respect to hardware utilisation rates do no longer apply.

Finally, we want to address the management charges c_{TSP}. Those can be chosen arbitrarily. Charges can be structured in two primary ways:

- Fixed Rate: A fixed monthly or yearly rate guarantees predictability of income for the TSP. However, this approach results in variable energy prices for the customer, as the per-unit cost depends on the total energy consumed.
- Consumption-Based Rate: Alternatively, charges can be set as a fixed amount per kWh. While this leads to well-defined energy prices for the customer, it inherently introduces a small risk for the TSP regarding fluctuations in usage.

3 Conclusions

This paper introduced *Mobility Communities* (MCs) as the next-level extension of *Energy Communities* (ECs) defined by the European Commission. With this concept, it is possible to remotely charge the "own" energy produced by one's PV system. However, some prerequisites are necessary: First, the remote charging station needs to be member of the same MC. Second, additional (smart) devices must be installed at all MC members' locations to ensure accurate energy accounting. Normally, it is most convenient when those devices are provided and operated by a third-party service provider. Third, the composition of the energy prices needs to be chosen carefully such that all participants benefit from the MC membership. However, the changes to classic ECs are rather small and an implementation is straight forward opening a rather interesting field for e-vehicle owners who possess their own PV system at home.

For future work, it is necessary to extend this concept with two additional aspects: First, it is necessary to examine how the accounting concepts need to be adapted when not only private persons but also companies are being MC members. It can be assumed that in those cases, these new members might also provide more powerful charging stations which will lead to additional pricing conditions. Second, local battery electric storage systems (BESS) need to be considered in two settings: On the one hand, they might be locally installed at some MC members' homes. It can be assumed that they can then be treated quite similar to PV systems for accounting rules. On the other hand, *community storages*, i.e., BESS that are possessed by the MC, need to be considered as in this case, for example, grid usage tariffs need to be paid twice (during charging and during discharging).

Further, we want to highlight that important factors like user acceptance or financial and ecological issues need to be discussed in more detail. Unfortunately, the supporting project is not yet progressed so far that we can answer these questions. This will, however, be done in the future works.

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References

1. Biermayr, P., et al.: Innovative Energietechnologien in österreich Marktentwicklung 2024 (2025). https://nachhaltigwirtschaften.at/resources/nw_pdf/schriftenreihe-2025-23a-marktstatistik-2024.pdf
2. E-Control: Eag-monitoringbericht 2024 (2024). https://www.e-control.at/eag-monitoringbericht
3. European Commission: Regulation (eu) 2023/1804 of the european parliament and of the council of 13 september 2023 on the deployment of alternative fuels infrastructure, and repealing directive 2014/94/eu (2023). https://eur-lex.europa.eu/eli/reg/2023/1804
4. EUROSTAT: New passenger cars by type of motor energy (2025). https://doi.org/10.2908/ROAD_EQR_CARPDA
5. Fina, B., Monsberger, C.: Measures and business model approaches to facilitate the diffusion and integration of energy communities - a special focus on the austrian case. Energ. Strat. Rev. **49**, 1–11 (2023). https://doi.org/10.1016/j.esr.2023.101161
6. Micari, S., Napoli, G.: Electric vehicles for a flexible energy system: challenges and opportunities. Energies **17**(22) (2024). https://doi.org/10.3390/en17225614
7. Mom, G.: The Electric Vehicle: Technology and Expectations in the Automobile Age. Johns Hopkins University Press, Baltimore (2013)
8. Sadeghian, O., Oshnoei, A., Mohammadi-ivatloo, B., Vahidinasab, V., Anvari-Moghaddam, A.: A comprehensive review on electric vehicles smart charging: solutions, strategies, technologies, and challenges. J. Energy Storage **54**, 105241 (2022). https://doi.org/10.1016/j.est.2022.105241

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Energy Consumption and GHG Emissions Forecasting in Positive Energy Districts (PEDs) Under Increasing EV Penetration and Travel Demand Management Strategies

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Abstract. Effective energy balancing and Greenhouse Gases (GHG) reduction in Positive Energy Districts require precise forecasting of the often-overlooked impacts of the transport sector within the intervention zone, especially considering growing Electric Vehilce (EV) impacts to the local energy grid. This study, presents a novel approach using microscopic traffic simulation to accurately predict transportation energy demand and emissions within PEDs. Varying scenarios of future adaptation to increased EV adoption rates and campus-relevant travel demand management strategies, such as parking pricing and carpooling schemes. At the input side, the simulation engine is supported by highly granular demand data captured via traffic monitoring video sensors with plate-reading capabilities, leveraged to derive a detailed energy/emission profile for each vehicle by querying the local vehicle registry API. Results show that the framework captures well the spatio-temporal dynamics of pollution and energy consumption, specifically identifying PED-relevant EV charging loads and pollution hotspots in BAU and extreme situations. These findings can directly inform critical policy decisions concerning EV infrastructure scaling for local grids, the application of EV charging management strategies and the improvement of local air quality.

Keywords: Microscopic traffic simulation · Positive Energy District (PED) · Traffic Management Strategies · GHG reduction · Electric vehicles (EVs)

1 Introduction and Study Background

Latvia's transport sector represents 27% of the total final energy consumption, underscoring its significance as an energy-intensive sector. Road transport emits more than any other sector in Riga, Latvia's capital, besides electricity and heating, and has grown by a quarter since 1990 [1], a trajectory that has placed vehicle electrification at the forefront of efforts to reduce the environmental cost of internal combustion engine (ICE) vehicles [2]. Adoption of electric vehicles (EVs) has accelerated significantly over the last few years. In Europe, one in twenty new vehicles are electric, while the worldwide electric vehicle fleet is predicted to grow to 250 million vehicles by 2030 [3].

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While electric vehicles assist in decarbonizing personal motorized travel, they do not address other structural inefficiencies such as low occupancy, space consumption, and congestion. Transportation Demand Management (TDM) measures, midway between engineering and behavioral sciences, offer a different approach, shifting their focus to behavioral change rather than techno-centric solutions. TDM proposes both hard ("stick") actions (regulation and economic disincentives like parking fees) and soft actions ("carrot") meant to increase the appeal of alternatives, e.g., public transportation development or encouraging people to carpool [4–7]. Evidence has linked TDM with several benefits, such as decreased congestion, cost savings to the users, improved safety, improved modal equity, and benefits to the environment [8, 9]. University campuses are especially promising locations for implementing TDM, since they exhibit focused activity patterns, bounded communities, and typically high levels of environmental conscience [10–12].

Ultimately, reaching sustainability targets in Positive Energy Districts (PEDs), which play a central role in several major environmental EU initiatives [13], requires considering energy consumption and emissions caused by transportation [14]. Although transportation is not included in most PED calculations, it is particularly relevant given the sector's substantial energy demand which is comparable to that of the EU building stock (which in turn is never omitted from the calculations) [15]. The continuous trend of electrification also ties electricity consumption of EVs to the local energy grid, whose efficient operation is essential to PEDs [16]. Equally, an assessment the energy consequences of TDM interventions across the district can assist understanding how citizens respond to parking pricing strategies, and incentives for alternative modes [17]. While literature has seen the need for the evaluation of EV impacts at the district or city scale [18–20], to our knowledge, the effects of TDM measures within a PED context have not yet been modelled.

In this context, the objectives for the present study include the modelling of traffic flows inside a PED district at the microscopic level leveraging highly granular video-based traffic monitoring sensors coupled with plate-reading capabilities. This facilitates a thorough assessment of present and projected energy demand, and pollutant emissions from the level of single vehicles to the complete PED scale. The study further assesses the implications of electric vehicle adoption and how traffic management strategies can save energy and reduce pollution by changing travel patterns to and from the campus.

The remainder of this paper is structured as follows. The methodology is described in Sect. 2, covering the traffic microsimulation framework and its application to a case-study PED zone. Section 3 discusses the results, and Sect. 4 concludes with the key insights, limitations, and directions for further research.

2 Methodology

2.1 Traffic Microsimulation for the Estimation of Energy Consumption and Pollutants Emissions

The traffic flow in this study is simulated microscopically, meaning every vehicle that moves within the simulated network is modelled individually, having a certain place and speed. Travel demand inputs, represented as individual vehicle trips within the

simulation area, can be reconstructed through video-based traffic monitoring, a method that effectively facilitates (and automates) vehicle detection and classification. In this work, the simulation is set up in Simulation of Urban MObility (SUMO) open-source traffic simulation package.

The Handbook Emission Factors for Road Transport (HBEFA) v4.2 methodology [21] is applied to estimate exhaust output and energy consumption based on the simulated vehicle dynamics. Emissions and fuel consumption are estimated from polynomial functions of velocity and acceleration, for different vehicle classes. The energy model also considers EV energy consumption, where changes in a vehicle's energy state are calculated by summing kinetic, potential, and rotational energy gains across time steps, minus energy losses due to drag forces.

The simulation model estimates electric energy consumed *within* the simulation zone. This value does not correspond directly to the electricity required from the campus grid during EV charging, since vehicles primarily recharge energy that was consumed during trips outside the campus.

To calculate the electricity demand on the grid, charging demand, and vehicle and charger characteristics are considered. Evidence from large workplace EV studies indicates 0.88 charging sessions per driver per week (0.15 per weekday), meaning that approximately 15% of drivers plug in on a typical workday [22]. The total number of EVs arriving daily on campus depends on demographics, demand management strategies, and EV penetration rates. Their calculation is presented in later sections of this study. On vehicle characteristics, a representative EV battery capacity of 50 kWh is assumed. With a state of charge (SOC) increase from 20% to 100%, each charging session requires 40 kWh. Eventually, 50 kW DC charging stations deliver 137 kWh per day per station on average in similar contexts [23].

2.2 Case Study: The RTU Positive Energy District

The Riga Technical University (RTU) campus in Riga, Latvia, is delineated as a Positive Energy District (PED) zone. The site serves as a case study for the EU Commission-funded H2020 exPEDite Project, and there is a declared institutional intent to develop infrastructures that support a PED.

Travel Demand Data from Video Sensors with Plate-Reading Capabilities. The location of RTU on the Ķīpsala island offers convenient geographic characteristics that enable the establishment of a cordon line for the monitoring of inbound and outbound traffic through a limited number of video sensors procured for exPEDite and positioned at entry and exit points. The resulting database consists of a series of 24-h timeseries of multimodal traffic flows, capturing every vehicle that enters, leaves, or passes through the campus.

To reconstruct the vehicle behavior within the campus once the entry and exit points of vehicles have been established, we adopt the assumption that vehicles follow a simple pattern: entry, parking, and departure. This assumption is validated by the small zone size and local knowledge: internal movements between campus buildings occur almost exclusively on foot. The specific parking location for each trip is determined by mapping available and frequently used parking spaces over time using digital historical imagery

and on-site fieldwork. Each simulated vehicle selects the shortest path to a parking location and the probability of a specific parking facility being chosen is modeled as proportional to its average occupied capacity.

After establishing the trip chain, the vehicle type is identified by matching license plates from the sensor data to Latvia's official vehicle registry (CSDD) via its API. The registry provides detailed information, including vehicle class, fuel type, and emission standard (EURO), which are directly coded into SUMO to create the individual vehicle profile for the trip.

Eventually, the multimodal microsimulation-compatible route definitions have been established for the "typical day" between 25 April 2025 and 10 June 2025, after excluding passthrough movements, non-relevant or misclassified objects and anomalous periods such as holidays, characterized by atypically low traffic volumes.

Mobility Scenarios for RTU in 2035. Five scenarios are modeled based on three transformative forces: Policy, Demographics, and Technology. Policy and Demographic changes shape the overall *demand* for travel to and from RTU. Technological change, on the other hand, redefines the *characteristics* of the vehicle fleet, driving the transition from ICE vehicles to EVs.

Evolution in Demographics: RTU has 13,760 students and 1,416 staff, with trends shaped by growth in engineering and internationalization but offset by Latvia's demographic decline. For 2035, stakeholders validated three scenarios: a 20% decrease, a 20% increase, or stability in RTU population and travel demand.

Evolution in Policy: A TDM bundle combining parking pricing around campus and the introduction of an organized carpooling scheme is considered for RTU. Initial literature-review based projections of the impact of the scheme on travel demand consider three pathways. The first limited success for the carpooling scheme and the parking pricing system with spillover of parking demand to places around the campus, with little or no reduction in private vehicle use. The second pathway anticipates a moderate effect, with a reduction of about 9% in car travel demand. The third pathway projects a 17% demand shift. This estimate is drawn from the long-term experience of the University of Bristol [24]. The Bristol case is considered especially relevant, as its urban context, implementation design and timeline comparable to those of RTU.

Evolution in Technology: Fleet electrification will make private cars GHG-emission free at the scale of the PED zone. Three electrification pathways for 2035 are adopted from the International Energy Agency [3] annual electromobility barometer, which respectively consider a 25% (Stated Policies Scenario), 30% (Announced Pledges Scenario) or 40% (Net Zero Emissions Scenario) penetration of EV vehicles in the total fleet.

A combination of the above pathways leads to the creation of 5 scenarios. that form the description of the state of the RTU campus in 2035. The Most Likely (ML) scenario serves as the baseline, assuming moderate demand shift (+9%) and 30% EV fleet penetration with no change in RTU population. The Optimistic (OPT) scenario combines strong behavioural change (including a 20% reduction in RTU population and a 17% demand shift away from private car use) with rapid electrification reaching 40% of the fleet. Conversely, the Pessimistic (PS) scenario assumes slow electrification (25% EV penetration), no meaningful demand management, and a 20% growth in RTU population.

The final two scenarios isolate competing decarbonization pathways. The Behavioural-Shift (BS) scenario assumes effective demand management policies reduce private travel (17% shift) but electrification remains slow at 25%. The Techno-centric (TC) scenario assumes the opposite: travel habits remain unchanged, but vehicle technology improves significantly, achieving 40% EV penetration.

3 Results and Discussion

The analysis indicates that all pollutants (CO_2, CO, HC, NO_n, PM_n) follow a proportional decline across scenarios (Table 1), a pattern consistent with the calculation approach of the HBEFA methodology.

Table 1. Emissions of major pollutants and energy consumption across decarbonisation scenarios and the 2025 baseline.

Scenario	CO2e (kg)	CO2 (kg)	CO (kg)	HC (kg)	NOx (kg)	PMx (kg)	Fuel (kg)	Electricity (kWh)
Baseline (2025)	546.97	497.56	1.71	0.01	0.17	0.06	161.3	11.5
BS (2035)	331.67 (−39.4%)	301.69	1.05	0.01	0.11	0.03	97.8	206.12
ML (2035)	349.91 (−36.0%)	318.28	1.1	0.01	0.11	0.04	103.18	270.56
OPT (2035)	209.49 (−61.7%)	190.54	0.68	0	0.07	0.02	61.77	1448.23
PS (2035)	496.76 (−9.2%)	451.86	1.57	0.01	0.16	0.05	146.49	311.2
TC (2035)	331.84 (−39.3%)	301.85	1.04	0.01	0.11	0.03	97.86	411.5

Even under the least favorable configuration (PS, 2035), the system achieves a 9.2% CO_2e reduction against the 2025 baseline. OPT achieves the best performance, with a 61.7% reduction in CO_2e, along with analogous decreases in all co-pollutants. For reference, this reduction is above Latvia's national transport sector target of 58.9% reduction by 2050 (against 2022).

Between the techno-centric (TC) and behavioral-shift (BS) scenarios, pollutant emission is similar, since both include a comparable number of ICE vehicles. However, the techno-centric scenario includes 20.45% additional vehicles (which are EVs), a distinction reflected in the significant difference in the electricity consumption between the two cases. While both approaches achieve local emission reductions of a similar order, TC does not address the broader challenges of private motorized mobility, such as space and resource consumption. Between the two, BS where the modal split shifts toward collective modes is preferable.

Eventually, a substantial increase in EV charging demand at RTU by 2035 across all projected scenarios (Table 2) is also revealed. Compared to the 2025 baseline, the energy required from the local grid is projected to increase by a factor of 20 to 40, necessitating between 78 and 156 fast chargers. The wide range between the Best-case (BS) and Techno-centric (TC) scenarios underscores the high sensitivity of infrastructure needs to policy and adoption rates, implying proactive grid upgrades and strategic infrastructure planning to accommodate future electrification.

Table 2. Projected EV charging demand per workday at RTU.

Scenario	# of EVs visiting RTU	# of EVs requiring charging	Energy from local grid (kWh)	Required fast chargers
Baseline (2025)	89	13	534	4
BS (2035)	1,784	268	10,704	78
ML (2035)	2,408	361	14,448	105
OPT (2035)	2,283	342	13,698	100
PS (2035)	2,675	401	16,050	117
TC (2035)	3,567	535	21,402	156

4 Conclusion

This study presents a methodology for the assessment of the environmental impact of a Positive Energy District by integrating fine-grained, video-based traffic data with microscopic simulation models to obtain an accurate assessment of existing and future energy demand and pollutant emissions. The developed scenarios account for the growing adoption of electric vehicles, the implementation of traffic demand management strategies and changes in the RTU population, and succeed in identifying the combination of measures that yields the most benefits. One of the limitations of the work to be expanded in subsequent papers is that this analysis did not situate transportation energy consumption within the context of the district's building stock and other energy systems and were therefore unable to assess mobility's share contribution to district overall energy performance. Furthermore, a stated preferences survey is planned within the exPEDite project aiming to capture the unobserved segments of journeys—from origin to the sensor perimeter and from departure to final destination. By reconstructing complete trips via a trip planner, a comprehensive and accurate estimation of total energy consumption and emissions for each commute can be achieved, providing a more complete picture of the PED's environmental footprint, even outside the simulation zone.

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References

1. Oliveira, F.F., Sousa, D.M., Kotoviča, N.: Going beyond European emission targets: pathways for an urban energy transition in the city of Riga. Energy. **246**, 123352 (2022). https://doi.org/10.1016/j.energy.2022.123352
2. Higueras-Castillo, E., Guillén, A., Herrera, L.-J., F.L.-C.: Adoption of electric vehicles: which factors are really important? Int. J. Sustain. Transp. **15**, 799–813 (2021). https://doi.org/10.1080/15568318.2020.1818330
3. Global EV Outlook 2025. International Energy Agency (IEA) (2025)
4. Seik, F.T.: An advanced demand management instrument in urban transport: electronic road pricing in Singapore. Cities. **17**, 33–45 (2000). https://doi.org/10.1016/S0264-2751(99)00050-5
5. Barata, E., Cruz, L., Ferreira, J.-P.: Parking at the UC campus: problems and solutions. Cities. **28**, 406–413 (2011). https://doi.org/10.1016/j.cities.2011.04.001
6. Bruglieri, M., Ciccarelli, D., Colorni, A., Luè, A.: PoliUniPool: a carpooling system for universities. Procedia. Soc. Behav. Sci. **20**, 558–567 (2011). https://doi.org/10.1016/j.sbspro.2011.08.062
7. Tomás, R., Fernandes, P., Macedo, J., Coelho, M.C.: Carpooling as an immediate strategy to post-lockdown mobility: a case study in university campuses. Sustainability. **13**, 5512 (2021). https://doi.org/10.3390/su13105512
8. Batur, İ., Koç, M.: Travel demand management (TDM) case study for social behavioral change towards sustainable urban transportation in Istanbul. Cities. **69**, 20–35 (2017). https://doi.org/10.1016/j.cities.2017.05.017
9. Christovasili, K., Mantouka, E., Vlahogianni, E.: A user acceptance survey of pay-how-you-drive urban pricing schemes. In: Nathanail, E.G., Adamos, G., Karakikes, I. (eds.) Advances in Mobility-as-a-Service Systems, pp. 584–594. Springer International Publishing, Cham (2021)
10. Azzali, S., Sabour, E.A.: A framework for improving sustainable mobility in higher education campuses: the case study of Qatar University. Case Stud. Transp. Policy. **6**, 603–612 (2018). https://doi.org/10.1016/j.cstp.2018.07.010
11. Vlahogianni, E. et al.: Analysis of mobility patterns in selected university campus areas. In: Nathanail, E.G., Karakikes, I.D. (eds.) Data Analytics: Paving the Way to Sustainable Urban Mobility, pp. 426–433. Springer International Publishing, Cham (2019)
12. Papantoniou, P. et al.: Developing a sustainable mobility action plan for university campuses. Transp. Res. Procedia. **48**, 1908–1917 (2020). https://doi.org/10.1016/j.trpro.2020.08.223
13. Lindholm, O., Rehman, H.U., Reda, F.: Positioning positive energy districts in European cities. Buildings. **11**, 19 (2021). https://doi.org/10.3390/buildings11010019
14. Fafoutellis, P., Mantouka, E.G., Vlahogianni, E.I.: Eco-driving and its impacts on fuel efficiency: an overview of technologies and data-driven methods. Sustainability. **13**, 226 (2020). https://doi.org/10.3390/su13010226
15. Greenhouse gas emissions from transport in Europe. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12
16. Castillo-Calzadilla, T., Alonso-Vicario, A., Borges, C.E., Martin, C.: E-mobility in positive energy districts. Buildings. **12**, 264 (2022). https://doi.org/10.3390/buildings12030264
17. Ioannidis, R. et al.: Solar-powered bus route: introducing renewable energy into a university campus transport system. Adv. Geosci. **49**, 215–224 (2019). https://doi.org/10.5194/adgeo-49-215-2019
18. Uimonen, S., Lehtonen, M.: Simulation of electric vehicle charging stations load profiles in office buildings based on occupancy data. Energies. **13**, 5700 (2020). https://doi.org/10.3390/en13215700

19. Tomić, J., Kempton, W.: Using fleets of electric-drive vehicles for grid support. J. Power Sources. **168**, 459–468 (2007). https://doi.org/10.1016/j.jpowsour.2007.03.010
20. Kempton, W., Tomić, J.: Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J. Power Sources. **144**, 280–294 (2005). https://doi.org/10.1016/j.jpowsour.2004.12.022
21. Keller, M., Hausberger, S., Wüthrich, P.: Handbook Emission Factors for Road Transport (HBEFA) Version 3.3. MKC Consulting GmbH, IVT Institute for Internal Combustion Engines and Thermodynamics of TU Graz, and INFRAS, Berne, Switzerland (2017)
22. Garg, T., Hanna, R., Myers, J., Tebbe, S., Victor, D.G.: Electric Vehicle Charging at the Workplace: Experimental Evidence on Incentives and Environmental Nudges. CESifo Working Paper (2024)
23. Rautiainen, A. et al.: Anatomy of electric vehicle fast charging: peak shaving through a battery energy storage—a case study from Oslo. IET Electrical Syst. in Trans. **11**, 69–80 (2021). https://doi.org/10.1049/els2.12005
24. Brockman, R., Fox, K.R.: Physical activity by stealth? The potential health benefits of a workplace transport plan. Public Health. **125**, 210–216 (2011). https://doi.org/10.1016/j.puhe.2011.01.005

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Adapting Road Transport Decarbonization Strategies: A Comparative Study Between Spain, Norway, and the United Kingdom

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Abstract. Transport is the second largest emitter of CO2, responsible for 23.8% of total emissions in Europe. Yet decarbonization in transport is progressing more slowly than in other sectors. This highlights the challenge of decarbonizing a sector deeply linked to economic growth, where options are constrained. Meeting the challenges requires more than high-level models and demands instead concrete, context-specific policy evaluations to meet the objectives of the Paris Agreement. This paper assesses how Norway, Spain, and the United Kingdom design and implement decarbonization pathways in road transport, with a focus on alternative fuel (AF) deployment for buses, light-duty vehicles (LDVs), and heavy-duty vehicles. Drawing on national policy reviews, Path2Zero project data, and an Ambition-Achievement framework, we compare policy targets with current fleet data to identify gaps and takeaways. Results show that Norway leads in both policy ambition and adoption, particularly its AF LDV share (30.4%), which is more than ten times Spain's (2.2%), while the UK shows strong regulatory ambition but uneven results. Long-standing fiscal consistency, rather than regulatory targets alone, explains Norway's leadership. These findings can be useful for policymakers and companies working toward transport decarbonization by 2050.

Keywords: Alternative Fuels · Transport Decarbonization · Policy Evaluation

1 Introduction

Decarbonization is key to mitigating and adapting to the current climate situation. The latest IPCC report (2023) [1] states that further greenhouse gas (GHG) emissions will intensify global warming and exceed the 1.5 °C limit of the Paris Agreement. Transport

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is crucial, as it is the second largest emitter of CO_2 in Europe, responsible for 23.8% of total emissions [2], but is decarbonizing three times more slowly than other sectors [3]. Achieving net-zero emissions by 2050 requires significant reductions in GHG emissions [4]. Countries have strengthened policies to decarbonize transport. In the EU, this includes National Energy and Climate Plans (NECPs) for 2030 and long-term strategies for net zero by 2050 [5, 6], aligned with the European Green Deal and related initiatives [5]. Outside the EU, frameworks differ but pursue similar goals, such as the UK Climate Change Act (2008) and Norway's Climate Change Act (2017) with its 2021–2030 Action Plan.

The transition from fossil fuels to Alternative Fuels (AF) is expected to have the greatest impact [2], as declining fossil fuel use has driven GHG reductions in Europe [7]. AF are essential, particularly in road transport, responsible for over 70% of transport emissions in the EU [4], although no single fuel solution exists and a mix of AF options is required [8]. The energy transition is a main solution to reduce emissions and meet climate targets [9], relying on Zero Emission Vehicles (ZEVs) and electric vehicles (EV) [10]. However, AF vehicle uptake remains low in the EU [10] and declined in 2024 [11], and comparative cross-country evaluations remain limited.

This paper aims to compare how national policy frameworks in Norway, Spain, and the United Kingdom influence the deployment of alternative fuels in road transport, and to assess the gap between policy ambition and actual achievement. The paper is structured as follows: Sect. 2 presents the methodology, Sect. 3 includes the results, Sect. 4 discusses the results, and Sect. 5 presents the conclusions.

2 Methodology

This study is conducted within the framework of the EU-funded project Path2Zero [12]. It relies on a bibliographic review of National Climate and Energy Plans and official databases.

The selected countries present a range of governance contexts and levels of progress. Norway represents a frontrunner with an incentive approach, the UK a regulatory-driven system, and Spain a lower AF adoption and a mixed policy approach. Together, they provide a comparison across different policy frameworks and performance levels. The analysis has two main steps.

First, a national policy assessment was conducted for Spain, Norway, and the UK. For each country, policies and targets related to the deployment of AF in road transport were reviewed, with a focus on light-duty vehicles (LDVs), heavy-duty vehicles (HDVs), and buses. These policy objectives were then contrasted with the current vehicle fleet, using 2024 data from the European Alternative Fuels Observatory (EAFO) [13] and national statistics sources. From this comparison, gaps and risks were identified. To improve transparency, Table 1 summarizes the main policy elements, data sources, and indicators.

Second, a cross-sectional analysis was performed, which led to a qualitative Ambition-Achievement chart that resembles the widespread Importance-Performance chart [14]. The chart visualizes the comparison between countries and their road transport decarbonization progress. This step made it possible to highlight common challenges and opportunities in the transition towards AF.

In this study, policy ambition is defined based on the presence, specificity, and stringency of policy targets (e.g., ZEV mandates, phase-out dates, and quantitative deployment targets), as well as the mix of policy instruments. Achievement is measured using the current share of AF vehicles in the national fleet, based on 2024 data.

The Ambition-Achievement chart is qualitative and does not rely on a formal weighting or normalization procedure. Countries are positioned based on a comparative interpretation of policy ambition (targets and policies) and achievements (fleet).

Table 1. Essential policy elements with data sources and indicators

Component	Description	Data sources	Indicator used
Policy targets (ambition)	National targets for AF deployment	NECPs, national policy documents	Targets presence and stringency
Policy instruments	Economic, regulatory, and behavioral measures	National policy reports, Path2Zero	Type and mix of instruments
Fleet data (achievement)	Current AF vehicle penetration	EAFO (2024), national statistics	% of AF vehicles of total fleet
Comparative framework	Ambition-Achievement	Combined sources	Relative positioning (qualitative)

3 Results

The results are presented in two sections. First, the national policy assessment and second, the cross-sectional analysis comparing the three cases by transport modes. To provide a clear overview, Table 2 summarizes the main policy instruments.

Table 2. Summary of policy instruments: economic, regulatory, and behavioral measures

Country	Economic	Regulatory	Behavioral
Norway	Tax exemptions, toll reductions, subsidies	ZEV targets, emission and procurement standards	Indirect (symbolic incentives, social norms)
Spain	EV subsidies (MOVES), tax benefits	Renewable targets, fleet renewal policies	Limited (low public awareness)
UK	Purchase subsidies, infrastructure funding	ZEV Mandate, phase-out targets	Limited (local campaigns, awareness initiatives)

3.1 National Policy Assessment

Norway's Climate Action Plan for 2021–2030 [15] sets a unified framework for road transport, including a biofuel mandate, CO_2 taxes, toll discounts for EVs, and taxes on conventional fuels, with incentives focused on tax benefits.

For buses, from 2025 all new local buses must be ZEV or biogas-powered, and by 2030, 75% of new long-distance buses must be ZEVs. The AF bus fleet represents 17.2% of the total. For LDVs, all new vehicles must be ZEV by 2025, and urban freight distribution nearly zero emission by 2030. Policies combine fiscal incentives (VAT discount, toll and parking reductions, charging infrastructure subsidies) with taxes and emission standards. The AF LDV share is 30.4%. For HDVs, targets include all new HDVs ZEV/biogas by 2030, nearly zero-emission urban freight, and 50% of new trucks ZEVs, supported by investments, emission standards, and charging subsidies. The AF truck fleet is 5.4%. Risks include equity concerns, limited charging capacity, imported biofuels dependence, impacts on public transport, and political opposition to tax increases. Good practices include consistent taxation policies, coordinated incentives, and multi-level governance cooperation.

The Spanish NECP [16] emphasizes a diversified approach to decarbonize road transport, including the promotion of AF (biogas, biomethane, and hydrogen) expansion of refueling infrastructure, and a 29% renewable energy target for the transport sector (5.5% advanced biofuels). EV support includes MOVES III subsidies and investments in charging infrastructure.

Table 3. Comparative Overview of Zero Emission Buses Policies: Norway, Spain, and the UK

Country	Norway	Spain	United Kingdom
Target	Zero-emission fleet: New local buses (2025); 75% new long-distance buses (2030)	150–200 hydrogen-powered buses No target fixed for electric buses	4,000 zero-emission buses; phase-out consultation for diesel buses (2025–2032)
Policy	Emission standards in public bus procurement	Fleet renewal with efficient/electric buses; intermodality	Deadline for new non-zero emissions buses & ZEBRA scheme funding for ZEBs
2024 AF Fleet (% total)	2,485 (17.2%)	5,689 (8.4%)	5,381 (3.8%)

Hydrogen deployment is central, with 150–200 buses and 5,000–7,500 units planned. Bus decarbonization focuses on hydrogen, fleet renewal, and intermodality, with an AF bus fleet of 8.4%. For LDVs, the 2030 target is 250,000 EVs, combining incentives for purchase and manufacturing. The AF LDVs fleet accounts for 2.2%. HDVs rely on subsidies and tax benefits, especially for companies, with the AF truck fleet at 0.4%. Risks and gaps include reliance on private investment (85%), policy uncertainty, insufficient monitoring, weak public awareness, and low technological maturity of biofuels.

Good practices include streamlined grants, promotion of waste-based biofuels, and R&D investment.

The UK combines incentives and regulations for EV adoption. The ZEV Mandate sets mandatory sales targets for manufacturers, who must purchase ZEV certificates or face fines if targets are not met [17]. Besides, subsidies for new EVs and charging infrastructure.

Table 4. Comparative Overview of Zero Emission LDVs Policies: Norway, Spain, and the UK

Country	Norway	Spain	United Kingdom
Target	All new LDVs ZEV (2025); Urban freight distribution nearly zero emission (2030)	250,000 EVs + 5,000–7,500 hydrogen vehicles by 2030	ZEV Mandate: sales shares of 100% ZEVs (2035)
Policy	VAT discount, bus lane access, parking discount, no registration tax; emissions standards; subsidies for charging stations	Promotion of EVs and EV manufacturing; subsidies, tax benefits	Ban of new petrol/diesel sales (2030); hybrids (2035)
2024 AF Fleet (% total)	1,035,355 (30.4%)	641,263 (2.2%)	2,088,585 (5.4%)

The National Bus Strategy sets the phase-out of new diesel buses between 2025 and 2032 and aims to deploy 4,000 zero-emission buses through the ZEBRA programme; the AF bus fleet is 3.8% of the total. For LDVs, the ZEV Mandate requires 100% ZEV sales by 2035, alongside the ban on new petrol and diesel cars from 2030 (hybrids allowed until 2035). The AF LDV fleet represents 5.4%. For HDVs, the UK plans to end the sale of new non-zero emission HDVs by 2035–2040, supported by the ZEHID programme; the AF truck fleet accounts for 1.2%. Main risks include fragmented governance across devolved countries, high costs, uneven funding, and mixed policy signals regarding phase-out dates. Good practices include collaborative funding through the ZEBRA scheme, a clear regulatory trajectory (ZEV Mandate), local investments, and strong oversight by the Climate Change Committee.

3.2 Cross-Sectional Analysis and Discussion

Bus

All three countries pursue bus decarbonization but differ in scope and ambition. Norway stands out for the strictest and earliest target (Table 3). Spain focuses on deploying hydrogen buses and accelerating fleet renewal, while the UK combines clear targets and structured funding through the ZEBRA scheme. Norway leads with a bus fleet share of 17.2%, well ahead of Spain (8.4%) and the UK (3.8%).

Light-Duty Vehicles

The difference between countries is particularly significant for LDVs. Norway's share

(30.4%) is nearly 14 times Spain's (2.2%) and more than five times the UK's (5.4%), illustrating the cumulative effect of long-standing fiscal incentives. As shown in Table 4, Norway has set ambitious targets: all new LDVs ZEVs by 2025 and nearly zero-emission urban freight by 2030. This strong policy framework, combined with fiscal incentives, has enabled the highest penetration of AF LDVs (30.4%). Spain has set quantitative goals for 2030, but its AF share remains low at 2.2%. The UK follows a regulatory approach with the ZEV Mandate, targeting 100% new ZEV sales by 2035, with an intermediate AF share (5.4%).

Heavy-Duty Vehicles

Decarbonization in HDVs is promoted in Norway, Spain, and the UK, though ambition and approaches differ (Table 5). Norway has set explicit targets for 2030, Spain relies on hydrogen deployment but lacks electrification targets, and the UK follows a regulatory approach, committing to end the sale of new non-zero emission HDVs by 2035–2040. However, these deadlines remain distant and are not yet supported by sales. In relative terms, Norway shows the highest AF HDV penetration (5.4%), followed by the UK (1.2%) and Spain (0.4%). In absolute terms, Spain has the largest AF HDV fleet but the lowest penetration. Overall, the HDV segment shows the greatest policy uncertainty and technological challenge across the three countries.

Table 5. Comparative Overview of Zero Emission HDVs Policies: Norway, Spain, and the UK

Country	Norway	Spain	United Kingdom
Target	By 2030, new HDVs shall be ZEV/biogas, urban freight distribution nearly zero emission, and 50% all new trucks ZEVs	5,000–7,500 hydrogen vehicles by 2030	By 2030, new HDVs shall be ZEV/biogas, urban freight distribution nearly zero emission, and 50% all new trucks ZEVs
Policy	Investment in ZEVs; emission standards, subsidies for charging stations	Promotion of EVs; subsidies and tax benefits (companies)	Accelerating transition to zero-emission HDVs and the ZEHID programme
2024 AF Fleet (% total)	3,575 (5.4%)	9,806 (0.4%)	6,244 (1.2%)

4 Ambition-Achievement Overview and Conclusions

Figure 1 shows clear differences between the relative ambition and achievement of AF policies across countries. Norway leads in both, supported by long-term fiscal incentives, stable policies, clear targets, and strong infrastructure development. In contrast, Spain shows lower levels of both ambition and achievement, with challenges related to policy continuity, infrastructure deployment, and public awareness. The UK presents strong regulatory ambition but uneven implementation.

These findings indicate that high policy ambition alone does not guarantee successful outcomes. Factors such as regulations, fiscal design, infrastructure availability, and social acceptance play a critical role in translating targets into actual adoption.

Norway's success is linked to consistent fiscal incentives over time, including tax exemptions, toll reductions, and infrastructure support. The UK benefits from regulatory clarity, particularly through the ZEV mandate, which provides clear signals to manufacturers. Spain faces challenges related to reliance on private investment and lower levels of social engagement.

Overall, Fig. 1 positions Norway as the frontrunner, the UK as an ambitious but uneven performer, and Spain as falling behind. Most policy measures in all countries remain economic (subsidies, taxes, fiscal incentives), as noted by Zell-Ziegler et al. [6]. Few measures address sufficiency or societal engagement. Beyond economics, policies can shape behavior and perceptions, encouraging pro-environmental choices. In the Norwegian context, Ingeborgrud and Ryghaug [18] found that incentives also serve as "symbolic certification", promoting ZEV adoption for reasons that go beyond financial motivations. Policies not only affect costs but also influence perceptions and social norms. These results highlight the importance of combining economic, regulatory, and behavioral instruments in transport decarbonization strategies.

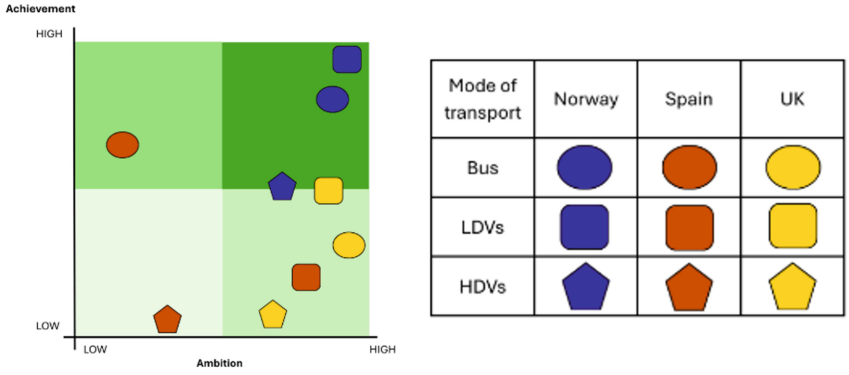


Fig. 1. Ambition-Achievement for AF in road transport. Horizontal axis: Ambition (target stringency and instrument mix). Vertical axis: Achievement (2024 AF fleet penetration).

Decarbonizing road transport remains challenging, as targets do not automatically drive AF adoption. This study assessed policies in Norway, Spain, and the UK, combining national policy analysis with cross-sectional comparisons of 2030–2050 commitments

and achievements. Results show that ambition alone is insufficient: Norway benefits from long-standing incentives, the UK from regulatory mandates, and Spain faces structural and social constraints. Policymakers and companies should combine long-term fiscal consistency with regulatory mandates, infrastructure deployment, behavioral measures (public awareness, social campaigns), and improved monitoring based on standardized fleet indicators for cross-country comparison.

While limited by qualitative methods and general fleet data that provide only a snapshot in time, the study highlights key lessons for national decarbonization strategies. Future research could focus on quantitative models for AF adoption and improved monitoring systems. It could also assess how infrastructure, incentives, and non-economic factors support adoption and decarbonization goals.

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References

1. Lee, H., Romero, J.: Summary for policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC (2023). https://doi.org/10.59327/IPCC/AR6-9789291691647.001
2. Patil, G., Pode, G., Diouf, B., Pode, R.: Sustainable decarbonization of road transport: policies, current status, and challenges of electric vehicles. Sustainability. **16**(18), 8058 (2024). https://doi.org/10.3390/su16188058
3. Transport & Environment: The State of European Transport https://www.transportenvironment.org/state-of-european-transport/state-of-transport (2024). Last Accessed 20 Sep 2025
4. European Environment Agency: Greenhouse gas emissions from transport in Europe https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport (2024). Last Accessed 20 Sep 2025
5. European Commission: National energy and climate plans https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en (2023). Last Accessed 12 Sep 2025
6. Zell-Ziegler, C., Thema, J., Best, B., Wiese, F.: Sufficiency in transport policy: an analysis of EU countries' national energy and climate plans and long-term strategies. In: ECEEE Summer Study Proceedings, pp. 723–730 (2021)
7. European Environment Agency: Monitoring Report on Progress towards the 8th EAP Objectives (2024). https://doi.org/10.2800/2208311
8. European Commission: Clean power for transport: a European alternative fuels strategy https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52013PC0017 (2013)
9. Apostu, S.A., Panait, M., Vasile, V.: The energy transition in Europe-a solution for net zero carbon? Environ. Sci. Pollut. Res. **29**(71), 71358–71379 (2022). https://doi.org/10.1007/s11356-022-20730-z
10. Biresselioglu, M.E., Kaplan, M.D., Yilmaz, B.K.: Electric mobility in Europe: a comprehensive review of motivators and barriers in decision making processes. Transp. Res. A Policy Pract. **109**, 1–13 (2018). https://doi.org/10.1016/j.tra.2018.01.017
11. International Energy Agency: Global EV data explorer, https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer. Last Accessed 23 Sep 2025

12. Path2Zero. Path2Zero: Accelerating net-zero transformation by advancing Europe's transport pathways and cross-sectoral synergies, https://path2zero.eu/. Last Accessed 29 Sep 2025
13. European Commission: European alternative fuels observatory, https://alternative-fuels-observatory.ec.europa.eu/. Last Accessed 19 Sep 2025
14. Martilla, J.A., James, J.C.: Importance-performance analysis. J. Mark. **41**(1), 77 (1977). https://doi.org/10.2307/1250495
15. Norwegian Ministry of Climate and Environment: Norway's climate action plan for 2021–2030 https://www.regjeringen.no/en/documents/meld.-st.-13-20202021/id2827405/ (2021)
16. Ministry for Ecological Transition and Demographic Challenge (MITECO): Spain's final updated national energy and climate plan (NECP) 2021–2030 https://commission.europa.eu/publications/spain-final-updated-necp-2021-2030-submitted-2024_en (2024)
17. Department for Transport (DfT): Zero emission vehicle mandate consultation: final cost-benefit analysis https://www.gov.uk/government/consultations/a-zero-emission-vehicle-zev-mandate-and-co2-emissions-regulation-for-new-cars-and-vans-in-the-uk (2023)
18. Ingeborgrud, L., Ryghaug, M.: The role of practical, cognitive and symbolic factors in the successful implementation of battery electric vehicles in Norway. Transp. Res. A Policy Pract. **130**, 507–516 (2019). https://doi.org/10.1016/j.tra.2019.09.045

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Simulating ERS Deployment in The Netherlands for Freight Electrification and Grid Planning, and an Outlook to Extension to TEN-T Corridors with Integration of MOSTACHI and Euro-Calliope

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Abstract. Electrifying long-haul freight presents challenges related to battery size, infrastructure deployment, and electricity system impacts. This study applies the MOSTACHI freight transport model to assess the Electric Road System (ERS) deployment in the Netherlands. Results show that targeting ERS deployment on high-traffic corridors enables utilisation levels consistent with economic viability while limiting infrastructure investment. Dynamic charging reduces battery capacity requirements and shifts electricity demand towards daytime operation, resulting in a more distributed load profile but creating localised grid constraints along key corridors. These findings highlight the importance of coordinated transport and energy system planning to support efficient ERS deployment. The next step in research is to link the MOSTACHI model with the Euro-Calliope energy system model to assess system-wide energy impacts at European scale.

Keywords: Electric Road Systems (ERS) · Battery Electric Trucks (BET) · infrastructure planning

1 Introduction

The decarbonisation of road freight is central to achieving the European Union's climate neutrality targets. Heavy-duty vehicles account for a substantial share of transport emissions and remain difficult to electrify due to high energy demand and operational constraints [1]. Battery-electric trucks (BETs) are a key pathway, but long-haul applications require large batteries, increasing vehicle cost and placing pressure on electricity infrastructure [2, 3]. Future battery cost developments remain uncertain, with wide variation across forecasting approaches [4].

Electric Road Systems (ERS) offer a complementary solution by enabling dynamic charging during driving. This reduces onboard battery requirements and redistributes electricity demand across transport corridors. Their economic viability depends on high utilisation, typically achieved on dense freight corridors such as those in the TEN-T network [5, 6]. The framework is applied to the Dutch network as a case study,

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providing insights into infrastructure utilisation, battery requirements, and electricity demand patterns.

2 Background

Electric Road Systems (ERS) enable dynamic charging of heavy-duty vehicles while driving and are increasingly considered a complement to battery-electric freight transport. By supplying energy along road corridors, ERS reduces the need for large onboard batteries and alters charging behaviour. Previous studies indicate that ERS can reduce battery capacity requirements by 50–65% on high-utilisation routes, improving vehicle cost and operational efficiency [2]. However, economic viability depends on traffic density, with utilisation thresholds of around 70% of heavy-duty vehicle flows often cited as necessary [5, 7]. This implies that ERS deployment must be targeted at corridors with concentrated freight demand.

At the European level, such corridors are defined within the Trans-European Transport Network (TEN-T), which connects major logistics hubs and international freight routes. While TEN-T provides a strategic framework, large-scale assessments are complex due to cross-border flows, heterogeneous electricity systems, and differing national policies. National case studies offer a more controlled setting. The Netherlands is a relevant example, as freight flows are dense and concentrated along a limited number of corridors linking the Port of Rotterdam, the Randstad, and the German hinterland. This structure supports high ERS utilisation with relatively limited network coverage, while also reflecting key TEN-T corridors.

ERS can be implemented through overhead catenary, conductive rail, or inductive systems, with overhead solutions currently the most mature [6, 8]. In this study, ERS is treated as a generic dynamic charging option, as the analysis focuses on system-level impacts rather than technology comparison.

Existing research remains fragmented between transport and energy system perspectives. Transport studies focus on corridor selection and utilisation, while energy models assess electricity demand and grid impacts, often with aggregated transport inputs [5, 9]. This limits the assessment of system- level interactions, such as how ERS deployment affects both battery requirements and spatial electricity demand. The present study addresses this gap by integrating transport and energy modelling to evaluate these interactions in a consistent framework.

3 Methodology

This study applies an integrated modelling approach to analyse ERS deployment on the Dutch road network. The framework is based on the MOSTACHI (Model for Optimisation and Simulation of Traffic and Charging Infrastructure) model [6], which simulates freight transport flows, charging behaviour, and infrastructure utilisation in a unified optimisation environment. The objective is to assess how ERS deployment affects corridor utilisation, battery requirements, and charging demand patterns.

MOSTACHI is an agent-based simulation model developed to evaluate ERS rollout strategies [7]. It combines transport demand, infrastructure placement, and vehicle-level

decision-making. Road freight flows are derived from the BasGoed dataset, which provides origin–destination relations between regions (about 4000 regions in the Netherlands) [11]. These flows are mapped onto a road network based on OpenStreetMap and enriched with traffic intensity data to identify high-volume corridors.

The model represents four charging options: depot charging, destination charging, public fast charging at rest stops, and dynamic charging via ERS. Vehicles select charging strategies that minimise annual operating costs, taking into account battery size, infrastructure availability, and energy prices. This allows endogenous determination of battery capacity and charging behaviour as a function of infrastructure deployment.

ERS rollout is modelled as a phased expansion of infrastructure along selected road segments. Corridors are prioritised based on freight intensity, enabling high utilisation of installed infrastructure. A key performance indicator is the utilisation rate of ERS segments, defined as the share of heavy-duty vehicle flows using equipped road sections. Consistent with previous studies, a threshold of approximately 70% utilisation is used as an indicator of economic viability [5].

The analysis focuses on the Dutch network over the period 2030–2060. Freight demand is anchored to baseline and future projection years, and infrastructure deployment increases gradually over time. The ERS network is defined by a limited coverage of major corridors, with a total length of approximately 1,500 km and a coverage ratio of around 35% of the core network. Charging power levels differ by infrastructure type, with higher capacities for roadside fast charging and lower continuous power for dynamic ERS segments. These parameters are selected to reflect current technological expectations and are applied consistently across scenarios.

Model outputs include corridor-level utilisation rates, spatial and temporal charging demand profiles, and estimates of infrastructure requirements. These outputs enable assessment of trade-offs between infrastructure investment, vehicle battery size, and system performance.

The modelling framework is designed to be extended with the Euro-Calliope energy system model, which represents electricity supply, transmission, and demand at high spatial and temporal resolution. MOSTACHI outputs can be translated into electricity demand profiles and integrated into Euro-Calliope to assess grid impacts, renewable integration, and system costs [10]. However, this integration is still under development, and no definitive results are presented in this study. By coupling MOSTACHI outputs with Euro-Calliope, the study will evaluate the implications of ERS deployment for Europe's electricity system.

4 Results

4.1 ERS Network Utilisation and Cost Trade-Offs

The results indicate that ERS deployment focused on high-traffic corridors leads to utilisation levels approaching or exceeding the 70% threshold commonly associated with economic viability [5, 6]. Corridors connecting major logistics hubs, including routes between Rotterdam and the eastern border, show the highest utilisation due to concentrated freight flows.

Scenarios with limited network coverage achieve high utilisation on a small number of core segments but provide benefits only to a subset of freight movements. Expanding the ERS network increases coverage across the system but results in lower average utilisation on peripheral segments. This highlights a trade-off between maximising utilisation and extending network reach.

Infrastructure costs follow a similar pattern. Targeted deployment on core corridors limits total investment while maintaining high efficiency of use. In contrast, broader rollout strategies increase total infrastructure length without proportional increases in utilisation, leading to higher cost per kilometre.

Overall, the results suggest that early ERS deployment should prioritise a limited set of high-intensity corridors. Such an approach maximises utilisation and cost-effectiveness, while providing a foundation for gradual network expansion as demand increases.).

4.2 Battery Size Reduction and Fleet Implications

A second output concerns the effect of ERS on battery requirements for battery-electric trucks. Previous studies suggest that ERS-equipped corridors can reduce battery capacity needs by 50–65%, from 600 kWh to around 200–300 kWh per truck [2]. Smaller batteries translate into lower vehicle purchase costs and increased payload capacity.

The simulations will provide updated estimates under rollout scenarios. For the minimal network, reductions may be limited to trucks that frequently operate on core corridors. In contrast, the intermediate and full-scale scenarios are expected to show broader reductions in battery capacity across the fleet.

4.3 Results for a Restricted Network

The figures below illustrates a schematic representation of the projected deployment of ERS infrastructure across a selected corridor. The highlighted segments indicate the sections of the road network where dynamic charging (via overhead catenary, in-road rail, or inductive systems) is planned or under consideration. Node clusters represent major logistics hubs and freight demand centres, emphasizing locations with high potential for ERS utilization [7].

Figure 1 presents a network map of the Dutch road system, highlighting freight transport intensity per link. The thickness and shading of the blue lines indicate the relative edge weight, which corresponds to the tonnage or number of freight movements along each road segment based on a ETIS-plus dataset [12].

Figure 2 shows the 2040 MOSTACHI scenario for ERS deployment in the Dutch freight network based on BasGoed [11]. Blue points represent road segments with ERS infrastructure, while green nodes indicate depots and orange nodes destinations. The map shows ERS segments forming a corridor from the Port of Rotterdam through the central Netherlands toward the eastern border, with additional segments extending toward the Antwerp region.

Figure 3 shows the 2060 MOSTACHI scenario for ERS deployment in the Dutch freight network based on BasGoed. Blue points represent road segments with ERS infrastructure, while green nodes indicate depots (the starting point of the trip), orange nodes

indicate destinations, and red nodes rest stops. Rest-stop charging refers to charging at public or semi-public locations along the road network. The map shows ERS segments distributed across a larger share of the national road network, including corridors connecting Rotterdam, Amsterdam, Utrecht, Eindhoven, Arnhem, and the eastern border, with additional connections toward Antwerp and the southern Netherlands.



Fig. 1. Network map of the Dutch road system

Charging locations in MOSTACHI are determined by linking BasGoed freight flows to the road network. The model identifies locations where freight movements originate, terminate, and concentrate along routes. Depots are derived from freight origins and operator bases, destinations from delivery and pick-up locations, and rest stops from accessible charging opportunities along major corridors. The model then determines the most cost-effective charging strategy for each vehicle, subject to constraints such as battery capacity, charging availability, energy prices, and route requirements. As a result, infrastructure deployment is prioritised in locations with high freight intensity, including major logistics nodes and heavily used corridors.

The Dutch BasGoed scenario is simulated over the period 2040–2060. Freight flows are anchored to 2018, 2040, 2050 and 2060, with a 2% movement sample. ERS and public charging station deployment both begin in 2040 and reach full planned rollout by 2060. Depot and destination charging infrastructure are expanded more selectively, reaching 75% and 40% of the planned build-out, respectively. The ERS network is

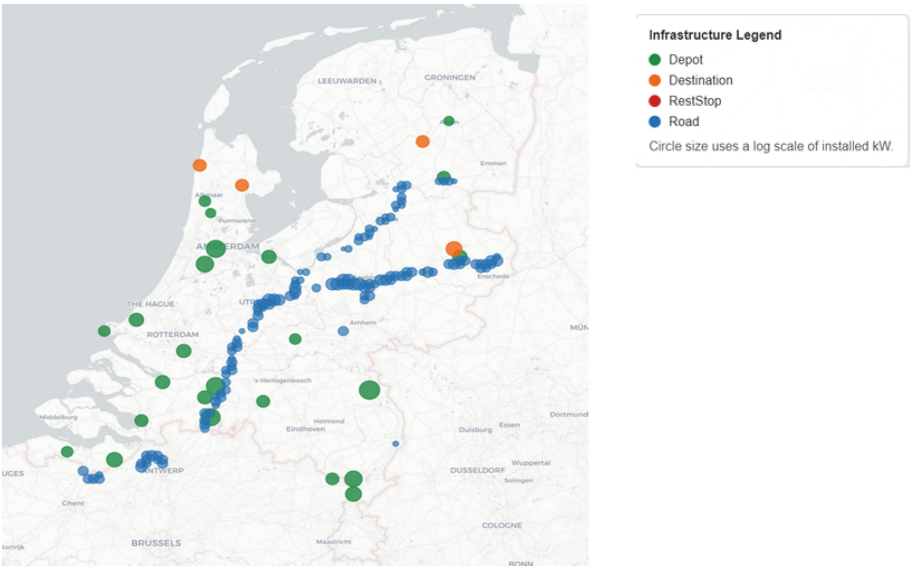


Fig. 2. Road segments potential or prioritized candidates for ERS 2040

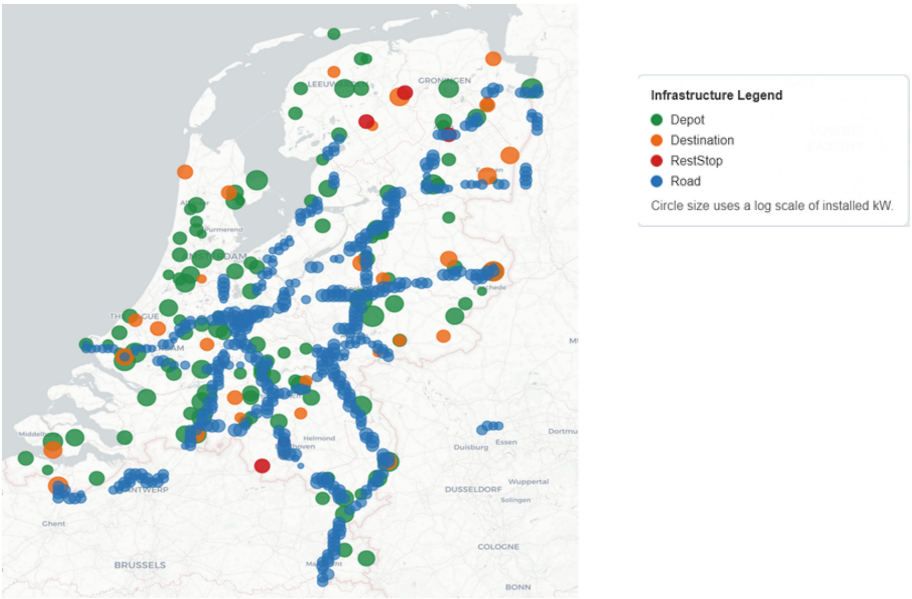


Fig. 3. Road segments potential or prioritized candidates for ERS 2060

defined by a reference speed of 85 km/h, a coverage ratio of 35%, and a total network extent of 1,500 km. Charging power is differentiated by infrastructure type, from 150 kW at depots to 1,500 kW at rest stops, while road-based ERS segments provide 375 kW.

Vehicle battery options vary by class and are combined with multiple charging strategies, including depot charging, public static charging, and dynamic ERS charging.

5 Conclusion

This study analyses the deployment of ERS on the Dutch freight network using an integrated transport modelling approach. The results show that ERS deployment concentrated on high-traffic corridors can achieve utilisation levels around or above 70%, consistent with economic viability thresholds identified in previous studies [5, 13]. Dynamic charging enables substantial reductions in battery capacity requirements, with indicative reductions from 600 kWh to approximately 200–300 kWh for vehicles operating on equipped routes [2]. This highlights a key trade-off between infrastructure investment and vehicle cost, where targeted corridor deployment can maximise system efficiency. The analysis demonstrates the value of modelling charging behaviour and infrastructure use jointly, allowing a more consistent assessment of freight electrification strategies. At the same time, the study has limitations. Results depend on assumptions regarding freight demand, technology performance, and cost parameters, and the current framework does not yet fully capture interactions with the electricity system. Further work is required to integrate energy system modelling and to test the robustness of results under alternative scenario.

References

1. Shoman, W., et al.: Battery electric long-haul trucks in Europe: public charging, energy, and power requirements. Transp. Res. Part D Transp. Environ. **121**, 103825 (2023). https://doi.org/10.1016/j.trd.2023.103825
2. Link, S., Stephan, A., Speth, D., Plötz, P.: Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. Nat. Energy. **9**, 1032–1039 (2024). https://doi.org/10.1038/s41560-024-01577-1
3. Speth, D., Plötz, P.: Depot slow charging is sufficient for most electric trucks in Germany. Transp. Res. D: Transp. Environ. **128**, 104078 (2024). https://doi.org/10.1016/j.trd.2024.104078
4. Mauler, L., Duffner, F., Zeier, W.G., Leker, J.: Battery cost forecasting: a review of methods and results with an outlook to 2050. Energy Environ. Sci. **14**, 4712–4739 (2021). https://doi.org/10.1039/D1EE01530C
5. Tavasszy, L., et al.: Prospects for Electric Road Systems (ERS) on the Dutch Freight Corridors. In: Vervoerslogistieke Werkdagen 2024. Tegelen, Netherlands (2024) https://vervoerslogistiekewerkdagen.com/wp-content/uploads/2024/03/prospects-for-electric-road-systems-ers-on-thedutch-freight-corridors.pdf
6. Rogstadius, J.: Utilization and Economic-Environmental Impacts of Future Electric Road Systems for Heavy Trucks in Sweden. RISE Research Institutes of Sweden, Gothenburg (2024a)
7. Rogstadius, J.: MOSTACHI Simulation Tool for Traffic and Charging Infrastructure. RISE Research Institutes of Sweden, Gothenburg (2024b)
8. Van Ommeren, K., et al.: Cost-Effectiveness Analysis of Electric Road Systems (ERS) for the Netherlands. Ministry of Infrastructure and Water Management, The Hague (2022)

9. Kunze, R., et al.: Determining the share of renewable electricity in electric vehicle charging in Europe. Energy Rep. **12**. Open Access under CC BY license, 5834–5845 (2024). https://doi.org/10.1016/j.egyr.2024.11.044
10. Calliope Consortium: Euro-Calliope energy system model. https://euro-calliope.readthedocs.io/en/stable/. Last Accessed 21 Feb 2026
11. Ministry of Infrastructure and Water Management: BasGoed: The Dutch national freight model and dataset, The Hague, The Netherlands (2021)
12. European Commission: ETISplus: European Transport Policy Information System. DG MOVE, Brussels (2014) https://transport.ec.europa.eu/index_en
13. Rogstadius, J., et al.: Electric road systems: a no-regret investment with policy support. Tech. Rep. Research Square. (2023). https://doi.org/10.21203/rs.3.rs-3372572/v1

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Integrated Digital Solutions for Managing Electric Truck Fleets in Medium Haulage

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Abstract. The integrated suite of tools developed within the NextETRUCK EC funded project, including the Logistics Planner, the Eco-Charging Strategy Tool, and the Automated Fleet Management Tool is presented in paper. Together, these tools enable comprehensive mission planning, real-time vehicle tracking, and optimized route and charging management. The Logistics Planner platform offers a user-friendly interface for operators and drivers, ensuring seamless data exchange across systems. The Eco-Charging Strategy Tool, divided into depot (FIST) and en-route (TEIDE) planning modules, guides infrastructure deployment based on operational needs and projected utilization. The Automated Fleet Management Tool plays a pivotal role by leveraging real-time GPS data and embedded predictive algorithms to support operational decision-making. Using historical and live data, it forecasts arrival times, evaluates fleet punctuality to improve scheduling. By combining digital innovation with practical fleet applications, NextETRUCK contributes to the scalable adoption of zero-emission freight transport across Europe.

Keywords: Zero-emission freight · Fleet management · Electric trucks · Digital tools

1 Introduction

The electrification of heavy-duty vehicle fleets is emerging as a key enabler for decarbonising road freight and logistics across Europe and beyond. However, the transition from diesel to battery-electric trucks presents challenges in infrastructure deployment, fleet scheduling, and real-time operational management. Existing research has addressed charging infrastructure planning, fleet-level routing and scheduling, and integrated grid–vehicle interactions, yet few approaches offer a comprehensive system architecture that connects strategic planning, mission assignment, real-time routing, and vehicle monitoring. The NextETRUCK project contributes to filling this gap by proposing an integrated digital ecosystem centred on the Logistics Planner, which orchestrates fleet missions, charging, and subsystem interactions.

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In the domain of charging infrastructure planning, a number of analytical and simulation-based tools have been developed. Gnann et al. [1] present a framework for assessing the infrastructure required for large-scale deployment of battery electric vehicles, highlighting the role of traffic flow and charging demand modelling. Similarly, Unterluggauer et al. [2] provide a comprehensive review of planning approaches at strategic, tactical, and operational levels, emphasising the need for coordination between long-term infrastructure rollout and short-term operational feasibility. Strategic optimisation methods, such as those explored by Schiffer and Walther [3], demonstrate how facility location and vehicle routing problems can be integrated to design efficient electric logistics networks.

From an operational scheduling perspective, recent studies focus on combining route optimisation with recharge scheduling. Parmentier et al. [4] develop a scalable column-generation algorithm that addresses battery-constrained routing for large EV fleets, while Geerts et al. [5] suggested a method for finding the charging moments of a fleet of electric vehicles. Geng et al. [6] propose an integer-clustering approach for large-scale fleet planning that balances accuracy with computational efficiency, showing how operational and infrastructure decisions can be co-optimised. Complementary to this, EV-EcoSim, a co-simulation platform used by Balogun et al. [7], integrates vehicle, charging, and grid models to evaluate infrastructure deployment scenarios in real-world conditions.

While these contributions provide valuable advances in individual aspects of planning or operation, they often remain siloed, with infrastructure tools not directly connected to live vehicle data, and fleet scheduling systems lacking links to long-term strategic infrastructure planning. As highlighted by van der Kin et al. [8], interoperability between fleet management, charging networks, and vehicle systems is crucial to ensure efficiency and reliability in electric freight transport. The NextETRUCK system architecture addresses this by integrating the Logistics Planner with subsystems for routing, charge management, eco-charging strategy, and automated fleet management.

The remainder of this paper presents the design and implementation of the NextETRUCK integrated architecture. Section 3 outlines the Logistics Planner and its role as the core of the system. Section 4 introduces the Eco-Charging Strategy Tool, including the Fleet Infrastructure Strategy Tool (FIST) and the Tool Evaluating Infrastructure Deployment En-Route (TEIDE). Section 5 describes the Automated Fleet Management Tool, while Sect. 6 concludes with the benefits and opportunities for large-scale e-truck deployment.

2 Integrated System Approach

The NextETRUCK digital ecosystem integrates several tools that collectively support the planning and operation of electric truck fleets. The system architecture places the Logistics Planner and Mission Assignment module at its core, acting as the central coordination platform between fleet operators, vehicles, drivers, and external services.

On the operator side, mission specifications are entered through the Logistics Planner interface. Based on this information, the system provides fleet status updates, charging infrastructure information, and operational notifications through a cloud-based platform. Operators can therefore monitor mission execution and adjust operational parameters when necessary.

On the vehicle side, the Logistics Planner communicates with a driver-facing mobile application that provides route guidance, charging station availability, and mission-related notifications. In parallel, vehicles continuously transmit operational data to the platform, including battery state of charge, vehicle position, speed, and energy consumption. These real-time data streams allow the system to update mission execution status and support operational decision making.

The Logistics Planner also interacts with external subsystems. It connects to the Traffic Flow Information and Routing service, which provides real-time route calculations and updated information about charging station availability. This integration ensures that route planning considers both traffic conditions and vehicle energy requirements. In addition, the system exchanges information with the Charge Management Platform, which manages charging infrastructure data and provides information about charger capacity and availability along potential routes.

The architecture also integrates the Eco-Charging Fleet Management Strategy Planning Tool, which supports strategic infrastructure planning. Through this interface, the Logistics Planner provides operational fleet data while receiving analytical reports regarding optimal depot charging configurations and potential infrastructure deployment strategies.

3 Logistics Planner

The Logistics Planner serves as the central operational platform of the ecosystem. It enables fleet operators to manage transport missions, electric truck fleets, and driver guidance within a single digital environment. The subsystem stores operational data related to missions, vehicles, depots, and charging infrastructure provided by the fleet operator. Based on this information, the platform coordinates the execution of transport missions and supports communication between the various subsystems of the NextETRUCK architecture. Fleet operators interact with the system through a web-based interface that allows them to define missions, monitor fleet status, and access information related to vehicles, depots, and charging infrastructure. The platform also provides data visualisation tools that support operational monitoring and decision making.

From a system architecture perspective, the Logistics Planner consists of several main components: a web-based user interface, a backend processing and management module, a relational database storing operational data, and web services enabling communication with external subsystems. Through these components, the Logistics Planner facilitates data exchange between operators, vehicles, routing services, and infrastructure planning tools. By acting as the central integration layer of the NextETRUCK ecosystem, the Logistics Planner ensures that operational fleet management and infrastructure planning processes remain interconnected.

The software architecture of the Logistics Planner follows a three-tier architecture, which separates the system into presentation, application, and data layers. This architectural approach improves scalability, maintainability, and interoperability with the other components of the ecosystem.

The presentation layer provides the user interface through which fleet operators interact with the system. It allows users to create and manage missions, view fleet status,

and monitor operational data related to vehicles, depots, and charging infrastructure. The user interface is implemented using web-based technologies, including HTML5, CSS3, and JavaScript, and integrates the Grafana analytics and visualisation platform to support real-time data monitoring and graphical dashboards.

The application layer contains the core processing logic of the Logistics Planner. This layer manages mission creation, data processing, and communication with external subsystems. It exposes a set of RESTful web services, implemented using the Java programming language and the Jersey framework, which enable secure and structured data exchange with other NextETRUCK components such as routing services, charging management platforms, and fleet monitoring systems. These services handle requests from the user interface, process operational data, and coordinate communication with external APIs.

The data layer is responsible for storing and managing all operational information required by the platform. This includes mission definitions, vehicle specifications, depot configurations, charging infrastructure information, and historical operational records. The system uses the MySQL relational database management system to store structured data and ensure reliable data retrieval. The database schema is designed to support efficient queries and integration with external subsystems.

Data exchange between the presentation and application layers is performed using JSON-formatted messages, which ensures compatibility with modern web services and simplifies integration with external systems. This modular architecture allows the Logistics Planner to operate as a central coordination platform while remaining flexible enough to integrate additional services or data sources.

4 Eco-Charging Strategy Tool

4.1 Fleet Infrastructure Strategy Tool (FIST)

The Fleet Infrastructure Strategy Tool (FIST) supports fleet operators in determining the optimal number and type of charging stations to deploy across fleet depots. The tool evaluates charging infrastructure configurations while balancing operational requirements, vehicle energy needs, and installation costs. By analysing vehicle schedules, depot constraints, and charging technologies, FIST identifies feasible charging solutions that ensure the completion of planned vehicle missions. When depot charging alone cannot satisfy the operational energy demand, the tool also identifies energy shortfalls that may require additional en-route charging infrastructure, which can then be further assessed using the Tool Evaluating Infrastructure Deployment En-route (TEIDE) model.

The methodology implemented in FIST begins with the provision of input data describing fleet depots, vehicle characteristics, and typical schedules of vehicle movements between depots. Energy consumption for each journey is estimated using the NNG Routing API, which calculates route distances and expected energy requirements based on vehicle technical specifications. Using these estimates, the model evaluates all feasible charger deployment configurations that satisfy depot-level constraints, including the maximum number of chargers and the total available electrical power.

For each candidate configuration, the charging process is simulated over the full operational schedule. Vehicles are assigned to chargers according to a priority rule that

selects the lowest-power charger capable of providing sufficient energy for the next planned trip segment. When multiple vehicles require charging simultaneously, a first-come, first-served allocation rule is applied to resolve potential conflicts. If charging cannot be immediately performed, the model evaluates whether the vehicle can continue its route using its remaining battery capacity or recover energy at a later stop.

During the simulation, the system records the minimum state of charge reached by each vehicle and verifies whether the full operational schedule can be completed without violating battery constraints. Configurations that allow all planned journeys to be completed are considered feasible. Among these feasible solutions, the optimal configuration is defined as the one that minimises the total infrastructure installation cost, which can be expressed as:

$$\min C = \sum_{i=1}^{n} NiCi \tag{1}$$

where N_i represents the number of chargers of type i installed at the depot and c_i represents the installation cost associated with each charger type. If no configuration fully satisfies the operational requirements, the model identifies the closest feasible solution and reports the locations and situations where energy shortages occur.

The FIST tool has been implemented in Python and can operate either as a standalone application or as a service integrated with the Logistics Planner platform. Integration is enabled through an API module built using the FastAPI framework, which allows the Logistics Planner to exchange data with the model using JSON-formatted requests. The API triggers route energy calculations through the NNG Routing API and passes the resulting dataset to the core optimisation module. Simulation results and recommended charger configurations are then returned to the frontend for interpretation by fleet operators.

4.2 Tool Evaluating Infrastructure Deployment En-Route (TEIDE)

The Tool Evaluating Infrastructure Deployment En-Route (TEIDE) supports charge point operators (CPOs) and infrastructure planners in determining suitable locations for installing en-route charging infrastructure. The tool provides a data-driven framework for estimating charging demand, forecasting utilisation levels, and evaluating potential revenues, thereby supporting robust business cases for infrastructure deployment.

The methodology implemented in TEIDE combines geospatial analysis with demand forecasting. The analysis begins when a user specifies a potential charging site location. Using a transport network graph derived from OpenStreetMap data, the model calculates the daily traffic flows passing within travel-time isochrones of five, ten, and fifteen minutes around the proposed site. Based on these traffic volumes, the model estimates the number of electric vehicles that may require recharging at the location, considering factors such as trip distances, vehicle battery ranges, and charging behaviour assumptions, including the potential availability of home or depot charging.

The estimated charging demand is then distributed between the candidate site and nearby charging stations identified through infrastructure registries such as Open Charge Map. In this step, the model incorporates an “added value” parameter reflecting the

relative attractiveness of the proposed location compared with competing charging sites. Based on the resulting charging demand allocation, the model generates forecasts of charging events, annual energy delivered, daily load profiles, utilisation rates, and potential revenue streams.

The TEIDE tool has been implemented in Python, with an interactive user interface developed using the Streamlit framework. The application operates as a web-based platform that can be embedded within existing digital environments and accessed without specialised software. External datasets are dynamically retrieved through APIs, including OpenStreetMap for geospatial data and Open Charge Map for charging infrastructure information. The results are presented through interactive visualisations, including maps displaying candidate sites, isochrone areas, and nearby charging infrastructure, as well as charts and tables summarising forecasted utilisation and energy demand. This combination of analytical modelling and accessible visualisation enables planners and decision-makers to evaluate infrastructure deployment strategies under different market and adoption scenarios.

5 Automated Fleet Management Tool

The Automated Fleet Management Tool supports real-time monitoring and operational decision-making for electric truck fleets. The system integrates planning data and GPS information provided by Datik's Computing Brain (DCB), enabling continuous updates on vehicle location and operational status. By mapping vehicle positions along predefined routes, the system monitors fleet punctuality and predicts arrival times at scheduled stops.

Operational data collected from vehicles and fleet management platforms are processed using predictive algorithms that analyse both historical and real-time information. A genetic algorithm is used to generate operational recommendations for fleet controllers, supporting improved scheduling, proactive delay management, and enhanced operational reliability. Through this approach, the system enables fleet operators to respond dynamically to changing traffic conditions, vehicle performance variations, and mission constraints.

The Tool consists of three main components: the embedded hardware module (DCB), the route tracking subsystem, and the recommendation engine, which together enable real-time fleet monitoring and predictive decision support.

The DCB hardware module is responsible for collecting and transmitting vehicle telemetry data to cloud-based services. It reads data from multiple Controller Area Network (CAN) interfaces and collects additional sensor information such as GPS coordinates and acceleration metrics. These data streams are transmitted to remote databases using communication protocols such as MQTT and standard web APIs, enabling reliable and scalable real-time data exchange.

The tracking subsystem processes the incoming GPS traces and maps them onto the planned vehicle routes. By integrating with Datik's fleet management platform Ipanel, the tracker continuously evaluates fleet punctuality and estimates arrival times at future stops. In demonstration cases, each pickup location is defined as a route stop, allowing the system to dynamically evaluate operational performance and respond to unexpected delays.

The recommendation engine processes the combined operational and historical datasets to generate decision-support recommendations for fleet operators. The engine applies machine-learning techniques and evolutionary optimisation algorithms to analyse patterns in operational behaviour and predict future vehicle performance. The system continuously improves its predictions by incorporating new operational data while maintaining a record of previously executed recommendations to prevent bias in future predictions. In cases where multiple vehicles operate on similar routes, shared traffic and operational information further improves prediction accuracy and supports coordinated fleet management decisions.

6 Conclusions

This paper presented an integrated digital ecosystem supporting the electrification of heavy-duty transport by combining strategic infrastructure planning tools with operational fleet management capabilities. The integration of the Logistics Planner and the Automated Fleet Management Tool enables coordinated mission planning, real-time vehicle monitoring, and data-driven operational decision-making.

The Eco-Charging Strategy Tool complements this operational layer through two planning models: the Fleet Infrastructure Strategy Tool (FIST), which supports depot charger configuration, and the Tool Evaluating Infrastructure Deployment En-Route (TEIDE), which identifies suitable locations for en-route charging infrastructure. Both tools rely on operational data and analytical modelling to support infrastructure planning for fleet operators and charge point operators.

By linking infrastructure planning with real-time fleet monitoring, the proposed ecosystem improves mission reliability, optimises charging infrastructure utilisation, and enhances operational visibility. The combination of predictive arrival-time estimation and infrastructure planning tools enables operators to better anticipate energy demand and optimise charging schedules.

The modular and interoperable architecture also facilitates integration with external routing services and charging infrastructure platforms. The scalability and adaptability of the proposed tools enable their deployment across different fleet configurations and operational environments, supporting Europe's transition towards sustainable freight transport.

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References

1. Gnann, T., Funke, S.Á., Jakobsson, N., Plötz, P., Sprei, F., Bennehag, A.: Fast charging infrastructure for electric vehicles: Today's situation and future needs. Transp. Res. Part D: Transp. Environ. **62**, 314–329 (2018). https://doi.org/10.1016/j.trd.2018.03.004

2. Unterluggauer, T., Rich, J., Andersen, P.B., Hashemi, S.: Electric vehicle charging infrastructure planning for integrated transportation and power distribution networks: a review. eTransportation. **12**, 100163 (2022). https://doi.org/10.1016/j.etran.2022.100163
3. Schiffer, M., Walther, G.: Strategic planning of electric logistics fleet networks: a robust location-routing approach. Omega. **80**, 31–42 (2018). https://doi.org/10.1016/j.omega.2017.09.003
4. Parmentier, A., Martinelli, R., Vidal, T.: Electric vehicle fleets: scalable route and recharge scheduling through column generation. Transp. Sci. **55**(3), 576–596 (2021). https://doi.org/10.1287/trsc.2023.1199
5. Geerts, D., Medina, R., van Sark, W., Wilkins, S.: Charge scheduling of electric vehicle fleets: maximizing battery remaining useful life using machine learning models. Batteries. **10**(2), 60 (2024). https://doi.org/10.3390/batteries10020060
6. Geng, S., Lee, T., Mallapragada, D., Botterud, A.: An integer clustering approach for modeling large-scale EV fleets with guaranteed performance. Electr. Power Syst. Res. **236**, 110650 (2024). https://doi.org/10.1016/j.epsr.2024.110650
7. Balogun, E., Buechler, E., Bhela, S., Onori, S., Rajagopal, R.: EV-EcoSim: a grid-aware co-simulation platform for the design and optimization of electric vehicle charging infrastructure. IEEE Trans. Smart Grid. **15**(3), 3114–3125 (2024). https://doi.org/10.1109/TSG.2023.3339374
8. Kin, B., Hopman, M., Quak, H.: Different charging strategies for electric vehicle fleets in urban freight transport. Sustainability. **13**(23), 13080 (2021). https://doi.org/10.3390/su132313080
9. NextETRUCK: D6.7 Eco-charging strategy Tool. project report, 13 March (2025)
10. NextETRUCK: D4.4 Self-learning fleet management system. project report, 31 October (2024)

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Policy Options to Reduce Emissions of L-Category Vehicles in the European Union and Expected Effects

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Abstract. L-category vehicles, including mopeds, motorcycles, quadricycles, and all-terrain vehicles, represent a significant pollution source, particularly in urban areas. This study assesses the effectiveness of the following mitigation measures – introduction of Real Driving Emissions (RDE) testing, adoption of stricter World Motorcycle Test Cycle (WMTC) limits, enforcement of anti-tampering provisions, changes in the driving behavior, and acceleration of the fleet replacement. All of them are compared in parallel into two distinct baseline scenarios, a high and low electrification for the period 2025–2050, to quantify environmental benefits and support evidence-based policy decisions for L-category vehicles. The policies were simulated using fleet emission projection models and the assessment was based on existing and updated emission factors derived from emissions data collected through laboratory emission tests, on-road measurements and roadside tests. Results show that the introduction of RDE testing achieves the most substantial reductions in NOx and CO emissions, with declines exceeding 17% by 2050 compared to the baseline scenario, highlighting the significance of decreasing the gap between laboratory and real-world performance. The accelerated fleet replacement has its highest impact on HC emissions, whereas in other air pollutants, it shows significant impact as well. The remaining measures achieve consistent improvements across all pollutants.

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Keywords: Emissions · L-category · Motorcycles · Emission policies · Emission reduction policies

1 Introduction

L-category vehicles - including mopeds, motorcycles, quadricycles, and all-terrain vehicles – represent an essential source of pollution across Europe, especially in urban environments [1]. Despite their relatively small size compared to other road transport vehicles, they contribute severely to urban air pollutant concentrations of Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NOx) and Particulate Matter (PM) [2] corresponding roughly 15% of CO emissions from road traffic in European Union (EU) for the year 2015 [3]. These air pollutants pose serious concerns for policymakers due to their well-established adverse impact on public health [4].

L-category vehicles define their emission limits based on the World Motorcycle Test Cycle (WMTC), which serves as the EU type-approval standard [5]. Unlike passenger cars, for L-category vehicles, there is no obligatory regulation for Real Driving Emissions (RDE) testing [6]. In addition, a considerable share of L-category vehicles is tampered, through practices such as catalyst removal, non-compliant silencers, or exhaust modifications, leading to elevated emissions [7]. Aggressive driving patterns further influence emissions, as rapid or frequent gear changes and sharp acceleration from standstill increase pollutant release [8].

This paper assesses the impact of selected mitigation measures that could be introduced by local and EU authorities to reduce emissions from L-category vehicles. The examined measures are the introduction of RDE testing, the adoption of stricter WMTC limits, the enforcement of anti-tampering measures, aimed at reducing the share of tampered vehicles, the behavioral policy interventions to promote smoother driving patterns, and the accelerated fleet replacement.

To evaluate these mitigation measures, a baseline scenario is developed, assuming no additional regulatory interventions, reflecting the projected evolution of the European vehicle fleet from 2025 to 2050. Given the importance of electrification, the analysis considers two parallel pathways: (1) a high electrification scenario with rapid market uptake of electric L-category vehicles, and (2) a low electrification scenario assuming a slower transition.

2 Methodology

2.1 Baseline Scenario

Fleet Modelling

The baseline scenario simulates the evolution of the European L-category vehicle fleet for the period 2025–2050, based on the latest statistical data up to 2024, from existing statistical databases [9], assuming no further regulatory interventions. The L-category vehicle fleet is classified into the following categories, covering all major segments of this sector, namely Mopeds 2-stroke and 4-stroke (<50 cm^3), Motorcycles 2- stroke

(>50 cm^3) and 4-stroke (<250 cm^3, 250–750 cm^3, >750 cm^3), Quads and ATVs, and Micro-cars.

An annual growth rate in the new registrations is assumed for each L-category vehicle segment, based on the historical European market trends. The age-dependent Survival Rates (SR) for each vehicle segment for the period 2025 to 2050 are calculated based on the statistical average vehicle age up to 2024, derived from the last five years of statistical data. Therefore, the evolution of the vehicle fleet is calculated using the following formula:

$$Stock_x = Stock_{x-1}\ x\ SR_{x-1} + New\ Registrations_x \quad (1)$$

where, x represents a year of the examined time period.

Considering the potential electrification market trends, two parallel baseline scenarios are modelled, assessing the mitigation measures within both frameworks. Hence, the baseline scenarios are (a) the high electrification scenario, assuming accelerated penetration of electrified vehicles in the fleet, and (b) the low electrification scenario, which reflects a slower transition to electrification, continuing the current market trends

Emission Modelling

The emission calculations apply for the baseline scenario, and the mitigation measures are carried out for regulated air pollutants, such as NOx, CO, HC, NMHC, PM, and non-regulated, NH_3 and PN. The general scheme for calculating emissions for a specific pollutant, year and vehicle category is the following:

$$E_{p,j,x} = N_{j,x}\ x\ M_{j,x} + EF_{p,j,x} \quad (2)$$

where E represents the total annual emissions, N the number of vehicles in operation, M the annual mileage per vehicle, EF the estimated factor in g/km, p the pollutant (Air pollutants), j the vehicle category, and x the year of calculation.

The terms $N_{j,x}$ and $M_{j,x}$ stem from the fleet modelling. The $EF_{p,j,x}$ derives from different sources depending on the Euro standard vehicle technology. In addition, it depends on many parameters, including driving patterns, environmental conditions and the level of vehicle maintenance. Therefore, to estimate the impact of different mitigation measures, the emission factor separates the contribution of different emission parameters (i.e. hot emissions within and outside normal driving conditions, cold effect, impact of degradation and tampering). Emission factors vary between the baseline and each mitigation measure and are calculated using the following general scheme:

$$EF_{final} = EF_{combined}\ x\ DF\ x\ (1 - TS) + EF_{combined}\ x\ TS\ x\ TR \quad (3)$$

where, EF_{final} represents the final estimated emission factor in g/km, $EF_{combined}$ the emission factor depending on the Euro standard vehicle technology in g/km, DF the deterioration factor of emissions at mean fleet mileage, TS the percent share of tampered vehicles, and TR the tampering emission rate. The parameters of Eq. 3 derive from emissions data collected through laboratory chassis dyno emission tests, on-road RDE tests, roadside remote sensing tests conducted within the LENS project [10, 11] and further analyzed by Triantafyllopoulos et al. [12]. 150 active L-category vehicles were

selected for emissions testing to ensure representative coverage of the EU fleet's subcategory distribution.

The calculation of the $EF_{combined}$ differs based on the vehicle Euro standard technology. For vehicles with Euro 5 technology, data from the LENS measurements are processed to distinguish the operating points inside and outside the WMTC driving conditions. To calculate the operating points, speed-emission maps are established for each vehicle category to characterize pollutant behavior and determine the corresponding emission factors. Therefore, the $EF_{combined}$ for vehicles with Euro 5 technology is the following:

$$EF_{combined} = (w_1 x EF_{insideWMTC} + w_2 x EF_{outsideWMTC}) + EF_{cold\ effect} \quad (4)$$

where, w_1 represents the fraction of mileage inside WMTC conditions, w_2 the fraction of mileage outside WMTC conditions ($w_1 + w_2 = 1$), $EF_{insideWMTC}$ the average emission level in g/km in the operating points inside WMTC, $EF_{outsideWMTC}$ the average emission level in g/km in the operating points outside WMTC, and $EF_{coldeffect}$ the mean excess emissions due to cold starting in g/km.

For the existing Euro standard technologies up to Euro 4, the $EF_{combined}$ stems from already established European data sources, including European COPERT V road transport emission model [13] and the Handbook Emission Factors for Road Transport (HBEFA) [14]. Specifically, COPERT is the European standard model for calculating air pollutants and greenhouse gas emissions from road transport, while HBEFA provides detailed emission factors for various vehicle categories, pollutants, traffic conditions, and road gradients widely used for emission inventories and policy assessments across Europe.

2.2 Mitigation Measures

Five mitigation measures are evaluated against both high and low electrification baseline scenarios. M1a assesses the potential emission reductions from introducing RDE testing for newly registered L-category vehicles from 2029, On average, 20% of vehicle operation occurs outside WMTC conditions and 80% within; therefore, the $EF_{outsideWMTC}$ is reduced to the level of $EF_{insideWMTC}$. The adoption of stricter WMTC emission limits (M1b) assumes a 15% reduction in regulated WMTC emission limits ($EF_{insdeWMTC}$) for all new vehicles from 2029 onward. M2 investigates the impact of implementing anti-tampering measures by reducing the share of tampered vehicles in the fleet by 70%, applied to new registrations from 2027. M3 represents smoother driving behavior across the entire L-category fleet by implementing direct reductions to the $EF_{combined}$ from 2027, based on the assumption that the average vehicle load will be reduced by 10%. Finally, M4 simulates accelerated fleet renewal by increasing new registrations by 20% between 2027–2040 through adjusted survival rates, thereby promoting faster replacement of older vehicles while maintaining a constant total fleet size.

3 Results

3.1 Baseline Scenario

Two parallel baseline scenarios are developed: (1) a high electrification scenario, in which electrified vehicles represent 50% of the total fleet by 2050, and (2) a low electrification scenario, where electrified vehicles account for 17% of the total fleet by 2050. Mopeds are projected to experience the most significant shift towards electrification, with all newly registered mopeds expected to be electric in 2050 under the high electrification scenario. In contrast, under the low electrification scenario, mopeds are anticipated to reach a 65% electrification share by 2050. Regarding motorcycles, electrification is projected to be lower across both scenarios, with the share generally decreasing as engine capacity increases. Based on the analysis of the remote sensing tests [11] and the literature review, the tampering share is assumed to be 15% for motorcycles and 45% for mopeds. The estimated tampering rates are applied as multiplicative factors in Eq. 3, with values of 5.9 for CO, 2.1 for NOx, 3 for HC and NMHC, 1.1 for NH_3 and 1.3 for PM and PN. Deterioration factors are estimated for two representative fleet mileage intervals, namely from 0 to 30,000 km and from 30,000 to 60,000 km. Indicatively, at 60,000 km, the multiplicative factors are 4.8 for CO, 2.1 for NOx, 2.2 for HC and NMHC, and 1 for PM and PN.

3.2 Mitigation Measures

High Electrification Scenario

Figure 1 presents the comparison of the proposed mitigation measures against the high electrification baseline scenario. The percentage reductions for NOx, CO, HC, NH_3 and PN are shown in panels (a) to (e), respectively. The graphs for PM and NMHC are not presented, as the reduction trends for PM closely follow those of PN, and NMHC reductions are similar to those of HC, with only minor quantitative differences.

As shown in panels (a) – (e), the introduction of RDE (M1a) delivers the largest reductions for most pollutants achieving decreases of up to 17% for NOx and CO and more than 12% for PN by 2050. M3, namely changes in driving behavior, provides moderate but consistent reductions (around 7–10%), for all pollutants, while M1b, stricter WMTC limits, achieves notably smaller effects. The anti-tampering measure (M2) has limited impact on NOx, CO, HC, and PN, but for NH_3, it leads to higher emissions, due to the conversion of NOx to NH_3 in the exhaust system, hence, preventing alterations in the exhaust bring about higher NH_3 emissions.

Low Electrification Scenario

Figure 2 presents the comparison of the proposed mitigation measures against the low electrification baseline scenario. The percentage reductions for NOx, CO, HC, NH_3, and PN are shown in panels (a) to (e), respectively.

Under the low electrification baseline scenario, the examined interventions exhibit generally similar patterns to those in the high electrification case, albeit there are some

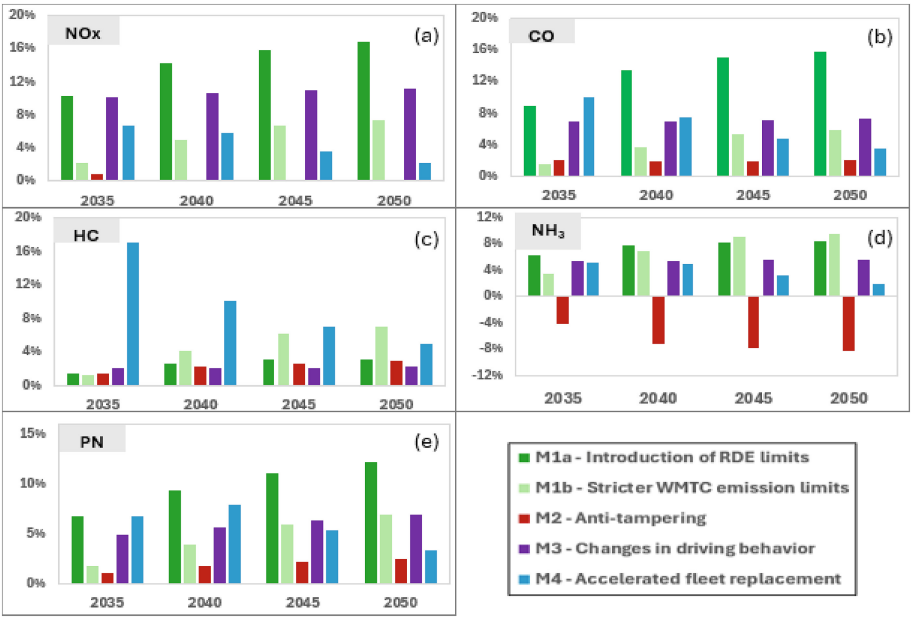


Fig. 1. Emission reductions of each mitigation measure compared to the high electrification baseline scenario: (a) NOx emission reductions, (b) CO emission reductions, (c) HC emission reductions, (d) NH_3 emission reductions, and (e) PN emission reductions.

notable differences. Specifically, for HC (Fig. 2c), M4 again delivers the largest reductions, although its effect declines over time. In contrast to the high electrification scenario, the reductions for M2 are stronger and more consistent over time. For CO (Fig. 2b), M2 reaches reductions of up to 6% by 2040, while the NH_3 trade-off (Fig. 2d) persists. For PN (Fig. 2e), the M1a continues to be the most effective measure, although the absolute reductions are slightly lower compared to the high electrification scenario.

Overall, the effectiveness of the mitigation measures depends on both the pollutant and intervention type. Accelerated fleet replacement performs better under high electrification due to the faster uptake of electric vehicles, leading to stronger early reductions. In contrast, the other measures perform better emission reductions in the low electrification scenario. Across both scenarios, RDE introduction provides the strongest overall reductions, except for HC, where fleet replacement remains the most effective strategy.



Fig. 2. Emission reductions of each mitigation measure compared to the low electrification baseline scenario: (a) NOx emission reductions, (b) CO emission reductions, (c) HC emission reductions, (d) NH_3 emission reductions, and (e) PN emission reductions

4 Conclusion

Despite their relatively small size, L-category vehicles (mopeds, motorcycles, quadricycles, and all-terrain vehicles) constitute a significant source of air pollution across Europe, especially in urban environments. Implementing strategies and measures that can combat this issue is of great importance. This study assesses five mitigation measures to reduce NOx, CO, HC, NMHC, NH_3, PM and PN emissions over 2025–2050: M1a (Introduction of RDE testing), M1b (stricter WMTC limits), M2 (anti-tampering measures), M3 (changes in driving behavior), and M4 (accelerated fleet replacement). These mitigation measures are compared in parallel under two distinct electrification pathways; a high electrification scenario achieving 50% vehicle electrification share of the total fleet by 2050, and a low electrification scenario reaching 17% electrification share by 2050.

The impact assessment shows that RDE testing (M1a) is the most effective intervention for most pollutants, achieving reductions of up to 17% for NOx and CO by 2050 compared to the baseline. Only for HC, accelerated fleet replacement (M4) delivers the greatest reductions, particularly in the early years. Anti-tampering (M2) and changes in driving behavior (M3) show moderate but steady reductions across pollutants. While overall impacts are similar under both electrification scenarios, the effectiveness of fleet renewal (M4) differs more substantially under the high electrification scenario, due to the faster replacement of older vehicles with electrified models. These findings provide a

quantitative basis for evidence-based policymaking to reduce emissions from L-category vehicles.

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References

1. Clairotte, M., Zardini, A., Martini, G.: Phase 1 of the Environmental Effect Study on the Euro 5 Step of L-Category Vehicles: Stocktaking and Data Mining, EUR 27994 EN. Publications Office of the European Union (2016). https://publications.jrc.ec.europa.eu/repository/handle/JRC102115
2. Kontses, A., Ntziachristos, L., Zardini, A.A., Papadopoulos, G., Giechaskiel, B.: Particulate emissions from L-category vehicles towards Euro 5. Environ. Res. **182**, 109071 (2020). https://doi.org/10.1016/j.envres.2019.109071
3. Ntziachristos, L., Papageorgiou, T., Mellios, G.: Input for the Preparation of Regulation (EU) No 168/2013 Article 23 Environmental Effect Study Report No: 13.RE.014.V1. EMISIA, Thessaloniki, Greece (2013)
4. World Health Organization: Air pollution. https://www.who.int/europe/health-topics/air-pollution. Last Accessed 28 Sep 2025
5. European Commission: Report from the commission to the European parliament and the council on the effects of the Euro 5 environmental step for L-category vehicles COM(2018) 136 final. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52018DC0136 (2018)
6. European Commission: Commission staff working document: report on the effects of the Euro 5 environmental step for L-category vehicles MEMO/18/3646. https://ec.europa.eu/commission/presscorner/detail/en/memo_18_3646 (2018)
7. Transport Research Laboratory: Tampering prevention in L-category vehicle approval legislation. PPR634. https://circabc.europa.eu/sd/a/21853310-427e-4333-a894-ca4047c84295/report-trl-ppr634_en.pdf (2012)
8. LENS Horizon Europe Project: D4.4: pollutants and noise emissions in the real world. https://lens-horizoneurope.eu/deliverables/ (2025). Last Accessed 26 Sep 2025
9. European Association of Motorcycle Manufacturers: Registrations. https://www.acem.eu/registrations/. Last Accessed 20 Sep 2025
10. LENS Horizon Europe Project: D4.2: Exhaust data from laboratory tests https://lens-horizoneurope.eu/deliverables/ (2025). Last Accessed 26 Sep 2025
11. LENS Horizon Europe Project: D5.3: results of field surveys on LV tampering https://lens-horizoneurope.eu/deliverables/ (2025). Last Accessed 26 Sep 2025
12. Triantafylopoulos, G., et al.: A comprehensive study on the on-road and chassis dyno emissions performance of motorcycles and other L-category vehicles. In: Proceedings of the TaP International Conference 2025, Paris, France (2025)
13. Emisia: COPERT – calculations of emissions from road transport. https://copert.emisia.com/. Last Accessed 25 Sep 2025
14. INFRAS: Handbook emission factors for road transport. https://www.hbefa.net/. Last Accessed 25 Sep 2025

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A Tracking Data-Based Evaluation of Truck Electrification Potential in Europe

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Abstract. This research explores challenges of transitioning heavy-duty truck (HDT) fleets to electric power, using real-world telematics data. By combining energy consumption modeling with total cost of ownership (TCO) analysis, the study identifies when battery-electric trucks (BETs) can viably replace diesel and liquefied natural gas (LNG) vehicles. As expected, battery capacity is a major barrier to widespread electrification. However, adopting customized battery configurations and enabling intermediate charging can greatly expand electrification opportunities while lowering yearly operating expenses. In addition to the approach with detailed daily route information from telematics data, this contribution presents a procedure to estimate the electrification potential for HDT fleets based on usage metadata, such as the distribution of daily driven kilometers and fuel consumption. Results of this approach for close to 300 fleets with about 22,500 trucks are presented. Further analyses show that differentiated toll costs can play a major role in the economic competitiveness of BETs. The study offers recommendations for fleet managers and policymakers, highlighting the importance of the deployment of reliable charging networks and the design of supportive regulations to accelerate the shift toward electric freight transportation.

Keywords: Green Freight Transport · Battery Electric Trucks (BETs) · Total Cost of Ownership (TCO) · Telematics Data · CO_2-Differentiated Toll Rates

1 Introduction

The road haulage sector accounts for a significant share of greenhouse gas emissions. HDTs, with high weight and mileage, are a central target for decarbonization. But their electrification faces significant technical and economic constraints. Unlike light-duty vehicles, the high energy consumption and long distances involved require large and costly batteries [1]. Thus, the key question is not only whether electrification is technically feasible but under what conditions it becomes competitive. We define electrifiability as the ability of a BET to meet two criteria: operational viability, i.e., completing routes without unplanned recharging, and financial viability, i.e., achieving a TCO no higher than by diesel or LNG truck.

Whereas operational viability is a prerequisite, oversizing batteries undermines financial viability by raising acquisition costs, weight and energy consumption [2]. Thus,

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optimal sizing involves matching battery capacity to the truck's mission profile rather than maximizing range [3]. [4] identify modular or configurable batteries as a key strategy. Nevertheless, limited range remains the main barrier to the electrification of long-haul transport. Achieving extended distances on a single charge requires massive and costly battery packs, often incompatible with carriers' constraints [1]. This challenge can nonetheless be mitigated by regulated driver breaks [5, 6], which represent an operational opportunity. Indeed, fast charging or battery swapping during mandatory stops, already integrated into logistics planning, could extend range without oversizing batteries and reduce TCO through better sizing. Modeling studies support this approach, showing that planned recharging can cover most long-haul routes with smaller, cost-competitive batteries, based respectively on statistical and real-world operational data, albeit for a specific driving cycle [7, 8].

Although several prior studies have addressed HDT electrification, many do not rely on telematics data from real-world logistics fleets. For example, [9] explored the feasibility of using BETs, but their analysis relied on randomly generated data to simulate operations, limiting its real-world relevance. In the context of electric buses, [10] proposed a model of energy demand based on data commonly available to public transit operators. Adopting a more pragmatic approach, [11, 12] estimated vehicle-specific battery capacity needs for truck fleets in Southern California and Germany, respectively. While both assessed the operational viability of truck electrification, neither one considered the economic dimension. In contrast, the present study also integrates an economic assessment into the estimation of the electrification potential.

2 Data and Sample Construction

The analysis is based on telematics data collected by a third-party company from 297 road freight fleets in Germany, comprising 266 diesel and 31 LNG fleets, totaling 22,488 trucks, of which 97.7% are diesel and 2.3% are LNG. The observation period covers the 2024 calendar year. To ensure statistical robustness, only vehicles with at least 120 distinct operating days and strictly positive fuel consumption data were retained, thereby excluding underutilized vehicles and incomplete datasets. Data governance and anonymization procedures were applied to protect sensitive information and ensure compliance with general data protection regulations. For each fleet, the available data comprise the fuel type, the number of vehicles, the total mileage in 2024, the median fuel consumption, and the distribution of maximum daily distances (MDDs). Trucks are classified into 100-km intervals according to their maximum recorded daily distance, after discarding outliers. The resulting counts per interval represent the empirical distribution of the fleet with respect to MDD. Figure 1 illustrates this distribution aggregated across all fleets. The histogram shows that less than 2% of vehicles operate in regional transport (MDD $<$ 200 km), while the vast majority fall within the long-haul segment. About 73% of trucks reach a MDD of 700–1,000 km, with a pronounced peak at 800 km, a range that typically requires two drivers to comply with driving time regulations.

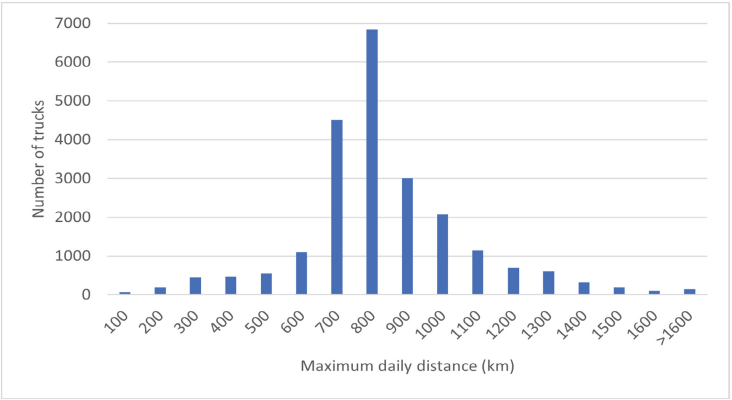


Fig. 1. Distribution of trucks by MDD

3 Operational Viability and Financial Viability

Each vehicle's daily electricity demand is estimated using the fleet's median fuel consumption, the MDD, and an energy conversion factor based on caloric values (10 kWh/L for diesel and 14 kWh/kg for LNG) and drivetrain efficiencies (45% for internal combustion engines and 90% for electric motors). The operational viability of fleet electrification is assessed under a cautious scenario, assuming that each vehicle systematically travels the upper bound of its observed daily distance class. Thus, a truck in the 300–400 km class is assumed to travel 400 km. This conservative approach guarantees electrifiability throughout the interval. The median value is preferred to the arithmetic mean, as it is less sensitive to outliers. A truck's daily fuel consumption is thus converted into an equivalent electricity demand. If this remains within the assumed battery capacity for its MDD, all annual operating days are feasible and the truck is technically electrifiable.

The financial viability of fleet electrification is assessed with a TCO analysis capturing fixed and operating costs, including vehicle and battery purchase, energy, tolls, maintenance, insurance, taxation, and key component replacement. A BET is economically competitive if its annual TCO does not exceed that of a comparable internal combustion truck (ICT). The method builds on [13] but differs by calculating TCO at the fleet rather than at the individual vehicle level. However, for subsequent analysis combining financial and operational viability, results are expressed per vehicle, with all trucks in the same fleet sharing the same TCO value. A representative over-18-tons gross vehicle weight, three-axle truck was used. For the purpose of this study, the diesel and LNG versions are assumed to be Euro VI and assigned to CO_2 class 1, while the electric model falls into CO_2 class 5. A detailed overview of all input parameters applied in the TCO analysis is provided in the base scenario of [13]. In the present study, only the toll rates have been adjusted. Based on the characteristics of the representative truck, the toll rate in Germany is 30.30 ct/km for LNG and diesel trucks, while BETs are exempt [14]. Annual mileage per vehicle is estimated by dividing each fleet's yearly distance by its number of trucks.

4 Results

The share of electrifiable vehicles by battery capacity is evaluated from three perspectives: operational, financial and combined viability. Operational viability increases modestly from 2.9% at 400 kWh to 9.8% at 800 kWh, revealing that most vehicles are limited by battery capacity. Financial viability applies to over 97% of vehicles, indicating that costs are not a limiting factor under toll exemptions. Combined viability, reflecting the overlap of both criteria, closely follows operational viability, highlighting the dominance of technical constraints. While the largest electrifiable share occurs at 800 kWh, some trucks meet operational viability with smaller capacities but become uneconomic due to battery oversizing. To address this, the analysis is refined by adapting battery capacity to fleet needs and allowing intra-day recharging. The results are presented in the next section.

5 Customized Battery Sizes and Intra-Day Recharging

In addition to adapting battery capacity, electrification potential depends on intra-day rechargeability. As shown previously, battery limitations restrict long-haul truck electrification, but daily available energy can be extended if recharging is possible during mandatory breaks or (un)loading periods. The following assumptions apply: (1) a 400-kW high-power charging station is available as needed, (2) all trucks are compatible with this power level, (3) one hour of charging provides an additional 400 kWh per day.

Figure 2 presents the share of electrifiable vehicles as a function of maximum battery capacity. A scenario with heterogeneous, customized battery sizes across fleets and its extension including intermediate recharging is compared with the base case (combined viability). The difference between the baseline scenario and the customized battery size strategy is minimal. By contrast, an additional 400 kWh per day greatly improves viability. It should however be noted that the benefits of intermediate recharging also depend on the effective availability of high-power charging infrastructure, whose reliable deployment and access remain a major real-world challenge.

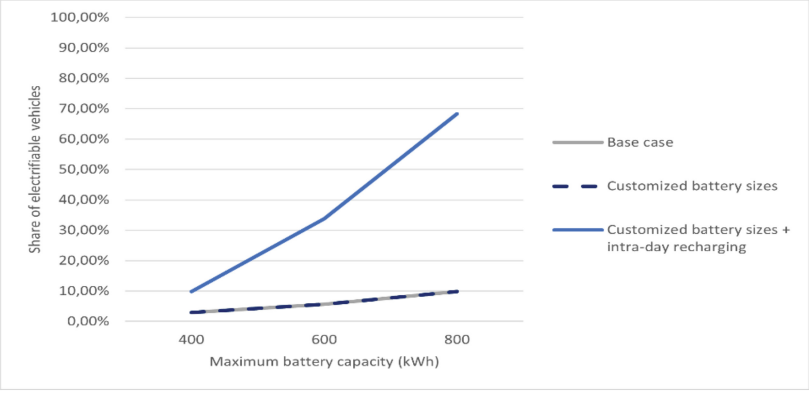


Fig. 2. Impact of customized battery sizes and intra-day recharging on electrification potential

6 Limitations of the Study

This study focuses on operational and economic feasibility. A full life-cycle CO_2 assessment was out of scope. However, the environmental benefits of electrification strongly depend on the electricity mix and battery production impacts, which vary significantly across European countries. Germany has set ambitious targets to decarbonize its power sector. In the first quarter of 2024, renewables accounted for 58.5% of electricity generation. However, in the first quarter of 2025, fossil fuels represented 50.5%, which is well above the European average [15]. This illustrates the current complexity and dynamic nature of estimating the environmental benefit of truck electrification.

As mentioned above, the availability of charging infrastructure is a critical factor in scenarios involving intermediate recharging and emerges as a key driver of truck electrification potential. This requires not only the presence of stations with sufficient capacity along the route, but also their effective accessibility, including adequate clearance for HDTs, compatibility with truck charging power, and operational availability (i.e., absence of prior occupation by another truck). To reflect the impact of temporary charging unavailability or limited charging power, a sensitivity test was conducted by reducing the assumed additional recharge energy by 10% (from 400 kWh to 360 kWh), while keeping the maximum onboard capacity at 600 kWh. Under this assumption, the electrifiable share of vehicles falls from 33.8% to 25.3%, corresponding to a 25% relative decrease.

Moreover, the model provides a rough assessment of electrification viability and is not intended to deliver precise values. The results should be interpreted as indicative estimates for assessing long-haul fleet electrification under stated assumptions and identifying key thresholds. Several simplifying assumptions contribute to this limitation. Indeed, energy conversion is based on standardized calorific values and efficiency factors, which cannot fully capture real-world variations in altitude, payload, temperature, or driving style. Likewise, relying on median fuel consumption smooths inter-vehicle variability but may conceal differences that are critical for technical assessments. In addition, the upper-bound approach derives daily electricity demand from each truck's maximum observed distance, ensuring vehicles remain electrifiable under pessimistic conditions, but likely overestimating energy demand.

Finally, it should be noted that the dataset is strongly biased toward long-haul operations. The results presented here may not be representative of fleets engaged in shorter-distance transport, where the economic benefits of toll exemptions for electric vehicles are likely to be less pronounced.

7 CO_2-Differentiated Toll Rates as a Driver of Electrification

The case study focuses on German-based fleets, where long-haul transport, frequently involving international routes, constitutes the dominant segment. For such fleets, economic viability must be ensured not only domestically but also along cross-border routes. In this context, CO_2-differentiated toll rates represent a key factor shaping the competitiveness of BETs across different regulatory environments. Table 1 presents the toll rates applied in selected European countries by fuel type for the representative truck.

Table 1. Country-specific toll rates by powertrain type

Country	Germany	France	Poland	Italy
Toll rate for ICTs	30.30 ct/km	26.02 ct/km	9.40 ct/km	11.05 ct/km
Toll rate for BETs	0.00 ct/km	26.02 ct/km	9.40 ct/km	11.05 ct/km

These toll rates are applied successively per country to assess their impact on electrification potential. In France, the weighted average infrastructure charge for HDTs amounted to 26.02 ct/km in 2023 [16]. The data for Poland have been converted based on the exchange rate of 1 Polish zloty = 0.235 euro (on 13 September 2025) [17]. In the case of Italy, the toll scenario reflects an average rate that accounts for the country's topography, including both mountainous and plain areas [18].

The results differ from those obtained for Germany but are identical for France, Italy and Poland, as no toll exemptions are currently granted in these countries. In the most favorable case – when intermediate recharging is possible – the electrification rate quickly reaches a plateau at 12.2%, since the electric option ceases to be economically viable once battery capacity reaches 600 kWh. This highlights the need for a clear toll differential between ICTs and BETs to make the latter a viable alternative. To illustrate this, the Polish case is examined under the assumption that BETs are exempt from tolls. Compared with Germany, electrification rates remain similar up to 700 kWh despite a smaller toll differential, as combustion trucks face lower toll rates in Poland. Beyond this capacity, electrification viability plateaus, but only at battery sizes not yet available on the market.

In summary, the economic viability of BETs fundamentally relies on toll differentiation by energy source. Given current battery limitations, even modest toll differences can have a significant impact.

8 Discussion and Conclusion

Beyond the upper-bound assumption, daily electricity demand was estimated from each truck's maximum observed distance, regardless of how often it was reached. However, the MDD often exceeds the typical operating range of the vehicle. Relying instead on the interpolated median distance yields lower demand estimates than the upper-bound approach. This highlights that electrification viability depends not only on battery capacity but also on route structuring: splitting or redistributing the longest routes could increase the share of electrifiable trucks. However, such adjustments may be challenging in long-haul operations, where routes are already tightly optimized.

According to [19], Germany ranked second in Europe for BET adoption in 2023, after the Netherlands. This position reflects the impact of German toll exemption policy, which significantly improved the economic viability of these vehicles. Although [20] requires motorway tolls to vary with CO_2 emissions, Article 7(7) allows Member States to defer application where concession contracts make amendments legally difficult. France relies on this exemption, so tolls on concession motorways are not differentiated by CO_2 class. By contrast, new concession agreements will have to comply with EU

rules. Nevertheless, if policymakers aim to accelerate BET adoption, CO_2-based toll modulation will need to be applied across the entire motorway network.

In summary, technical constraints of long-haul truck electrification may be mitigated through recharging during mandatory breaks or (un)loading periods. Thus, in the German scenario, the electrifiable share rises from 5.6% to 33.8% with a 600-kWh battery and a 400-kWh intermediate recharge. However, the economic dimension remains a major barrier when no toll differentiation is applied between ICTs and BETs. Indeed, for Poland, even with intermediate recharging, only 12.2% of the fleet is electrifiable, whereas this share reaches 33.7% when BETs are exempt from tolls.

From a policy perspective, the findings underline the need for harmonized and ambitious toll regulations across Member States. Even relatively modest incentives, when applied consistently, can significantly increase the share of viable BETs. In this sense, the EU framework provides an essential basis, but its effectiveness ultimately depends on national implementation of CO_2-differentiated toll rates. Germany's exemption policy for BETs has significantly accelerated their adoption, whereas France's concession-based system illustrates how legal and institutional constraints can delay their implementation. In summary, achieving large-scale electrification of road freight requires not only technological advances in battery capacity and the deployment of charging infrastructure but also a coherent policy environment that structurally favors zero-emission vehicles. Without such conditions, the uptake of BETs in long-haul transport is likely to fall short of mass adoption.

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References

1. Sripad, S., Viswanathan, V.: Quantifying the economic case for electric semi-trucks. ACS Energy Lett. **4**(1), 149–155 (2019)
2. Smith, D., et al.: Medium- and Heavy-Duty Vehicle Electrification: an Assessment of Technology and Knowledge Gaps. Oak Ridge National Laboratory and National Renewable Energy Laboratory, United States (2020)
3. Schneider, J., Teichert, O., Zähringer, M., Götz, K., Lienkamp, M.: Spoilt for choice: user-centric choice of battery size and chemistry for battery-electric long-haul trucks. Energies. **17**(1), 158 (2024)
4. Becker, J., Nemeth, T., Wegmann, R., Sauer, D.U.: Dimensioning and optimization of hybrid li-ion battery systems for EVs. World Electr. Veh. J. **9**(2), 19 (2018)
5. European Union: Directive 2006/22/EC on Minimum Conditions for the Implementation of Council Regulations (EEC) no 3820/85 and (EEC) no 3821/85 Concerning Social Legislation Relating to Road Transport Activities, L102, pp. 35–43. Official Journal of the European Union (2006)
6. Federal Motor Carrier Safety Administration: Hours of service of drivers. Fed. Regist. **85**(105), 33396–33452 (2020)

7. Mareev, I., Becker, J., Sauer, D.U.: Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. Energies. **11**(1), 55 (2018)
8. Sader, K.M., Biswas, S., Jones, R., Mennig, M., Rezaei, R., Green, W.H.: Battery electric long-haul trucking with overnight charging in the United States: a comprehensive costing and emissions analysis. Appl. Energy. **384**, 125443 (2025)
9. Dessouky, M., Yao, S.: Routing of Battery Electric Heavy-Duty Trucks for Drayage Operations. National Center for Sustainable Transportation, University of Southern California (2023)
10. Gallet, M., Massier, T., Hamacher, T.: Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. Appl. Energy. **230**, 344–356 (2018)
11. Feng, G., Rindt, C.R., Ritchie, S.G.: From diesel to electric: potential of drayage trucks transition in Southern California. iScience. **28**, 112629 (2025)
12. Speth, D., Plötz, P.: Depot slow charging is sufficient for most electric trucks in Germany. Transp. Res. Part D: Transp. Environ. **128**, 104078 (2024)
13. Meyer, M., Bousonville, T.: Analysis of truck electrification potential based on real-world data. Transp. Res. Procedia. **91**, 107–114 (2025)
14. Bundesministerium für Verkehr: Mautsätze für mautpflichtige Lkw ab 1. Juli 2024 bis 31. Dezember. https://www.bmv.de/SharedDocs/DE/Anlage/StV/mautsaetze-fuer-mautpflichtige-lkw-2024-2025.html (2025). Last Accessed 14 Sep 2025
15. Statistisches Bundesamt: Stromerzeugung im 1. Quartal: Anteil der fossilen Energiequellen und erneuerbaren Energien. https://www.destatis.de/DE/Presse/Pressemitteilungen/2025/06/PD25_200_43312.html (2025). Last Accessed 04 Feb 2026
16. Ministère de l'aménagement du territoire et de la décentralisation: Les péages perçus sur le territoire français. https://www.ecologie.gouv.fr/politiques-publiques/peages-autoroutes-francaises. Last Accessed 14 Sep 2025
17. e-TOLL: Change in toll rates for heavy vehicles from 1 January. https://etoll.gov.pl/en/news/change-in-toll-rates-for-heavy-vehicles-from-1-january-2025/ (2025). Last Accessed 14 Sep 2025
18. Autostrade per l'Italia: How the toll is calculated. https://www.autostrade.it/en/servizi-al-cliente/pedaggio/come-si-calcola-il-pedaggio. Last Accessed 14 Sep 2025
19. ACEA: New commercial vehicle registrations: vans +14.6%, trucks +16.3%, buses +19.4% in 2023. https://www.acea.auto/cv-registrations/new-commercial-vehicle-registrations-vans-14-6-trucks-16-3-buses-19-4-in-2023/. Last Accessed 14 Sep 2025
20. European Union: Directive (EU) 2022/362 Amending Directives 19999/62/EC, 1999/37/EC and (EU) 2019/520, as Regards the Charging of Vehicles for the Use of Certain Infrastructures, L69, pp. 1–39. Official Journal of the European Union (2022)

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2030 and 2050 Foresight Scenarios for Zero Emissions Waterborne Transport Deployment

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Abstract. Europe is facing an existential transformation as it strives to meet climate neutrality by 2050, with shipping as a cornerstone in achieving climate objectives while ensuring Europe's security and competitiveness.

Clear and comprehensive foresight scenarios in which ZEWT (Zero Emission Waterborne Transport) will be deployed are essential to provide ZEWT decision makers and indirect stakeholders at policy, investment, industry, technology and operational level with the necessary comprehensive and reasoned set of knowledge and recommendations. The clarity of positive and negative externalities of a future system, the limited uncertainties on factors shaping and quantifying the demand and type of future services, and the capability to progress under an ecosystemic approach towards novel business models and technologies are crucial to overcome resistance to change and leverage efficient investments, under regulatory pressures. The paper will provide an overview of the most possibly realistic picture of boundaries, uncertainties, and dependencies resulting from socio-cultural, political, technological, and economic trends that will determine the context in which surveyed technologies and concepts will be allegedly incorporated in the 2030 and 2050 target time horizons.

Keywords: Zero Emission Waterborne Transport · Strategic Foresight · Maritime Decarbonization · Alternative Marine Fuels · Fit for 55

1 Introduction

The European maritime transport sector represents a critical component of regional and global transport infrastructure. Currently, Europe controls approximately 20% of the global merchant fleet (measured in gross tonnage or number of vessels), despite representing only 5% of the world's population and 15.2% of global GDP [1].

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However, this sector is facing an existential transformation driven by the imperative to achieve climate neutrality by 2050, in line with the European Green Deal and the "Fit for 55" legislative package. Historically largely excluded from EU climate policies, maritime transport is now at the center of a new regulatory and technological trajectory, being responsible for approximately 144 million tonnes of CO_2 within the European Economic Area [2]. The objective of this document is to establish a knowledge base to guide the transition toward Zero Emission Waterborne Transport (ZEWT) within the 2030 and 2050 time horizons. By integrating scientific and technical data, including findings from the *Fourth IMO Greenhouse Gas (GHG) Study*, the paper assesses how socio-political, technological, and economic trends are reshaping maritime transport [3]. The transition requires not only the adoption of alternative fuels but also the integration of critical enablers such as digitalization and automation, alongside a holistic assessment of physical climate change risks and geopolitical dynamics.

2 Methodology

The methodological framework adopted in this study is based on strategic foresight techniques. The purpose of strategic foresight is not to predict the future with absolute certainty by extrapolating past data, but rather to build plausible representations of how global systems might evolve in light of economic, social, technological, environmental, and political variables. In the context of maritime sustainability, the "foresight scenarios" methodology is essential to help stakeholders anticipate the long-term implications of decarbonization policies, regulatory shifts, and the impact of climate change. The scenario construction was conducted through an "exploring the future" approach, which is divided into four cumulative analytical phases: [4]

- **Horizon Scanning**: The systematic identification and collection of weak signals and early indicators of change that could evolve into significant transformation drivers.
- **Driver Mapping**: Mapping the key forces (economic, technological, regulatory, environmental) shaping the current system, analyzing their interdependencies to outline the landscape of possible futures.
- **Trend Analysis**: The aggregation of signals and events to reveal the most likely directions of change, distinguishing short-term fluctuations from long-term structural transformations.
- **Futures/Implications Analysis Wheel**: A structured and visual exploration of the cascading impacts, both direct and indirect, of the identified trends to understand their systemic interactions.

For the analysis of the current state of the fleet, the methodology relied on the taxonomy established in the *Fourth IMO GHG Study*, allowing for a detailed classification of ship types. The baseline data reflects the state of the global fleet as of mid-2025, excluding vessels classified as scrapped, sunk, or lost.

3 Key Drivers of the ZEWT Transition

The transition toward Zero Emission Waterborne Transport (ZEWT) is driven by a complex interplay of regulatory factors, financing mechanisms, technological developments, safety imperatives, and global macro-trends. These elements constitute the strategic pillars necessitating a radical restructuring of European naval architectures and logistical infrastructures, outlining the decarbonization pathway through 2050.

3.1 Technological Evolution

Technological evolution for the 2030 decade is based on "fuel-ready" naval architectures, characterized by structural integration standards designed to allow rapid adaptation to future fuels such as ammonia, methanol, hydrogen, or advanced biofuels. Currently, methanol engines see a solid adoption rate due to simpler supply chains, while the residual role of Liquefied Natural Gas (LNG) is tied to the need to mitigate "methane slip" to remain compliant. Propulsion plants are moving away from the concept of a single primary engine in favor of hybrid systems: engines, fuel cells, and battery banks operate in an orchestrated manner via an Energy Management System (EMS) to reduce consumption and manage transient loads. Digitalization is consolidating as an infrastructure system layer. The use of interoperable "digital twins", demonstrated in projects like DT4GS [5], allows for continuous simulations of efficiency and emissions. In parallel, traffic synchronization through ecosystems like Port Collaborative Decision-Making and Just-in-Time arrival procedures has quantified fuel savings of up to 8% in the last 24 h of a voyage, with port waiting time reductions reaching 20%. Regarding land-based infrastructure, fast charging and Onshore Power Supply are becoming essential; the AFIR regulation mandates that by 2030, all passenger and container ships must have the possibility to connect to the electrical grid in main TEN-T ports, ending the use of auxiliary generators at the quay [2].

3.2 Regulatory Framework

The regulatory architecture serves as the primary coercive mechanism to internalize environmental externalities. Globally, the IMO strategy revised in 2023 sets the goal of reaching net-zero greenhouse gas (GHG) emissions "by or around" 2050. To ensure this progress, the IMO has introduced indicative targets to reduce GHG emissions by 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040, based on 2008 levels. At the regional level, the European Commission has established an even more stringent regulatory pace through the "Fit for 55" package. The FuelEU Maritime regulation imposes progressive restrictions on the GHG intensity of fuels used by ships of 5,000 GT or more, requiring a 2% cut in 2025 up to an 80% reduction by 2050, evaluated on a "well-to-wake" basis. This regulation introduces dynamic compliance mechanisms such as banking, borrowing, and pooling, which allows different fleets to combine emission balances for joint compliance. Simultaneously, Directive (EU) 2023/959 [6] extended the EU ETS to the maritime sector, requiring operators to purchase emission allowances; offsets will start at 40% of 2024 emissions, reaching 100% coverage by 2027. From 2026, the EU ETS will also penalize methane and nitrous oxide, in line with new monitoring obligations dictated by the MRV regulation revision active since January 2024 [2].

3.3 Safety and Security

The integration of zero-emission fuels and automation exposes the fleet to unprecedented risk categories. New energy carriers bring chemical and physical hazards: ammonia is severely toxic if leaked, hydrogen presents extreme flammability requiring cryogenic containment, and methanol burns with a virtually invisible flame. An IMO survey highlighted significant gaps in "regulatory readiness," confirming the urgency of developing universal fuel quality standards, containment codes, and spill management procedures. Regarding Maritime Autonomous Surface Ships (MASS), there is a regulatory vacuum in historical conventions such as SOLAS, STCW, and COLREG, which were designed for a responsible human presence on board. To govern this innovation, the IMO expects to adopt a non-mandatory MASS Code in 2026, intended to evolve into a binding instrument by 2032 [7, 8]. The operation and monitoring of these units will fall to Land-Based Control Centers (LBCC), which must handle remote supervision, diagnostics, and emergency shutdowns in case of failures. This model exponentially increases cyber risk. Vulnerabilities in onboard OT/IT systems, such as bridge systems or power control, can cause serious accidents; the IMO has therefore issued resolution MSC.428(98), mandating companies to integrate robust cyber risk management defenses into their SMS manuals.

3.4 Current Business Models, Investment and Financing Mechanisms

The high capital expenditure (CAPEX) required for zero-emission fleets has made traditional operating models obsolete. The industry is transitioning toward new "servitized" business models (such as *Propulsion-as-a-Service*), where technological and financial risks are shared with providers, who are remunerated based on guaranteed performance and verified fuel savings. Cross-sector alliances are also emerging through innovation consortia and "green chartering" agreements that link freight rates to environmental metrics. To bridge the financial gap, investment mechanisms combining private funds with public support (blended finance) and public-private partnerships are becoming more established.

Central to this effort is the support of the European Union: The Innovation Fund, financed by EU ETS revenues with an estimated budget of approximately €40 billion for the 2020–2030 period, covers up to 60% of costs for high-risk, pre-commercial projects [9]. These initiatives are complemented by research programs such as Horizon Europe, infrastructure development through the Connecting Europe Facility (CEF), and advantageous credit lines from the European Investment Bank (EIB), creating an ecosystem capable of making the technological transition commercially viable.

3.5 European and Global Trends

Finally, the European waterborne transport sector is impacted by profound exogenous instabilities. From a geopolitical standpoint, conflicts and instability reorganize supply chains and drive up costs. The proliferation of "shadow fleets" to transport sanctioned crude has saturated between 17% and 63% of the global capacity of certain tankers,

causing a vertical surge in maritime accidents and triggering an increase in "war-risk" insurance premiums of up to 1,500%.

Parallelly, an urgent demographic challenge is emerging. The maritime workforce is aging (with an average age for officers and captains in Europe of 43.6 years). In 2021, the shortage of STCW-certified officers was already 26,240 units, a number projected to rise sharply by 2026. The lack of qualified technical personnel directly hinders the upskilling essential for managing hi-tech propulsion and hazardous fuels. Regarding social acceptance, the "NIMBY" phenomenon often emerges concerning infrastructure for dangerous fuels near urban centers or toward nuclear propulsion, which, despite being energy-dense, remains an option blocked by public skepticism and complex regulatory frameworks. Finally, the fallout of climate change forces the industry to adapt: extreme events, changes in wave patterns, and droughts threaten port infrastructure and the regularity of river and ocean routes. The receding ice has made the Northern Sea Route (NSR) navigable, capable of reducing Euro-Asian routes by 40%, while simultaneously sparking serious concerns for delicate Arctic ecosystems.

4 2030 and 2050 Foresight Scenarios

The evolution of the European maritime and port system is a complex trajectory driven by multiple interacting variables. To navigate this uncertainty, a strategic foresight methodology establishes three plausible scenarios: "Regulated Transition," "Accelerated Transition," and "Fragmentation and Delays." These are projected across two critical horizons: 2030, serving as a baseline for intermediate technological adoption and policy efficacy, and 2050, reflecting long-term structural transformations in technology, governance, and the global context [10].

4.1 Scenario 1: Regulated Transition

This scenario envisions a gradual, policy-driven transformation anchored in steady technological adoption and the enforcement of EU regulations.

- **2030 Horizon:** By 2030, the European maritime system undergoes a carefully managed evolution. Key regulatory frameworks, notably the FuelEU Maritime regulation and the inclusion of shipping in the EU Emissions Trading System (ETS), are fully operational. These mechanisms increase the cost of carbon emissions, incentivizing cleaner technologies. However, shipowners predominantly adopt a cautious strategy, prioritizing retrofits and the deployment of dual-fuel vessels to control capital expenditure while maintaining operational flexibility. Infrastructure development is highly concentrated: major ports expand their capacity for alternative fuels like LNG and ammonia, while smaller, regional ports lag due to financial constraints. Digitalization, including energy monitoring and route optimization, advances steadily, though comprehensive data integration between vessels and ports remains limited. Consequently, emission reductions are moderate and not yet aligned with the pace required for full climate neutrality.

- **2050 Horizon:** By mid-century, this trajectory results in a stable, moderately decarbonized, but uneven maritime ecosystem. The fleet is heterogeneous, combining new zero-emission vessels powered by green ammonia, hydrogen, and synthetic fuels with older ships relying on transitional options. Large ports operate as multi-fuel energy hubs, while regional disparities persist. Ultimately, the transition is controlled but risks locking into transitional technologies, achieving only partial climate neutrality.

4.2 Scenario 2: Accelerated Transition

The "Accelerated Transition" scenario is characterized by a rapid, coordinated transformation driven by strong policy alignment, robust financial support, and widespread innovation.

- **2030 Horizon:** By 2030, governments, financial institutions, and private sectors operate in strict alignment. Ambitious mandates are paired with aggressive green incentives (such as tax breaks, co-financing schemes, and low-interest loans) making sustainable technologies highly competitive. Shipowners rapidly procure zero-emission-ready vessels, and ports proactively deploy large-scale infrastructure for hydrogen, ammonia, and e-fuels. Digital platforms facilitate real-time ship-port communication, optimizing routing and fuel consumption, while automation enhances both safety and efficiency. This rapid shift stimulates green industrial growth, though it introduces risks of overconcentration of capital and exacerbates the shortage of skilled maritime labor, leaving smaller operators struggling to adapt.
- **2050 Horizon:** By 2050, Europe secures a position as the global leader in sustainable maritime technology. The fleet is fully decarbonized and highly automated, operating within a digitally integrated logistical network. Ports function as integrated renewable energy hubs that manage local generation, storage, and distribution. While environmental sustainability and strong economic competitiveness are achieved, new systemic challenges arise regarding social equity and the monopolistic concentration of resources among large corporate entities.

4.3 Scenario 3: Fragmentation and Delays

The "Fragmentation and Delays" scenario outlines a regressive trajectory marked by policy incoherence, underinvestment, and geopolitical instability, resulting in a slow and uneven adaptation.

- **2030 Horizon:** In this scenario, the policy landscape across Member States is disjointed: while some nations invest in clean technologies, others maintain a persistent reliance on fossil fuels to avoid the economic shock of the transition. This lack of coordination generates market distortions. Infrastructure investment is localized and reactive, with a few advanced hubs attracting capital while the vast majority of ports lack necessary upgrades. Furthermore, rising climate-related disruptions, such as extreme storms and flooding, expose the vulnerabilities of the sector, leading to declining logistical reliability and surging insurance costs.
- **2050 Horizon:** The cumulative effect of delayed action results in the structural decline of the European maritime system by 2050. The absence of a unified green market and chronic underinvestment means that older, fossil-fuel-consuming vessels remain

dominant, driving up operational and maintenance costs. Europe loses its competitive edge to Asian and American fleets that successfully navigated their transitions. Environmentally, chronic climate impacts cause severe degradation of coastal infrastructure, leading to recurring port closures. The ultimate socio-economic consequences include widespread job losses, exacerbated regional inequalities, and significantly higher trade costs, highlighting the profound risks of systemic vulnerability.

5 Discussion and Policy Recommendations

The strategic foresight analysis indicates that the European maritime sector's transition toward Zero Emission Waterborne Transport (ZEWT) depends on collective governance, strategic vision, and decisive stakeholder action to overcome persistent barriers. Critical bottlenecks include financial and technological uncertainties—stemming from the early maturity of zero-emission technologies and external infrastructure dependencies—alongside international regulatory ambiguity and policy fragmentation, which deter investment. Regardless of the unfolding scenario, ensuring a resilient, competitive, and sustainable transition requires prioritizing the following policy recommendations:

- **Strengthening Policy Coherence and Long-Term Vision:** A stable, harmonized regulatory framework is essential. The EU and its Member States must align maritime, energy, and industrial policies to prevent conflicting objectives, provide predictable investment signals, and mitigate regulatory fragmentation.
- **Promote an Inclusive and Just Transition:** Decarbonization must avoid exacerbating industry inequalities. The shift toward digitalized, alternative-fuel vessels necessitates extensive workforce upskilling. Dedicated funding and training must target SMEs, peripheral port authorities, and seafarers to prevent their marginalization amid rapid technological changes.
- **Invest in Dual-Use and Climate-Resilient Infrastructure:** Developing flexible, modular port infrastructure for multiple alternative fuels is necessary to prevent technological lock-in and stranded assets. Furthermore, ports require climate-informed design, asset elevation, and coastal protection to withstand escalating environmental risks.
- **Enhance Digital Integration and Cyber Resilience:** Digitalization must be coupled with robust cybersecurity and data interoperability. As vessels evolve into interconnected cyber-physical systems linked with LBCC and Port Community Systems, securing these networks is paramount to ensure operational continuity.
- **Embed Foresight and Monitoring Mechanisms:** Establishing a permanent monitoring unit is critical for continuously assessing emerging signals, technological trends, and regulatory shifts. Regular scenario reviews (every 3 to 5 years) will ensure policies remain adaptive, evidence-based, and responsive to both geopolitical and technological developments.

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References

1. Eurostat news articles. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240530-2. Last Accessed 30 Mar 2026
2. TRUSTEE project: D1.1 - ZEWT foresight scenarios Horizon Europe - Grant Agreement 101192328 (2025)
3. International Maritime Organization: Fourth IMO GHG study 2020 - full report and annexes (2020)
4. UNDP: UNDP RBAP: foresight playbook, New York (2022)
5. DT4GS Consortium: Deliverable D2.3 – digital twin architecture for green shipping, Horizon Europe grant agreement 101095331 (2024)
6. European Commission: Directive (EU) 2023/959 Official Journal L 130 (2023)
7. IMO. https://www.imo.org/en/mediacentre/pressbriefings/pages/massrse2021.aspx. Last Accessed 30 Mar 2026
8. Batista, R.: Non-Mandatory MASS Code Development - Current Status and Report from MSC 108. International Maritime Organization, London (2024)
9. Osipova, L., Carraro, C.: The Maritime Sector in the European Union Emissions Trading System. International Council On Clean Transportation (2023)
10. The Japan Association of Marine Safety: Northern Sea Route Handbook (2015)

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A Data-Driven Physics-Based Model for Energy Optimization and Electrification of Indian Freight Transport

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Abstract. India's freight transport sector faces critical electrification challenges due to diverse terrain, variable infrastructure, and cost-sensitive markets. This study develops a physics-based energy consumption model integrated with real-world route data to enable accurate energy prediction for commercial electric vehicles. The model incorporates vehicle dynamics, terrain profiles, and operational parameters across seven truck segments (14 T–55 T) validated against 26 routes spanning expressways to mining circuits. Statistical analysis reveals strong predictive capability ($R^2 = 0.813$) significantly outperforming pure data-driven regression approaches ($R^2 = 0.28$) on the same dataset. Loading elasticity analysis demonstrates sub-proportional energy increases (elasticity 0.75–0.78), enabling efficiency improvements through intelligent load management. The framework delivers route-specific energy predictions for infrastructure planning and total cost of ownership analysis. While calibrated for Indian conditions, the modular methodology is transferable to other emerging markets with appropriate parameter recalibration.

Keywords: Electric vehicles · freight transport · energy consumption modelling · physics-based simulation · Indian freight corridors

1 Introduction

India's freight transportation sector faces critical challenges, with logistics expenses accounting for 14% of GDP [1] while generating substantial inefficiencies through excessive fuel consumption and rising emissions. Electric trucks offer dual benefits of decarbonization and operational cost reduction, aligning with India's cost-first economic approach. However, current transportation planning methodologies [2] rely on oversimplified approaches—generic drive cycles and rough multiplication factors—that fail to capture diverse terrain, route profiles, and loading conditions characteristic of large heterogeneous freight networks.

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Energy consumption in freight operations varies significantly with terrain, payload, and driving patterns. While operational variability is a feature of freight networks globally—including in European and North American corridors—the combination of terrain diversity (sea-level coastal plains to 3,500 m Himalayan passes), irregular loading practices including routine overloading, predominantly owner-operator business models, and limited instrumented fleet data creates particular challenges for accurate energy estimation in India and comparable emerging markets.

This research develops an integrated physics-data framework combining vehicle dynamics with real-world Indian freight corridor data, incorporating route gradients, speed profiles, vehicle specifications, and payload variations. The key contribution is demonstrating that physics-based approaches substantially outperform pure data-driven methods in data-scarce environments ($R^2 = 0.813$ vs. 0.28 for regression on the same dataset), while providing a deployable framework requiring only vehicle specifications and route elevation data as inputs.

2 Literature Review

Existing energy consumption models fall into three categories: physics-based, data-driven, and hybrid approaches. Physics-based models using Newtonian mechanics offer transparency and generalizability but require calibration for local conditions [3]. Data-driven approaches have demonstrated strong performance in instrumented environments; one study achieved 86.58% accuracy using random forest algorithms [4], while another showed that multivariate adaptive regression splines enhance prediction when extensive datasets are available [5].

Several studies have advanced terrain-sensitive modelling. One research highlighted the need for terrain corrections in heavy-duty drive cycle development [6]. Another research developed computationally efficient approaches for real-world EV energy estimation [7]. One more study demonstrated that route choice significantly impacts energy consumption [8]. Another paper developed sophisticated models for heavy-duty trucks, though validation relied on standardized testing conditions [9]. Lastly, one study provided link-level energy decomposition under real-world traffic but focused on developed-market infrastructure [10].

A critical gap remains: the comparative performance of physics-based versus pure data-driven models in heterogeneous, data-scarce environments. Most existing comparisons are conducted in data-rich contexts. This study addresses this gap by benchmarking a physics-based model against multiple regression approaches on the same dataset of 26 routes across seven vehicle segments.

3 Methodology

3.1 Model Architecture and Data Sources

The energy consumption model integrates fundamental vehicle dynamics with empirical correction factors. The core energy equation is:

$$E_{total} = E_{traction} + E_{auxiliary} + E_{losses} \tag{1}$$

From Eq. 1, $E_{traction}$ is a function of traction force, which again comprises of four components:

$$F_{total} = F_{rolling} + F_{aerodynamic} + F_{gravitational} + F_{acceleration} \tag{2}$$

Further, in Eq. 2, $F_{rolling}, F_{aerodynamic}, F_{gravitational}, F_{acceleration}$ are defined as

$$F_{rolling\ resistance} = C_{rr} \times m \times g \times cos\theta \tag{3}$$

$$F_{aerodynamic\ drag} = 0.5 \times \rho \times C_d \times A \times v^2 \tag{4}$$

$$F_{gravitrational\ force} = m \times g \times sin\theta \tag{5}$$

$$F_{acceleration\ force} = m \times a \tag{6}$$

Constant coefficients for rolling resistance and aerodynamic parameters are applied within each vehicle category.

Energy conversion losses are modelled through composite efficiency factors: motor efficiency (90–95%), power electronics (92–96%), and battery discharge characteristics [11, 12]. Regenerative braking energy recovery is modelled as a function of deceleration events and terrain gradient, with recovery efficiency scaled by motor characteristics and battery state of charge, contributing 5–15% energy recovery on routes with significant descent profiles.

Route elevation profiles were obtained through Google Maps Elevation API at 30-m spatial resolution. Speed profiles were categorized into urban (25–35 kph), highway (70–85 kph), and mixed conditions. Energy consumption was computed by integrating traction forces over the speed-elevation profile at one-second intervals. Model outputs (kWh/km) were validated against fleet operational data from pManifold Business Solutions, including EV energy meter readings and diesel fleet telemetry benchmarks.

3.2 Vehicle Segments and Route Selection

Seven commercial vehicle categories (14 T–55 T) were analyzed: light commercial vehicles (14 T) for urban delivery, medium-duty trucks (19 T, 28 T) for regional distribution, heavy-duty vehicles (40 T) for long-haul freight, and ultra-heavy segments (49 T–55 T) for mining and bulk transport. Vehicle specifications were sourced from manufacturer data.

Twenty-six routes were selected spanning the Mumbai–Pune corridor, Chhattisgarh mining circuits (Dipka, Gevra, Kusmunda), Chennai urban routes, Tamil Nadu fish transport corridors, IKEA logistics routes, Rajasthan long-haul corridors, and Nepal cross-border routes, yielding 207 route-vehicle combinations.

Loading scenarios were analyzed at 80%, 100%, and 110%. Loading elasticity was calculated using Eq. 7 [13]. Statistical analysis employed linear regression, cross-validation, and residual diagnostics.

$$S_{load} = \frac{\left(\frac{\Delta E}{E_{baseline}}\right)}{\left(\frac{\Delta m}{m_{baseline}}\right)} \tag{7}$$

3.3 Benchmarking Against Data-Driven Models

Multiple regression models were fitted on the same 207-observation dataset using only observable parameters (vehicle weight and loading percentage) without physics-derived features. Models tested included multivariate linear regression, polynomial regression (degree 2), random forest (200 estimators, max depth 8), and gradient boosting regressors, evaluated using 5-fold cross-validation.

4 Results and Analysis

4.1 Energy Consumption Scaling and Model Comparison

Statistical analysis of 207 route-vehicle combinations reveals strong linear correlation between vehicle weight and energy consumption ($r = 0.889$, $p < 0.001$). The overall scaling coefficient is 0.0487 kWh/km per tonne [3]. Light-duty trucks (14 T–19 T) show 0.0392 kWh/km/t and heavy-duty trucks (40 T–55 T) show 0.0521 kWh/km/t. The physics-based model achieves $R^2 = 0.813$ (Durbin–Watson = 1.89, Shapiro–Wilk $p = 0.067$). As shown in Fig. 1, each point represents segment-averaged consumption with the trendline fitted across all 207 observations.

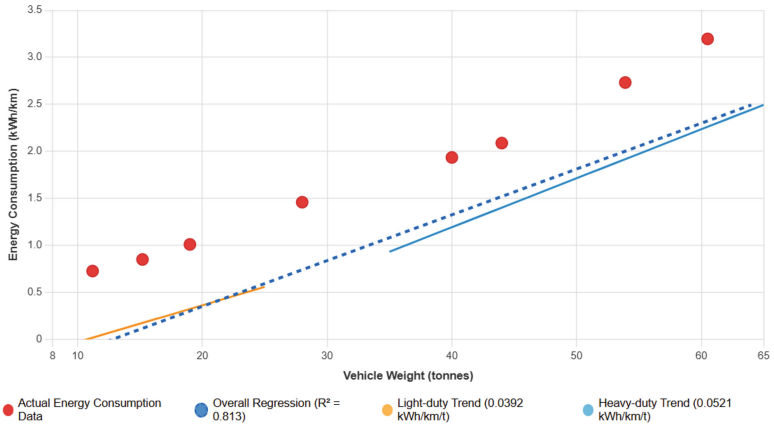


Fig. 1. Physics-based energy consumption model validation ($R^2 = 0.813$)

Pure data-driven approaches achieve R^2 of 0.28–0.29 (Table 1). The physics-based model captures route-specific variability inaccessible from vehicle parameters alone. Polynomial regression and random forest show negative cross-validated R^2, indicating overfitting. When operator identity is added as a proxy, ML models approach $R^2 = 0.75$, but this requires prior data for each operator-route pair.

Table 1. Model performance comparison

Model	R^2 (Train)	R^2 (5-fold CV)	RMSE (kWh/km)
Physics-based (this study)	0.813	–	–
Multivariate linear regression	0.282	0.240	1.094
Polynomial regression (deg. 2)	0.287	−0.184	1.090
Random forest	0.288	−0.022	1.089

Table 2. Loading elasticity results

Truck Segment	Weight Change	Energy Change	Elasticity	Significance
19 T (80% → 100%)	25.00%	18.80%	0.752	$p < 0.001$
40 T (100% → 110%)	10.00%	7.80%	0.780	$p < 0.01$

4.2 Loading Sensitivity Analysis

Loading elasticity values below 1.0 (Table 2) indicate sub-proportional energy increases with weight [14]. Highway operations show lower overloading penalties; urban environments amplify penalties. Mining operations show variable impact (−5% to +35%): downhill, additional weight improves regenerative recovery [10].

4.3 Operational Performance Benchmarking

Top-performing e-commerce and FMCG fleets achieve 35–45% better efficiency (CV = 18.2%). Mining operators show specialized downhill regenerative efficiency. Diverse portfolio operators exhibit high variability (CV = 28.9–51.2%). Application averages range from 1.156 kWh/km (mining) to 1.487 kWh/km (urban delivery) [5].

5 Discussion

The physics model's advantage over regression ($R^2 = 0.813$ vs. 0.28) validates incorporating physical principles in data-scarce environments. For new routes, it requires only vehicle specifications and elevation data, whereas data-driven models need extensive route-specific training data.

Limitations include constant rolling resistance and aerodynamic coefficients within each vehicle category, and generalized speed profiles rather than real-time traffic [4]. The model does not account for battery thermal degradation under extreme temperatures.

Applied to India's 7.5 million truck fleet, identified improvements translate to 45–67 TWh annual savings. The model enables 2–3 year payback versus 7–10 years with poor planning. Tiered infrastructure: 50–100 kW for light-duty, 300–500 kW DC fast-charging for heavy-duty corridors.

5.1 Transferability and Limitations

The core physics equations are universally applicable. However, rolling resistance coefficients, speed profiles, and loading scenarios are calibrated to Indian conditions. Transferring requires recalibrating using local road data, speed distributions, loading practices, and ambient temperature effects. The modular architecture facilitates this: core dynamics remain unchanged while parameters are updated for the target context.

6 Conclusions

This study delivers a validated, terrain-sensitive energy consumption model for Indian freight transport. The physics-based model achieves $R^2 = 0.813$, outperforming regression ($R^2 = 0.28$) on 207 route-vehicle combinations. Energy scales at 0.0487 kWh/km/t with segment-specific variations supporting phased electrification. Sub-proportional loading elasticity (0.75–0.78) and 35–45% efficiency advantages of leading operators confirm that load management, route planning, and driver training are immediately actionable. Future work: real-time telematics, battery thermal modelling, probabilistic frameworks.

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References

1. ResearchAndMarkets.com: India Road Freight Transport Industry Report 2023–2024 & 2029. Research and Markets, Dublin (2024)
2. SteadieSeifi, M., Dellaert, N.P., Nuijten, W., et al.: Multimodal freight transportation planning: a literature review. Eur. J. Oper. Res. **233**(1), 1–15 (2014). https://doi.org/10.1016/j.ejor.2013.06.055
3. Ehsani, M., Ahmadi, A., Fadai, D.: Modeling of vehicle fuel consumption and carbon dioxide emission in road transport. Renew. Sust. Energ. Rev. **53**, 1638–1648 (2016). https://doi.org/10.1016/j.rser.2015.08.062
4. Gong, J., Shang, J., Li, L., et al.: A comparative study on fuel consumption prediction methods of heavy-duty diesel trucks considering 21 influencing factors. Energies. **14**(23), 8106 (2021). https://doi.org/10.3390/EN14238106
5. Chen, Y., Zhu, L., Gonder, J., et al.: Data-driven fuel consumption estimation: A multivariate adaptive regression spline approach. Transp. Res. C. **83**, 134–145 (2017). https://doi.org/10.1016/j.trc.2017.08.003
6. Zhang, C., Kotz, A., Kelly, K., Rippelmeyer, L.: Development of heavy-duty vehicle representative driving cycles via decision tree regression. Transp. Res. D. **95**, 102843 (2021). https://doi.org/10.1016/J.TRD.2021.102843
7. Genikomsakis, K.N., Mitrentsis, G.: A computationally efficient simulation model for estimating energy consumption of electric vehicles. Transp. Res. D. **50**, 98–118 (2017). https://doi.org/10.1016/j.trd.2016.10.014
8. Ahn, K., Rakha, H.: The effects of route choice decisions on vehicle energy consumption and emissions. Transp. Res. D. **13**(3), 151–167 (2008). https://doi.org/10.1016/j.trd.2008.01.005

9. Wang, J., Rakha, H.A.: Fuel consumption model for heavy duty diesel trucks: model development and testing. Transp. Res. D. **55**, 127–141 (2017). https://doi.org/10.1016/J.TRD.2017.06.011
10. Qi, X., Wu, G., Boriboonsomsin, K., Barth, M.J.: Data-driven decomposition analysis and estimation of link-level electric vehicle energy consumption. Transp. Res. D. **64**, 36–52 (2018). https://doi.org/10.1016/j.trd.2017.08.008
11. Hayes, J.G., De Oliveira, R.P.R., Vaughan, S., Egan, M.G.: Simplified electric vehicle power train models and range estimation. In: 2011 IEEE Vehicle Power and Propulsion Conference, pp. 1–5. IEEE, Chicago (2011). https://doi.org/10.1109/VPPC.2011.6043163
12. Shankar, R., Marco, J.: Method for estimating the energy consumption of electric vehicles and plug-in hybrid electric vehicles under real-world driving conditions. IET Intell. Transp. Syst. **7**(1), 138–150 (2013). https://doi.org/10.1049/IET-ITS.2012.0114
13. Yuan, X., Zhang, C., Hong, G., et al.: Method for evaluating the real-world driving energy consumptions of electric vehicles. Energy. **141**, 1955–1968 (2017). https://doi.org/10.1016/J.ENERGY.2017.11.134
14. Zhou, B., Wu, Y., Zhou, B., et al.: Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. Energy. **96**, 603–613 (2016). https://doi.org/10.1016/j.energy.2015.12.041

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Combining User Needs and Predictive Control for Efficient User-Centric Energy Management Systems

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Abstract. The driving range of electric vehicles (EVs) is heavily influenced by thermal comfort settings, often leading to inconsistent range predictions and user "range anxiety". While technical energy management systems exist, aligning them with actual user behaviour and subjective comfort needs is rarely addressed holistically. This paper presents a novel methodology from the EFFEREST research project, bridging human factors research and advanced control engineering to develop a Holistic User-Centric Energy Management System Control (HUC). First, we detail an interview study that identified specific EV driver pain points, such as "overnight" range drops and non-transparent climate automation. Based on these insights, we introduce the HUC framework. This architecture utilizes AI-enhanced system design and Adaptive Digital Twins (ADTs) to dynamically balance powertrain efficiency with personalized thermal comfort. Finally, we outline a comprehensive multi-platform validation methodology. Utilizing virtual demonstrators, thermal test benches, and a physical vehicle demonstrator equipped with a thermal manikin, this setup is designed to quantitatively assess energy savings and comfort improvements against state-of-the-art EV baselines.

Keywords: Electric vehicles · user needs · holistic user-centric solutions · thermal management · energy management system · Horizon Europe

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1 Introduction

Following the "Paris Agreement", the European Union committed to a substantial reduction in greenhouse gas emissions [2]. The transportation sector accounts for approximately one-quarter of total EU greenhouse gas emissions, with passenger cars and vans contributing around 15% of the total carbon dioxide emissions [5]. To address this, improving the efficiency and affordability of electric vehicles (EVs) is a critical priority, aligned with both the "European Green Deal" [3] and the 2Zero partnership initiatives [4].

A major challenge in current EV development is the inherent trade-off between passenger thermal comfort and vehicle driving range (cf. [10]). Heating and cooling the vehicle cabin can drastically reduce the energy available for propulsion, leading to range limitations that are often perceived as inconsistent by drivers. This interconnection can be unexpected and leads to dissatisfaction and "range anxiety", concerns actively investigated in human-machine interface (HMI) research (e.g., [9]). Driver's requirements are complex and can change through EV experience [6]. Improving EV energy efficiency without compromising user acceptance requires a deep understanding of the drivers' challenges and the translation of these qualitative needs into intelligent vehicle control strategies.

This paper addresses this gap by presenting the holistic EFFEREST (Efficient User-Centric Energy Management Systems for Optimized EV) project [1] research approach that links user research with advanced predictive control engineering. The contributions of this work are threefold:

1. **Empirical Insights regarding user-centric requirements:** We present findings from an interview study on EV users' experiences regarding thermal comfort and range prediction.
2. **User-Centric Control Architecture:** We detail the development of the Holistic User-Centric Energy Management System Control (HUC), an AI-enhanced framework that translates user needs into dynamic energy distribution strategies using Adaptive Digital Twins (ADTs).
3. **Validation Methodology**: We establish a comprehensive evaluation framework utilizing both virtual and physical demonstrators to quantitatively assess performance improvements against state-of-the-art baselines.

2 Interview Study

2.1 Methodology

To establish a foundation for the HUC system design, an exploratory interview study was conducted to understand EV drivers' real-world experiences with range, range prediction, and thermal comfort.

Sample. The interview study sample consisted of ten experienced EV drivers (7 male, 3 female), aged 30 to 55 years ($M = 43.5$). All participants owned or leased an EV, representing five different vehicle brands. See Table 1 for further details of the sample.

Table 1. Details of the sample.

Characteristic	Details ($N = 10$)
Professional Background	4 Participants had a professional role related to EVs
Vehicle Models Driven	Tesla Model 3/S (5x) Renault ZOE (2x) BMW i3 (2x) VW ID.3 (1x), ID.4 (1x) Hyundai IONIQ 5 (1x) (Some had more than one car)
EV Experience	6 months to 8 years
Primary Charging	Home charging (7x), External only (3x)

Procedure and Analysis. Semi-structured interviews lasting approximately 40 min were conducted either in-person or via video conferencing (MS Teams). The interview guideline covered three main themes: (1) general EV usage and charging behaviour, (2) experiences with vehicle range and prediction consistency, and (3) experiences and interventions regarding climate control and thermal comfort. While most questions were open-ended, some asked the interviewee for a rating of their experience. Interviews were recorded, transcribed (utilizing aTrain software and manual correction), and subjected to a thematic analysis to identify recurring usage challenges, learning processes, and system requirements.

2.2 Interview Study Results

The thematic analysis of the interviews revealed specific pain points and behavioural adaptations that current energy management systems fail to adequately support.

Range Prediction Inconsistencies. While overall satisfaction with vehicle range was high (ratings between 6 and 10 on a 10-point scale), drivers reported significant challenges during winter months. Several drivers actively restricted their vehicle use for longer trips or noted the necessity for significantly increased route planning. One participant noted: "You don't get quite as far with it, and that's a bit disappointing, yes, but you get used to it extremely quickly." A critical finding was the phenomenon of the "overnight shock" (reported by 3 drivers), where the displayed range prediction is significantly reduced after the EV was parked for several hours in cold weather conditions. Because the underlying reasons (e.g., additional energy requirements for heating up the cabin and the battery) were unknown to the drivers and the range effect was not communicated by the vehicle's HMI at the end of the previous trip, it led to immediate uncertainty. The data showed that users undergo a harsh learning process regarding battery behaviour (e.g., differences between different battery chemistries in cold weather).

Climatization and Automation Deficits. Drivers generally rated their thermal comfort highly but reported frequent necessity for manual intervention, indicating a failure of the automated climate control systems to meet specific context-dependent needs. The most

frequent manual adjustments were setting the absolute temperature (7 drivers), altering air vent direction/intensity (5 drivers), and activating seat/steering wheel heating (4 drivers). An issue mentioned was the non-transparent behaviour of climate automation. For instance, unwanted automated AC activation during winter led one driver to completely abandon the automatic mode: "I really only use the air conditioning in summer, and in winter I don't want to have it on/off all the time... I actually almost always have it on manual." Other reported issues included slow heating on cold mornings, insufficient heating in transition periods, and loud, uncomfortable fan intensities on hot days.

Driving Modes and Eco-Functionality. All drivers were aware of their vehicle's driving modes (e.g., Eco, Regular, Sport), but only half reported actively switching between them based on the context. When asked about a dedicated "Eco Mode" that limits thermal comfort to preserve range, 6 out of 10 drivers supported the concept, provided it remained an optional setting for specific scenarios (e.g., short solo trips, or trips pushing the vehicle's range limits). However, participants heavily emphasized the need to retain manual override capabilities, indicating a desire for driver control within efficiency-optimized modes.

System Requirements Derived from Interview Insights. Based on the interview findings, the following requirements for an advanced energy management system were formulated:

- Range predictions should incorporate predictive usage and ambient condition forecasting (e.g., next-day weather impacts on energy requirements).
- Thermal comfort automation must be highly customisable, transparent, and responsive to ambient temperatures rather than relying on rigid, predefined logic.
- The system needs intelligent, self-adapting eco-modes that balance powertrain efficiency with targeted (e.g., localized heating) cabin heating.

3 System Control Design: Holistic User-Centric Energy Management System Control (HUC)

To address the derived requirements from the user study, a multi-layer architecture of predictive and model-based controllers was developed: the Holistic User-Centric Energy Management System Control (HUC). Rather than optimizing components in isolation, the HUC links cabin comfort and powertrain performance to make engineering trade-offs in the interest of fulfilling the user's specific needs.

3.1 The HUC Architecture

The HUC architecture (see Fig. 1) consists of two model-predictive control layers differentiated by their long-term or mid/short-term prediction horizon and corresponding controller time steps, external inputs as data source for control strategies and model adaptation and the vehicle plant, the controlled system which gives sensor feedback to the control layers.

The HUC utilizes Adaptive Digital Twins (ADTs). ADTs are computationally efficient models of all relevant components (powertrain, HVAC, cabin, battery, and the human comfort perception) that update in real-time to adapt internal model parameters to match the actual system response and to the characteristics of the individual person inside the vehicle. The ADTs are derived from high-fidelity physics-based simulation models, which are developed in a first project phase. Advanced model order reduction methods are applied to increase their computational efficiency while maintaining a high level of accuracy. In this process the introduction of flexible model parameters leads to the required adaptivity. The resulting ADTs perform fast enough to be integrated with the control algorithms and implemented within the vehicle central control unit or a car PC. Two versions of the ADTs are developed, with different levels of fidelity and granularity depending on the prediction horizon required by the associated control layer.

The long-term control layer combines strategies for static and driving situations. It utilizes cloud data, sensor data and user inputs to take strategic decisions about the preconditioning of the cabin or the battery and to continuously define optimal set-point values which affect the operation of the subsequent mid−/short-term control layer. Here the direct control of all technical components of the vehicle plant is performed during vehicle operation.

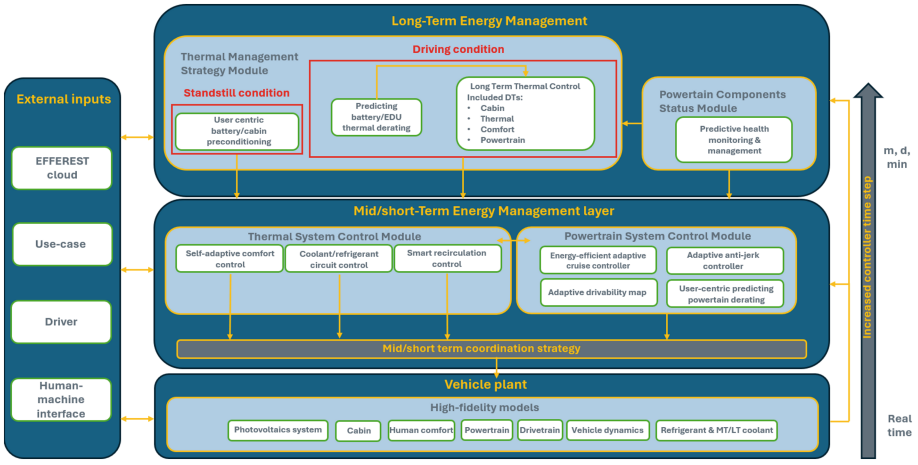


Fig. 1. The HUC multi-layer control architecture

Predictive Control Architecture to Fulfil User Needs. The "Long-Term Energy Management Layer" addresses the "overnight shock" and planning issues identified in the interviews. It uses long-term ADTs to make strategic decisions such as preheating the cabin or battery for next day use. Through the prediction of future scenarios, the usage planning is supported. The trade-off between thermal comfort and powertrain energy consumption is managed predictively based on cloud data (weather forecasts, traffic).

The "Mid/Short-Term Energy Management Layer" addresses the user frustration with climate system deficits and automation non-transparency. This layer features a

Self-Adapting Comfort Controller (SACC). The SACC embeds an ADT of human comfort perception, continuously updating according to specific cabin characteristics and preferences based on sensor data and manual interventions by the occupants. Instead of forcing unwanted AC in winter, the SACC learns the user's preference for manual-like ventilation. Simultaneously, the powertrain control acts in a similar way on the operation and the thermal management of components like the battery, the electric motor and the inverter. This includes an anti-jerk controller [7], for the compensation of the torsional drivetrain dynamics to enhance drivability and comfort and an adaptive drivability map algorithm using nonlinear model predictive control, which seamlessly modifies torque demand for efficiency while minimizing the intrusion on the driver's pedal inputs.

3.2 Validation and Demonstration Methodology

To provide quantitative performance comparisons and validate the improvements over state-of-the-art baselines, a comprehensive multi-platform validation and demonstration architecture has been established in the EFFEREST project.

Virtual Demonstrators. Two virtual demonstrators implemented in the MATLAB/Simulink environment allow for the simulation of the complete HUC functionality under extreme climate conditions and with application of diverse user profiles throughout an entire year. This setup allows for the quantification of energy savings and the evaluation of control algorithms (e.g., seasonal effects on battery degradation) before hardware deployment, effectively calculating the theoretical performance improvements of the HUC compared to baseline setups.

Physical Demonstration and Quantitative Assessment. The physical testing campaign utilizes a demonstrator vehicle (provided by TOGG and modified by MAGNA) equipped with the newly developed HUC, self-adapting comfort systems, and innovative heating surfaces. The methodology for quantitative evaluation includes a *Thermal Test Bench* for validation of specific refrigerant cycle control algorithms under defined transient thermal loads, a *Chassis Dynamometer with Climatic Chamber* in which the vehicle is subjected to reproducible driving scenarios across varying temperatures (0 °C, 20 °C, 35 °C). Crucially, this setup incorporates a thermal manikin (ANDI provided by CTAG) placed inside the vehicle. The manikin allows for the objective, quantitative evaluation of comfort relevant parameters and therefore the assessment of the Self-Adapting Comfort Controller under asymmetric thermal conditions (cf. [8]), supporting the goal to estimate how much energy can be saved while maintaining optimal comfort metrics. A further step is the *Open-Road Validation* and *OVPP.* Open-road tests on a dedicated test track with fast-charging capabilities, combined with evaluation of powertrain software features on the Open Vehicle Powertrain Platform (OVPP). This combination of subjective user data integration (HUC design) and objective, sensor-driven hardware testing (Manikin "ANDI" + Chassis-Dyno) ensures that performance improvements, both in terms of kWh saved and comfort metrics achieved, are consistently validated. See Fig. 2 for the test facilities used.



Fig. 2. Test facilities for validation including Chassis-Dyno with "ANDI" Thermal Manikin and Virtual Demonstrators

4 Discussion and Conclusion

The transition of electric vehicles to the mass market requires energy management systems that are not only technically efficient but also deeply aligned with user expectations. As our interview study highlighted, EV drivers face distinct challenges, such as unexpected range reductions due to cold climate conditions and frustration with non-transparent climate automations. If left unaddressed, these issues lead to increased planning effort, reliance on manual system overrides, and a general barrier to EV acceptance.

This research demonstrates that a holistic, user-centric approach can systematically resolve these challenges. By translating user needs into the architecture of the Holistic User-Centric Energy Management System Control (HUC), we shift the paradigm from isolated component optimization to integrated, predictive vehicle management. The use of Adaptive Digital Twins allows the vehicle to learn and anticipate the comfort preferences and driving behaviour of its specific occupant, offering personalized eco-functionality.

Furthermore, the presented validation methodology, combining virtual simulation with high-fidelity physical testing using thermal manikins in climatic chambers, provides a robust framework for quantifying the exact performance and efficiency gains achieved by the HUC compared to current state-of-the-art baselines. Ultimately, this approach provides a blueprint for the future of electric mobility, where intelligent energy management systems actively support the driver, mitigating range anxiety and optimizing comfort without sacrificing efficiency.

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References

1. EFFEREST Consortium: EFFEREST: Efficient User-Centric Energy Management Systems for Optimized EV. EFFEREST Project (2024). https://efferest-project.eu/
2. European Commission: The Paris protocol – a blueprint for tackling global climate change beyond 2020 COM(2015) 815 final, Brussels (2015)
3. European Commission: The European green deal COM(2019) 640 final Brussels (2019)
4. European Commission: Clean and competitive solutions for all transport modes (HORIZON-CL5-2023-D5-01-01) funding & tenders portal (2023)
5. European Environment Agency (EEA): Transport and mobility. https://www.eea.europa.eu (2024)
6. Franke, T., Krems, J.F.: What drives range preferences in electric vehicle users? Transp. Policy. **30**, 56–62 (2013)
7. Frison, G., Alberti, F., Ciravegna, L., Dimauro, L., Sorniotti, A.: Self-adaptive neural network model predictive anti-jerk control of electric powertrains. Mech. Mach. Theory. **214**, 106082 (2025). https://doi.org/10.1016/j.mechmachtheory.2025.106082
8. Paredes Barros, E. et al.: User-centric electrical vehicle thermal conditioning strategy based on close comfort elements in cold environment: thermal manikin and human participants assessment. Case Stud. Therm. Eng. **64**, 105435 (2024)
9. Westerkamp, P., Dautzenberg, P.S., Brockmeier, C., Ladwig, S., Eckstein, L.: HMI concept for the optimization of the used range in battery electric vehicles. In: Proceedings of the 29th Aachen Colloquium Sustainable Mobility (2020)
10. Zhao, C. et al.: Research on electric vehicle range under cold condition. Adv. Mech. Eng. **14**(3) (2022)

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Current Trends in Photovoltaic Applications for Railway Infrastructure: An Overview of Global Activities with Insights from the RailPV Project

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Abstract. The deployment of solar panels on and around railway tracks opens up a wide range of possibilities for generating renewable energy and optimizing land use. This paper provides an overview of international activities regarding photovoltaic (PV) power plants on railway infrastructure, with a special focus on track-integrated power plants using the example of the RailPV project at RWTH Aachen University. Possible application scenarios for track-integrated PV systems are presented, such as local use at sidings, off-grid systems for electrified level crossings and feeding directly into the railway power grid.

Opportunities and challenges are examined, including land-use optimization, regulatory aspects compared with ground-mounted systems, and operational limitations related to track maintenance. The specific yield characteristics of track-integrated PV systems are analyzed, and an initial classification of their levelized cost of electricity (LCOE) is provided relative to rooftop and ground-mounted PV. The aim is to offer insights into the integration of renewable energy systems into railway infrastructure and to outline prospects for future developments.

Keywords: Solar Power Generation · Renewable Energy · Green Mobility · Railway Infrastructure · Land Use Optimization

1 Introduction

Photovoltaic power plants are key to the transition to renewables and to achieving international climate targets. Demonstrators and pilot projects worldwide show that PV plants on railway infrastructure are technically feasible. This paper (i) reviews international activities related to PV on railway infrastructure, with a focus on linear, track-integrated installations, and (ii) analyses the specific characteristics of track-integrated PV systems and their expected energy yield and economics.

The motivation for track-integrated concepts is twofold. From a land-use perspective, railway corridors are already sealed or functionally dedicated areas. Using them for PV power generation can avoid land-use conflicts with agriculture [1]. Secondly, track-adjacent or track-integrated PV may face shorter permitting processes, whereas

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open-space, ground-mounted systems in Europe frequently involve lengthy planning and approval [1]. PV solutions designed as add-ons to existing railway infrastructure can therefore reduce time-to-deployment.

Although technical feasibility is proven, a deficit remains in the scientific state of the art: a systematic analysis of the energy yield of track-integrated PV power plants – considering irradiation and shading simulations and soiling analysis under railway operating conditions – is yet to be presented. This paper addresses this gap by outlining key characteristics of track-integrated PV power plants and their effects on yield, economic feasibility and potential application scenarios.

2 PV Power Plants on Railway Infrastructure

This paper considers the following spectrum of application locations on railway infrastructure. It does not include large ground-mounted systems in the vicinity of railway tracks although they might be feeding into the railway power grid.

- PV on adjacent railway structures (station roofs, maintenance depots, car sheds, etc.)
- PV on noise barriers or linear assets along the railway line like embankments, and
- PV integrated into the track area itself, i.e., between the rails in the area of sleepers and ballast. Track-integrated PV is the primary focus of this work due to its distinct technical and operational properties and as the subject of the RailPV project.

The three types of PV arrays described are depicted in Fig. 1. Available studies and project reports point to growing use of PV modules on station roofs, depots, and linear assets. Operators and infrastructure owners – including but not limited to Austrian, Japanese, Swiss and German Railways – have advanced PV deployment on such structures. These approaches leverage proven PV technology and benefit from simplified maintenance compared to track-integrated solutions. [2–6]

In contrast, installing PV modules on railway tracks themselves has its own challenges like mounting mechanisms and track maintenance. Approaches for integrating PV plants directly into the track area are presented below.



Fig. 1. PV arrays on (a) station roof, (b) noise barrier, (c) track-integrated (RailPV) [4, 7]

Solveig Project, SNCF, France [8, 9]
French national operator SNCF developed the Solveig project to use decommissioned tracks for solar energy generation by installing panels that cover both rails. In the current setup, the panels feed buffer batteries to meet temporary local demand (e.g., for

maintenance work or depots). Application-ready solar kits are delivered in ISO containers, with the existing track serving as the transport pathway: panels, batteries, inverters, and mounting equipment are placed onto the rails using a lifting arm. A non-permanent mounting system allows the panels to be removed and installed elsewhere if tracks are reactivated or repurposed. A prototype comprising PV modules and battery storage is being tested near Paris to evaluate handling and operation.

Railway Solar Power Generation Project, Japan [10]
As the first fully track-integrated approach, the Japanese Railway Solar Power Generation project installed and tested standard solar panels between the rails around 2013. The project claimed that up to 50,000 km of track in Japan could be equipped with 250 W panels every two meters and investigated different mounting methods to facilitate installation and removal. Wind-tunnel tests demonstrated sufficient panel stability under strong winds and airflow from passing trains, and cushioning between ties and panels was proposed to reduce transmitted vibration. The study also examined glare from sunlight reflected off the panels and funding strategies, particularly for local railways in economic deficit. However, no further data has been released since.

Sun-Ways, Switzerland
Swiss start-up Sun-Ways integrates PV generation into railway infrastructure by installing track-integrated PV power plants that can be fully or partially removed to allow routine maintenance. With Scheuchzer SA, a developer of railway maintenance machines, Sun-Ways developed a PV module installation vehicle. Reported installation speeds range from 1,000 m^2 per day to 150 m of modules per hour [11–13].

In a pilot project in April 2025, 48 solar panels were installed over 100 m, with an estimated annual yield of 16,000 kWh [11]. Initial tests indicate that the panels remain stable as trains pass at speeds of up to 150 km/h. During the test phase, limitations such as soiling-induced yield losses and glare that may obstruct drivers' vision were identified but not published. To address soiling, Sun-Ways proposes cylindrical brushes mounted at the ends of trains to clean the panels while they are passed over [13].

RailPV Project at RWTH Aachen University, Germany
The RailPV project of QINUM GmbH, Cologne, and the Institute for Rail Vehicles (ifs) at RWTH Aachen University contributes to this landscape of fully track-integrated installations. Its objectives include evaluating automated mechanical installation concepts with almost no manual labor required. This is considered crucial for the economic viability of track-integrated PV plants. Compatibility with track maintenance is ensured by being able to remove the panels the same automated way, as well as measuring electrical performance under operating conditions, and generating basic data for yield modeling and first economic assessments. A test plant for research purposes with four modules has been installed at ifs. In addition, a larger demonstrator with approximately 36 modules is to be installed on an industrial rail siding in Mid-Germany.

An overview of the previously presented solutions and projects is given in Table 1. Subsequent sections concentrate on the specific characteristics of track-integrated PV systems and their implications for energy yield.

Table 1. Overview of PV power plants on railway infrastructure

Type	Location	Usage	Status/TRL	Year	Source
Track-adjacent	Germany	roof areas; maintenance depots	in use, TRL 9	–	[2]
Track-adjacent	Austria; Switzerland	noise barriers; building/roof areas	in use, TRL 9	2020	[4, 5, 7]
Track-adjacent	Japan	noise barriers	prototype, TRL 7	2025	[6]
Track-covering	France	removable; on decommissioned tracks	prototype, TRL 6–7	2025	[8, 9]
Track-integrated	Japan	mounting methods tested	prototype, TRL 6	2014	[10]
Track-integrated	Switzerland	removable	prototype, TRL 6	2024	[11–13]
Track-integrated	Germany (RailPV)	automated, modular integration; removable	research plant, TRL 6	2024	

3 Characteristics of Track-Integrated PV Systems

Track-integrated PV differs from rooftop and ground-mounted PV in geometry and operation: modules must be installed almost flat to maintain clearance and avoid interference with rolling stock, and thus cannot be tilted at the optimized angles used on rooftop or ground-mounted systems [14]. Simulations with location-specific irradiance data for Central Europe indicate that near-horizontal placement reduces annual irradiation by about 10–15% compared to optimally tilted modules [15, 16].

These literature values are in line with the findings of the RailPV project. According to simulations conducted, approximately 87% of the yield of an optimally aligned system can be achieved with a track-integrated plant. However, the yield becomes even more unevenly distributed throughout the year, as can be seen in Fig. 2.

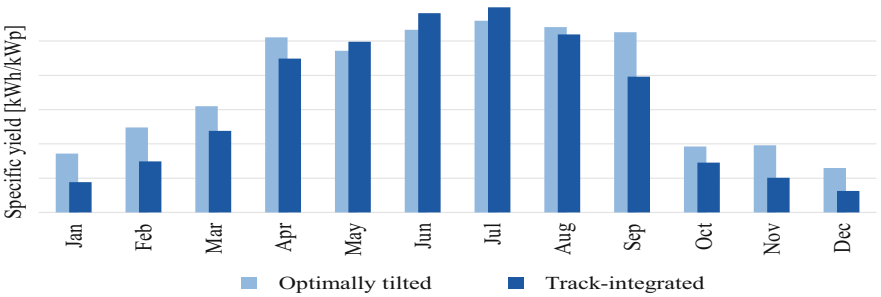


Fig. 2. Annual yield distribution of PV systems

This results in an expected yield of about 1000 kWh/kWp per year for Mid-Germany with otherwise unobstructed irradiation. For electrified railway tracks, a 3–5% decrease in yield due to shading from catenary lines and catenary masts was simulated.

Hydrological behavior is another key differentiator. Near-horizontal modules retain thin water films after rainfall, and puddling can occur if micro-tilt and surface planarity are not controlled [17]. Compared to ground-mounted systems with tilts of ca. 35° [15], water drainage is less effective on flat surfaces. RailPV investigations show that small tilts of 2–3° improve drainage and dry-up times after rainfall, reducing persistent moisture films on the glass. These small tilts are feasible within infrastructure clearance.

Drainage and geometry directly affect soiling. Water retention promotes dust deposition; during evaporation, residues such as brake dust, iron oxides, and biological debris accumulate and exacerbate soiling [18–20]. The influence of soiling on PV energy yield depends on local parameters [21]. Soiling losses increase with the sunlight's angle of incidence [22], so flat-laying modules are more affected than tilted arrays. Soiling also varies with regional climate [21]: in desert areas, rapid yield declines of 7–33% per month have been observed due to higher airborne sand loads and fewer precipitation events [17, 23]. In moderate climates, much lower soiling losses of 5% or less are reported [24], e.g., about 1.4% per year in Oregon, USA [25]. In the RailPV project, no major yield decline due to soiling has been observed so far. However, a quantitative characterization of soiling and cleanability for track-integrated PV across seasons and for specific debris and fluids remains an ongoing research task.

4 Economic Effects and Potential Application Scenarios

A common measure of cost of electricity generation is levelized cost of electricity (LCOE). LCOE for different types of power plants in Germany in 2024 is shown in Fig. 3. Accordingly, LCOE for roof-mounted and ground-mounted PV systems ranges from 4.1 to 14.4 €cents/kWh. In contrast to that, natural gas propelled plants exhibit a much higher LCOE of about 15 to 33 €cents/kWh. This underlines the potential of PV power generation for the transition to climate-neutral energy generation [26].

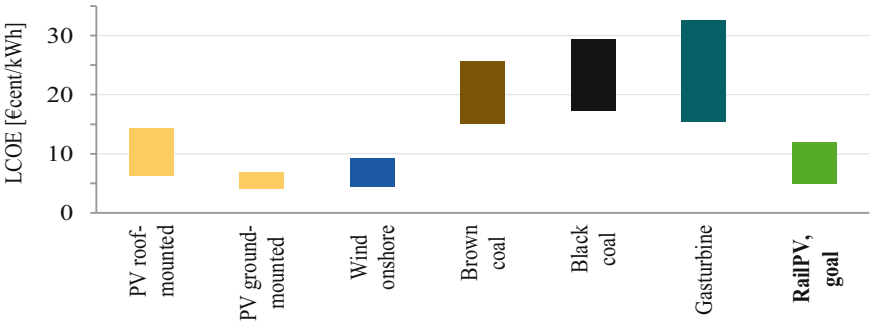


Fig. 3. LCOE for various types of power plants in Germany in 2024 [26]

Track-integrated PV power plants have a linear topology, in contrast to compact rooftop or ground-mounted arrays. Energy is collected along the track via a continuous DC backbone rather than a mostly star-shaped layout. Mechanically, the plant must coexist with track superstructure operations, requiring modular, removable designs. These features affect both capital and operating costs (e.g., cleaning and maintenance) and must be assessed along with the yield effects discussed in Sect. 3.

- A *continuous DC backbone* is laid along the route, to which strings connect at frequent intervals. This increases cable length per installed kWp and adds more connection points and electronic devices than in compact arrays.
- *Standard-sized PV modules:* Oversized formats are not suitable within the gauge due to the limited gauge. Standardized dimensions also simplify removal and logistics.
- *Removal for superstructure maintenance:* Activities such as tamping, ballast cleaning, sleeper replacement, and rail grinding can require temporary removal of PV elements. This introduces the necessity for more detailed scheduling of maintenance work as well as higher operational downtime that must be budgeted.
- *Cleaning effort:* As discussed in Sect. 3, the shallow tilt and water retention tendencies of track-integrated modules increase soiling risk and inhibit natural cleaning by rainfall. The need for more frequent cleaning cycles can be expected.

Various application scenarios are imaginable. Despite the challenges mentioned, **the following use cases** offer distinct value propositions.

- **Local off-grid solutions**: Track-integrated PV can supply off-grid systems such as electrified level crossings, signaling huts, or telecom assets. Combining PV with storage can avoid costly grid extensions. Here, the value is derived more from avoided infrastructure costs than from lowest LCOE.
- **Local industrial sidings**: Private or industrial tracks are typically less frequented, with fewer daily train movements and therefore less dynamic shading, and they have favorable maintenance intervals. They are often owned or managed by companies that can utilize energy locally (behind-the-meter consumption), improving economics by avoiding consumer charges and grid fees. The reduced operational disruptions and proximity to loads make sidings promising candidates for early adoption.
- **Network-wide deployment** with feed-in to railroad traction power grid: A broader rollout along main lines could contribute to increasing the renewable share of traction

energy. This scenario in comparison demands the most advanced plant design in terms of electric configuration. Due to having the largest spatial extent, it also exhibits the highest impact on recurring superstructure maintenance work. LCOE becomes most relevant in this scenario.

5 Conclusion

PV on railway infrastructure is an emerging field transitioning from concept to demonstrations and applications. In terms of track-integrated systems, international projects in France, Japan, Switzerland, and Germany demonstrate technical feasibility of on- and in-track installations. This paper reviewed these activities and highlighted the specific challenging characteristics of track-integrated systems that shape yield, operations, and costs: near-horizontal geometry, drainage and soiling behavior, and modular, removable designs to preserve maintainability of the track superstructure. The RailPV project addresses these challenges aiming to provide a modular PV plant solution that reduces soiling and is removable in an automated way.

Three application classes were outlined, each with distinct economics. Local off-grid solutions create value through avoided grid extensions. Industrial sidings enable behind-the-meter consumption with fewer maintenance interventions and less dynamic shading. Network-wide deployment with direct feed-in to the railway traction power grid offers the largest theoretical energy potential but faces the greatest cost pressure: linear topology increases the number of components required, interactions with track maintenance occur more frequently, and competitive LCOE becomes crucial.

For track-integrated PV, two priorities are vital to future research: quantifying soiling under railway-specific influences and translating the findings into cleaning strategies and design rules; and refining economic assessments based on validated yield simulations that include shading, soiling dynamics, and maintenance downtime. These research needs will be addressed by the Institute for Rail Vehicles at RWTH Aachen.

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References

1. European Commission, et al.: Technical support for RES policy development and implementation – Simplification of permission and administrative procedures for RES installations (RES Simplify). Publications Office of the European Union, Brussels (2023). https://doi.org/10.2833/894296
2. Deutsche Bahn AG: Wie die Deutsche Bahn Sonnenenergie nutzt. https://nachhaltigkeit.deutschebahn.com/de/massnahmen/sonnenenergie. Last Accessed 26 Sep 2025
3. Forster, J., et al.: Photovoltaic Noise Barriers as Energy Generating Infrastructure: Functional Overview about Five Solutions. In: 40th European Photovoltaic Solar Energy Conference and Exhibition (2023). https://doi.org/10.4229/EUPVSEC2023/4DO.5.2
4. ÖBB-Infrastruktur AG: Schallschutzwand Tullnerfeld. https://infrastruktur.oebb.at/de/projekte-fuer-oesterreich/bahn-dreh-strom/solarenergie/tullnerfeld. Last Accessed 26 Sep 2025
5. Wagner, T.: Strom aus der Schallschutzwand. https://www.deutschlandfunk.de/strom-aus-der-schallschutzwand-100.html. Last Accessed 26 Sep 2025

6. Bellini, E.: Japanese railway operator testing perovskite solar on noise barriers. https://www.pv-magazine.com/2025/01/07/japanese-railway-operator-testing-perovskite-solar-on-noise-barriers/. Last Accessed 27 Sep 2025
7. Wien Energie: Photovoltaik Klebefolien am U-Bahnhof Ottakring | Positionen. https://positionen.wienenergie.at/projekte/strom/pv-klebefolien-ubahn-station/. Last Accessed 29 Sep 2025
8. O'Donoghue, D.: French railway begins testing solar panels on train tracks. Travel tomorrow. https://traveltomorrow.com/french-railway-begins-testing-solar-panels-on-train-tracks/. Last Accessed 26 Sep 2025
9. SNCF Group: A rail-based solar setup that turns our tracks into clean energy sources. https://www.groupe-sncf.com/en/innovation/solveig-rail-based-solar-prototype. Last Accessed 26 Sep 2025
10. NEDO: Demonstration Project for Multi-Purpose Application of Solar Power / Study on the Potential for Multi-Purpose Application of Solar Power / Solar Power Generation within Railway Tracks. New Energy and Industrial Technology Development Organization (NEDO), Japan (2014)
11. Enkhardt, S.: Sun-Ways weiht seine erste Photovoltaik-Anlage zwischen Bahnschienen in der Schweiz ein. https://www.pv-magazine.de/2025/04/25/sun-ways-weiht-seine-erste-photovoltaik-anlage-zwischen-bahnschienen-in-der-schweiz-ein/. Last Accessed 26 Sep 2025
12. Oehrli, P.-Y.: Switzerland puts Sun-Ways' solar technology on the rails | GGBa. https://ggba.swiss/en/switzerland-puts-sun-ways-removable-solar-technology-on-the-rails/. Last Accessed 26 Sep 2025
13. Sun-ways: Sun-ways | Des panneaux entre les rails. https://www.sun-ways.ch/en. Last Accessed 26 Sep 2025
14. Abou Jieb, Y., Hossain, E.: Photovoltaic Systems. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-030-89780-2
15. Mertens, K.: Photovoltaik. Carl Hanser Verlag GmbH & Co. KG, München, Germany (2022). https://doi.org/10.1007/978-3-446-47429-1
16. Bauer, G.: Photovoltaik – Physikalische Grundlagen und Konzepte. Springer, Berlin, Heidelberg (2023). https://doi.org/10.1007/978-3-662-66291-5
17. Al-hasan, A.Y., Ghoneim, A.A.: A new correlation between photovoltaic panel's efficiency and amount of sand dust accumulated on their surface. Int. J. Sustain. Energy. **24**(4), 187–197 (2005). https://doi.org/10.1080/14786450500291834
18. Esveld, C.: Modern railway track, 2nd edn. MRT-Productions, Zaltbommel (2001)
19. Jaffé, J., Lanigan, J., Lewis, R.: Field-based investigation of low adhesion leaf layers: assessing layer initiation and environmental influences. Proc. Inst. Mech. Eng. F: J. Rail Rapid Transit. **239**(2), 116–131 (2025). https://doi.org/10.1177/09544097241302206
20. Moreno, T., et al.: A new look at inhalable metalliferous airborne particles on rail subway platforms. Sci. Total Environ. **505**, 367–375 (2015). https://doi.org/10.1016/j.scitotenv.2014.10.013
21. Sarver, T., Al-Qaraghuli, A., Kazmerski, L.L.: A comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches. Renew. Sustain. Energy Rev. **22**, 698–733 (2013). https://doi.org/10.1016/j.rser.2012.12.065
22. Hammond, R., Srinivasan, D., Harris, A., Whitfield, K., Wohlgemuth, J.: Effects of soiling on PV module and radiometer performance. In: Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997, pp. 1121–1124, Anaheim, CA, USA (1997). https://doi.org/10.1109/PVSC.1997.654285
23. Said, S.: Effects of dust accumulation on performances of thermal and photovoltaic flat-plate collectors. Appl. Energy. **37**(1), 73–84 (1990). https://doi.org/10.1016/0306-2619(90)90019-A

24. Friesen, G., et al.: Optimisation of Photovoltaic Systems for Different Climates (2025). https://doi.org/10.69766/QSYC8858
25. Ryan, C.P., Vignola, F., McDaniels, D.K.: Solar cell arrays: degradation due to dirt. Proc. Amer. Sect. Int. Sol. Energy Soc., 234–237 (1989)
26. Kost, C., Müller, P., Sepúlveda Schweiger, J., Fluri, V., Thomsen, J.: Stromgestehungskosten Erneuerbare Energien. Fraunhofer-Institut für Solare Energiesysteme, Freiburg (2024)

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A Modular System for Sampling and Measuring Non-Exhaust Particles of Light-Duty Vehicles in On-Road Testing

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Abstract. Non-exhaust particles contribute increasingly to road transport emissions, but consistent on-road measurement methods for brake and tyre particles are missing. This work introduces a modular system designed to sample and measure non-exhaust particles from light-duty vehicles in on-road testing. The goal was to create a flexible configuration requiring minimal adaptation, starting from a semi-enclosed system for brake particle sampling and validated through lab and road tests. It was then upgraded to a fully enclosed setup for brake particles and adapted for tyre particle collection by modifying the sampling nozzle. The full enclosure isolates the brake system from environmental interference, while the nozzle change enables tyre particle sampling. The modular system supports comprehensive testing of non-exhaust emissions and contributes to the development of reliable emission factors.

Keywords: Non-exhaust particles · Brake wear · Tyre abrasion

1 Introduction

Non-exhaust particles (NEP) receive increasing attention, due to their growing contribution to road transport particle emissions. Brake, tyre and road particles made up 54% and 69% of PM2.5 and PM10, respectively in 2020, and are estimated to increase above 90% by 2040 [1]. Aiming at the effective control, the EU has set specific limits for brake and tyre particle emissions in the Euro 7 emission standard [2]. While electrification has the potential to reduce brake particle emissions by up to ~60%, the increased weight of electric vehicles leads to higher tyre wear PM10 [3, 4].

Brake wear particles are produced during the deceleration events of the vehicle by the friction between the brake disc and pad or the brake shoe and drum. Although the former system dominates the market, particularly on light-duty vehicles (LDV), drum brake systems are receiving increased attention since they can reduce particle emissions by one quarter compared to disc brakes [1]. An additional mechanism of particle generation becomes relevant at higher temperatures, where the evaporation of

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pad components produces nanoparticles, which can increase the total number emissions by several orders of magnitude [5]. In the EU, brake particle emission limits, in terms of both mass and number (the latter from 2030 onwards), are included in the Euro 7 legislation [2] and are determined according to the procedure described in the UN GTR No. 24 [6], where particle emissions are measured on the brake dynamometer.

Tyre wear emissions are generated through mechanical and thermal interactions at the tyre-road interface [7]. As a vehicle accelerates, brakes, or corners, friction and heat cause the tyre tread to abrade. This process produces Tyre and Road Wear Particles (TRWP), consisting of rubber polymers and tyre fillers mixed with road material (minerals, dust) [8]. TRWPs are emitted under all driving conditions, with high-friction events (hard acceleration, sharp turning, sudden braking) generating the most. In the EU, tyre emissions are currently indirectly limited via the tyre abrasion rate in the Euro 7 legislation [2], which is based on the testing methodologies and limits that are currently developed in UN WP.29 for testing tyre abrasion in real world [9].

Although that emission limits for both brake and tyre particles have been set and the respective procedures have been developed, a unified system and procedure that could cover both sources of NEP under real-world driving conditions is still missing. Such an approach would enable the development of robust and consistent emission factors (EF), corresponding to real vehicle operation, and inform future policy development. A major challenge in collecting brake and tyre particles is the absence of a 'carrier gas' that contains the particles, as is the case with the combustion-generated exhaust particles. Due to the open nature of brakes and tyres, the onboard sampling system needs to effectively segregate the different sources of particles, accounting also for ambient concentrations and resuspension of particles from the road surface.

For brake particles collection various systems have been developed, ranging from fully open configurations [10], without any isolation from the environment, to fully enclosed ones [11], which encapsulate the brake system and remove the impact of ambient particle concentrations. An intermediate approach is the semi-enclosed systems [12, 13], with partial isolation from the environment. Each configuration has pros and cons in terms of complexity, particle losses and impact on temperature [14]. For tyre particles, probes are positioned directly in the airflow near the tyre, behind the wheel and close to the road, to sample particles as they are emitted [10, 15]. Nozzles with high collection efficiency are incorporated in recent studies [11, 16, 17]. Fully enclosed wheel-housing concepts have been demonstrated, but reports highlight several methodological and practical limitations [18, 19].

The current work aims at filling this gap by introducing a modular system for sampling and measuring brake and tyre particles emitted by LDV under real-world driving conditions. The system has been built gradually, starting from a semi-enclosed brake particle collector, which was then expanded to incorporate tyre particle sampling, by integrating another nozzle and upgraded to full brake system enclosure. The integrated system can be used for onboard measurements on the same vehicle, providing consistent input for the development of NEP EF.

2 Vehicle Setup and System Development

The system consists of the particle collector, the sampling tube, the sampling tunnel and the blower that creates the sample flow. For brake particles, either a cone-shaped collector is attached to the wheel, or a full encapsulation of the brake system is implemented, while for tyre particles, a nozzle is placed behind the wheel. An electrically conductive Teflon sampling tube is used, with smooth inner surface, to minimize particle losses from the collector to the tunnel, where the measuring equipment samples from. Figure 1 presents the system and its components, which are described in more detail in the next paragraphs.



Fig. 1. Top: General setup of the modular system for onboard non-exhaust particle collection. Bottom: Left: Semi-enclosed brake particle collection system, Middle: Fully enclosed brake particle collection system, Right: TRWP sampling nozzle.

2.1 Brake Particle Collection

Semi-Enclosed System. The rotating cone-shaped collector was made of aluminum, to minimize the additional weight on the wheel and ensure safe handling of the vehicle. Balancing of the wheel and vehicle steering (when the cone is installed on a front wheel) remained unaffected. In addition, this semi-enclosed system did not have any impact on the brake system temperature, as confirmed by continuous monitoring of temperature on both front wheels of the vehicle.

Fully-Enclosed System. A fully enclosed brake system requires minimal clearance between the static (brake calliper/pads and steering knuckle) and rotating parts (brake disc, wheel hub and rim) of the wheel assembly to provide a sealed interface. Various methods for isolating brake wear particles were investigated [11] with differences in collection efficiency, complexity of design, applicability to various rims/tyres and impact on air flow. In the modular system of this work, a static enclosure around the brake disc and calliper was designed and constructed. The enclosure is mounted on the steering knuckle and is supplied with filtered air for the cooling of the brake system. Measurements of brake disc temperature confirmed that cooling remained unaffected, ensuring reliable measurements under real-world operating conditions.

2.2 Tyre Particle Collection System

Unlike tailpipe emissions that exit through a single pipe, tyre wear particles disperse from an open interface at the road surface. This open system makes it difficult to capture and isolate tyre particles in on-road tests, as they mix with other particulate matter

such as brake dust and roadway debris. The modular system of this work incorporates a single nozzle placed on the front wheel (Fig. 1). To ensure consistent collection efficiency under various driving conditions, the nozzle is mounted directly on the wheel hub, maintaining its precise alignment with the wheel throughout vehicle maneuvers. The nozzle design aims at achieving maximum collection efficiency through isokinetic sampling, ensuring that the velocity at the nozzle entry matches the ambient air velocity within ±20% to minimize sampling biases. This ±20% criterion is used as a practical tolerance for the average collection efficiency (for vehicle speeds 30–120 km/h) to maintain near-isokinetic conditions in a dynamic environment – a compromise that minimizes sampling bias while recognizing the difficulty of perfect matching during real driving. Nozzle design was optimized with CFD simulations, providing quantitative and qualitative description of the airflow characteristics around the sampling point. Detailed calculations of velocity and pressure were conducted to reduce potential losses during particle collection and transport. The simulations incorporated diverse particle injection angles into the flow to evaluate nozzle performance.

The optimal nozzle geometry and positioning were decided to be 2 cm above the ground and behind the tyre. Sensitivity of the nozzle aspiration in the transverse position (Fig. 2) was revealed by the CFD simulations. For straight driving, by varying the nozzle position by 5% (outwards) of the nozzle cross-sectional length (L), particle aspiration increases compared to the aligned with the wheel case. This is due to the generated transverse outflow which diverts particle trajectories away from the nozzle, causing a small area of the nozzle to remain unutilized. However, a lower particle aspiration was observed when moving the nozzle by 15% (outwards), indicating that a well-fixed positioning of the nozzle behind the wheel is critical.

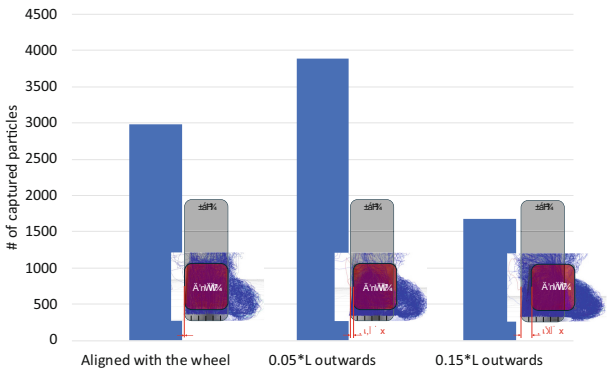


Fig. 2. Tyre particle collection for various transverse nozzle positions (outwards).

Based on the current design and CFD findings, it is estimated that the system captures roughly 60–70% of the airborne TRWP, with the remaining ~30–40% escaping collection due to the open airflow. This partial capture is in line with expectations for an open sampling setup and it motivates the ongoing development of the wheelhouse enclosure, which aims to raise the collection efficiency closer to unity. It was observed that the lateral outflow from the wheelhouse and the wake vortex of the tyre are still the main

mechanisms of escaped particles. A closed-rim approach indicated slight improvement and an air-deflector enclosure around the wheelhouse is currently considered to further improve the collection efficiency.

3 Testing Methodology

3.1 Brake and Tyre Particle Measurement

The system employs state-of-the-art instrumentation for particle characterization, including physical and subsequent chemical analysis. The system can be used for both lab and on-road testing, adapting accordingly the measuring equipment. Table 1 lists the equipment that can be integrated into the modular system and that has been used in various test campaigns. The equipment covers the physical characterization of brake and tyre particles, including number (both solid and total) at various cut-off sizes and mass (PM) emissions, as well as particle size distribution (PSD). To account for ambient effects, part of the equipment is used for the measurement of particle concentration in the ambient air, sampling either at the inner side of the wheel (for brakes) or at the front of the vehicle (for tyres). PM10 and PM2.5 particles are collected via the gravimetric method using cyclones, connected to two filter holders equipped with 47 mm quartz filters. Two Dekati ELPIs are employed to measure Total Particle Number (TPN) and Solid Particle Number (SPN) concentrations. For the removal of volatile and semi-volatile fractions, a thermodenuder and an e-diluter are used. Additional equipment (TSI CPC, AVL CPC, APC, HORIBA PN PEMS) is used for the characterization of PN emissions, while a TSI EEPS is implemented for a more detailed size distribution of smaller particles. Background particle concentrations are continuously monitored for TPN (TSI CPC), with periodic assessments of TPN and SPN (ELPIs). The quartz filters additionally support ICP-MS for metallic content analysis and GC-MS for organic compounds analysis.

Table 1. Measuring instrumentation.

Instrument	Measured parameter	Range	On-road	Lab
TSI CPC3010	SPN	23 nm ÷ ~1 µm		√
AVL APC	SPN	10 nm ÷ ~1 µm		√
HORIBA PN PEMS	SPN	10 nm ÷ ~1 µm	√	√
TSI CPC 3790	TPN	23 nm ÷ ~1 µm		√
TSI CPC 3750	TPN	10 nm ÷ ~1 µm	√	√
AVL CPC	TPN	10 nm ÷ ~1 µm		√
TSI CPC 3776	TPN	2.5 nm ÷ ~1 µm		√
TSI EEPS 3090	PSD	5.6 nm ÷ 560 nm	√	√
DEKATI ELPI No 1 & 2	TPN	7 nm ÷ 10 µm	√	√
Cyclone & filter holder	PM10 / PM2.5	10 µm / 2.5 µm	√	√

The brake EF are determined, expressing the cumulative emissions (per wheel) divided by the test distance. The TRWP EF is determined by correlating the mass of PM10 and PM2.5 to the corresponding tyre mass loss over the test distance, which is quantified through precise pre- and post-test weighing. To account for sampling losses, a collection efficiency correction is applied. Chemical markers are used to isolate the TRWP fraction of the collected particles. Pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) analysis is employed to detect polymer-specific pyrolytic fragments of tyre rubber in the sample. This method identifies unique decomposition products that are specific to tyre tread material. Further elaboration of the collected particles includes the investigation of health impacts through toxicological analyses.

3.2 Vehicle Testing

The test matrix of each measurement campaign is adapted according to the requirements and covers a wide range of conditions. Table 2 summarizes the driving profiles followed in test campaigns, either on the chassis dyno (WLTP Brake Cycle [6] replicated on the chassis dyno, WLTC, LACT20 [20], RDE/Real Driving Emissions – regular with moderate road gradients and smooth driving, 'On-road – Hilly' with aggressive driving, steep road gradients, severe braking) or on the road ('Test track').

Table 2. Driving profiles in lab and on-road testing.

Driving profile	Distance [km]	Duration [s]	Mean velocity [km/h]	Positive elevation gain [m/100 km]
WLTP Brake Cycle	192	15826	43.7	–
WLTC	23.3	1800	46.5	–
LACT20	15.4	1366	41.5	–
RDE (regular)	75.4	5430	50.1	315
On-road – Hilly	43.9	3364	47.0	2246
Test track	10–65	800–7500	30–45	–

4 Real-World Particle Emissions

For a complete verification of the measured data, a combined test campaign in the lab (chassis dyno) and on the road was conducted, focusing on brake particle emissions using the semi-enclosed collection system. The directly measured data were corrected accounting for the ambient particle concentration, to remove the impact of other particle sources, such as tailpipe, tyres, road and resuspension.

Figure 3 (Left) presents the results of this test campaign, where three bars are included for each test case, corresponding to the measured, ambient and brake data (the last is the difference of the first two). Chassis dyno and on-road results exhibit considerable overlap, with the respective average values being 3.5×10^9 and 2.9×10^9 #/km. These

findings validate the capacity of the system to be used effectively in both the chassis dyno, which represents a fully controlled environment, and on the road, which encompasses all possible real-world driving conditions. Figure 3 (Right) also shows the PSD for the complete on-road test, as recorded with the EEPS, with an overlay of all particle size distributions during the test. Two modes are observed, a first at 10 nm and a second at around 165 nm. The very high concentrations observed at smaller diameters, exceeding 10^6 #/cm^3, are associated with volatile particles, produced when the brake system components, particularly the pads, reach very high temperatures. At the specific case, the maximum temperature of brake discs and pads reached 290 °C.

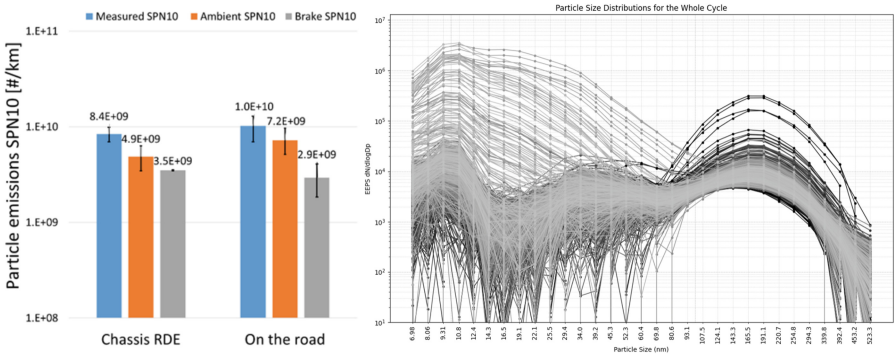


Fig. 3. Left: Brake SPN10 emissions. Right: Brake particle size distribution in on-road test.

5 Conclusion and Future Work

A modular system for sampling and measuring NEP has been developed and implemented in lab and on-road measurements. The system is fitted on an LDV and can be easily adapted for measuring either brake or tyre wear emissions. Extended test campaigns have been conducted for brake particle emissions, using the semi-enclosed particle collector, verifying the capacity of the system to be used in a wide range of driving conditions. The system has been upgraded by incorporating a fully enclosed brake system and an optimized nozzle for tyre particle collection, implemented in ongoing test campaigns. Further optimization of the system is also examined in two directions: analyzing the potential of a closed rim approach aiming at increasing the tyre particle collection efficiency and making a comparative evaluation of the semi-enclosed and full encapsulated versions for brake particle collection.

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References

1. Giechaskiel, B., Grigoratos, T., Dilara, P., Karageorgiou, T., Ntziachristos, L., Samaras, Z.: Light-duty vehicle brake emission factors. Atmos. **15**(1), 97 (2024)
2. European Parliament: Council of the European Union: Regulation (EU) 2024/1257. Official Journal of the European Union (2024)
3. Giechaskiel, B., Grigoratos, T., Dilara, P., Franco, V.: Environmental and health benefits of reducing Tyre Wear emissions in preparation for the new euro 7 standard. Sustainability. **16**(24), 10919 (2024)
4. Beddows, D., Harrison, R.: PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: dependence upon vehicle mass and implications for battery electric vehicles. Atmos. Environ. **244**, 117886 (2021)
5. Niemann, H., Winner, H., Asbach, C., Kaminski, H., Frentz, G., Milczarek, R.: Influence of disc temperature on ultrafine, fine, and coarse particle emissions of passenger car disc brakes with organic and inorganic pad binder materials. Atmos. **11**(10), 1060 (2020)
6. United Nations: Addendum 24: un global technical regulation no. 24 (2023)
7. Giechaskiel, B., Ferrarese, C., Grigoratos, T., Franco, V.: Wear of passenger car C1 tyres under regulatory on-road testing conditions. Vehicles. **7**(3), 91 (2025)
8. Fukahori, Y., Gabriel, P., Liang, H., Busfield, J.: A new generalized philosophy and theory for rubber friction and wear. Wear. **446-447**, 203166 (2020)
9. Economic Commission for Europe of the United Nations (UN/ECE): Regulation No 117, uniform provisions concerning the approval of tyres with regard to rolling sound emissions and to adhesion on wet surfaces and/or to rolling resistance (2011)
10. Oroumiyeh, F., Zhu, Y.: Brake and tire particles measured from on-road vehicles: effects of vehicle mass and braking intensity. Atmos. Environ. X. **12**, 100121 (2021)
11. Andersson, J. et al.: Measurement of Emissions from Brake and Tyre Wear, Final Report – Phase 1. Department for Transport (2023)
12. Huber, M.P., Fischer, P., Mamakos, A., Steiner, G., Klug, A.: Measuring brake Wear particles with a real-driving emissions sampling system on a brake dynamometer. In: SAE Technical Paper 2022-01-1180, 40th Annual Brake Colloquium & Exhibition (2022)
13. Dimaratos, A. et al.: Development of a sampling and measuring system of brake particles from passenger cars and application on chassis dyno testing. EB2024-TST-026, EuroBrake 2024 (2024)
14. Wang, Y. et al.: Assessing the brake particle emissions for sustainable transport: a review. Renew. Sust. Energ. Rev. **167**, 112737 (2022)
15. Beji, A., Deboudt, K., Khardi, S., Muresan, B., Lumière, L.: Determinants of rear-of-wheel and tire-road wear particle emissions by light-duty vehicles using on-road and test track experiments. Atmos. Pollut. Res. **12**(3), 278–291 (2021)
16. Charbouillot, T. et al.: Methodology for the direct measurement of tire emission factors. Sci. Total Environ. **863**, 160853 (2023)
17. Hesse, D., Feißel, T., Kunze, M., Bachmann, E., Bachmann, T., Gramstat, S.: Comparison of methods for sampling particulate emissions from tires under different test environments. Atmos. **13**(8), 1262 (2022)
18. García, J.: LEON-T: Low Particle Emissions and Low Noise Tyres. RTR Conference (2024)
19. Löber, M. et al.: Investigations of airborne tire and brake wear particles using a novel vehicle design. Environ. Sci. Pollut. Res. **31**, 53521–53531 (2024)
20. Mody, P., Rumold, W., Attia, F., Ansmann, S.: Mojacar and Los Angeles City traffic vehicle testing: a Comparison & Analysis of subjective ratings and objective measurements. In: 20th Annual Brake Colloquium and Exhibition (2002)

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Development of a Strategic Environmental Impact Module Within Large-Scale Transport Modelling Framework

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Abstract. The integration of environmental indicators into strategic transport models remains a key challenge in large-scale planning, especially in rapidly developing contexts with limited emissions data coverage. This paper presents methodology, coding structure, and calibration logic for embedding an environmental impact assessment module, covering noise and air pollutant emissions within a large-scale four-stage transport model. The model utilises established emission databases (e.g. HBEFA, COPERT), enriched with regionalised vehicle fleet profiles based on registration data, survey observations, and international standards. A disaggregated model demand segment structure enables the assignment of differentiated emissions by vehicle class, fuel type, and user group across time-of-day scenarios.

Outputs are automated for spatial and policy appraisal systems, supporting future-year scenarios aligned with transport policy testing, decarbonisation targets, and accessibility KPIs and supported by a complex fleet forecasting and e-vehicle penetration model. Noise and air pollutant emissions are estimated at link level and aggregated through a GIS-compatible output layer feeding into a prioritisation and impact framework. Model validation uses either observed sensor data and site-specific environmental measurements or fully validated model data. This work demonstrates a scalable, modular approach for enhancing transport models with credible environmental capabilities, enabling robust integration of mobility and sustainability objectives in planning practice.

Keywords: Environmental Impact Assessment · Transport Model Integration · Emission Modelling · Fleet Forecasting · Sustainability Planning

1 Introduction

The environmental impacts of road transport, particularly air and noise pollution, are increasingly important in planning, as motor vehicles significantly affect human health and environmental quality. Understanding how traffic systems contribute to these impacts is therefore essential.

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Traffic models provide detailed data on vehicle flows and speeds, forming a basis for estimating emissions and noise across networks with high resolution. These results support regulation and targeted interventions.

To address this, we enhanced the emission calculation procedure in PTV Visum by developing a more comprehensive, vehicle-specific module. The approach improves accuracy and allows calibration with measured data, supporting more reliable and integrated transport and environmental planning.

2 Literature Review

Road traffic emission modelling has become a central topic in transport research, as road transport remains a major source of urban air and noise pollution. Existing approaches are typically divided into macroscopic models, which rely on average speeds and fleet composition, and microscopic methods that capture detailed vehicle dynamics. Macroscopic applications (such as the integration of COPERT-based approaches into large-scale transport models [1–3]) have proven effective at regional and urban scales, although their accuracy can decrease under congested conditions.

To address these limitations, microscopic and hybrid approaches have been developed. These methods incorporate vehicle-specific behaviour and, in some cases, data-driven techniques to improve emission estimates [4, 5]. At the same time, the importance of calibration with measured data has been widely emphasised as a key requirement for ensuring model reliability and real-world applicability [6].

Recent literature also shows a clear shift towards more comprehensive assessments of transport-related impacts. Studies increasingly consider not only air pollution but also noise-related health effects [7], the role of urban morphology in shaping emission patterns [8], and the broader societal benefits of sustainable modes such as cycling [9]. In addition, freight transport has emerged as a critical area, where emission results are highly sensitive to input assumptions, highlighting the need for harmonised methodologies and detailed data [10].

Overall, the literature suggests that integrating COPERT-based emission modelling into traffic models provides a well-balanced approach. It combines the scalability of macroscopic methods with the potential for increased accuracy through calibration and complementary techniques, aligning with current trends towards more integrated and holistic transport and environmental modelling.

3 Emission Calculation Methods

The following section presents the currently applied HBEFA emission calculation module, outlines the essence of the COPERT methodology, and compares the two approaches.

3.1 The HBEFA and the COPERT Methodology

One of the additional modules in the PTV Visum traffic modelling software is the so-called Environment extension, which allows the estimation of environmental impacts

of road transport such as noise and air pollution. For air pollution, the software applies the **HBEFA** (Handbook Emission Factors for Road Transport) methodology, which is primarily used in a European context. Emission calculations are based on version 4.1 of HBEFA, released in October 2019.

COPERT (Computer Programme to Calculate Emissions from Road Transport) is an emission calculation tool developed by the European Environment Agency, widely used in Europe for estimating road transport emissions. The method relies on vehicle-specific emission factors that account for vehicle type, size, engine and fuel type, as well as operating conditions such as average speed, road characteristics and ambient temperature.

A key advantage of COPERT is that it does not only calculate hot emissions but also includes cold-start excess emissions, evaporative losses and non-exhaust particle emissions from brake wear, tyre wear and road surface abrasion. This enables the method to provide a much more comprehensive picture of road transport emissions compared to earlier and simpler tools.

3.2 Comparison

Several internationally recognised methods exist for estimating road transport emissions, among which the most frequently applied are HBEFA and COPERT. Both approaches are of European origin, yet they differ substantially in philosophy, operation and applicability.

Level of Detail and Vehicle Categories. HBEFA relies on traffic situations (e.g. urban congestion, free flow, motorways), assigning measured emission factors to these contexts. It is detailed in vehicle/fuel types but calibrated mainly for European fleets. COPERT instead estimates emissions by vehicle characteristics and average speed, covering a broader range of parameters and technologies such as hybrids, CNG/LNG and EVs.

Emission Types and Computational Complexity. HBEFA focuses mainly on exhaust emissions (CO_2, NOx, CO, PM, VOC), with optional cold-start and non-exhaust treatment. COPERT consistently includes hot, cold-start, evaporative and non-exhaust PM, thus modelling the full spectrum more comprehensively.

Applicability and Integration. HBEFA, developed in Germany/Switzerland, is common in European traffic models and already embedded in Visum but with limited flexibility. COPERT is stand-alone yet easily integrated (Visum, Cube, EMME) through scripts, with open tables that support automation and local calibration.

Regional Applicability. HBEFA emission factors are based on Western European fleets. For Asian, Middle Eastern or African contexts, where fleet composition differs, suitable calibration data are often lacking, which may reduce accuracy. COPERT, due to its flexibility, can be better adapted to different regions if local fleet profiles are available.

Summary. The following table summarises the main differences (Table 1):

HBEFA is well suited for European applications within existing Visum integration, particularly when detailed fleet data are not available. COPERT, however, offers a broader emission coverage and is advantageous for analysing complex sources and

Table 1. Main Differences between HBEFA and COPERT

Aspect	HBEFA	COPERT
Detail	Based on traffic situations (e.g. congestion, free flow)	Based on vehicle parameters (engine, age, technology)
Emission types	Hot emissions, optional cold start	Hot, cold start, evaporation, brake/tyre/road PM
Accurancy	Good in European context	High, if local fleet data are available
Vehicle fleet diversity	Limited	Detailed, including hybrid, CNG, LNG, EV
Data source	Moderate, traffic situation plus vehicle type	Higher, engine parameters, fuel, age
Integration	Built into Visum, limited flexibility	External script integration, high flexibility
Regional Useage	Primarily European	Applicable globally

for applications where local fleet-specific calibration is possible. The COPERT model is often preferred because it is transparent, well-documented, and widely used across Europe, ensuring consistency with official emission inventories and policy assessments.

4 Integration into Visum

4.1 Applicability and Implementation of the Emission Module

PTV Visum currently estimates emissions only with HBEFA, but its databases are outdated and logic limited. A future built-in COPERT module is planned, yet this will likely remain constrained in customisation.

To address this, an external COPERT-based module was developed with full flexibility for input parameters, fleet composition and traffic conditions. It directly adapts to the traffic model's categories and speed distributions, and includes calibration options to align with local data, making it suitable for urban to national applications and adaptable to evolving technologies and regulations.

Components of Air Pollution. The central element of the developed emission module is the structured and separate treatment of the four main components of air pollutant emissions. The following figure illustrates the logical framework of this system, showing the sources of the input data and how they are linked throughout the calculation process.

In line with approaches widely recognised in the literature, the emission calculation model divides total emissions into four distinct categories: (1) hot emissions, (2) cold-start excess emissions, (3) evaporative losses (VOC), and (4) non-exhaust particle emissions (PM), such as those generated by brake wear, tyre wear and road surface abrasion. Each component has been implemented as an independent sub-module, which allows for their separate management, calibration and calculation.

Calculation of Noise Emission. The noise emission calculation is based on RLS-19 method. It uses the following equation below for which the vehicles need to be separated into 3 categories. The following vehicle categories were used for the noise emission calculation: Car, Motorcycle, HGV1, HGV2.

The modelled vehicle classes were grouped into these 4 types. For the equation the speed, the share (in percentage) for all vehicle categories and the summarized traffic volume were needed. The following figure shows the usage of the data sources for the equation (Fig. 1).

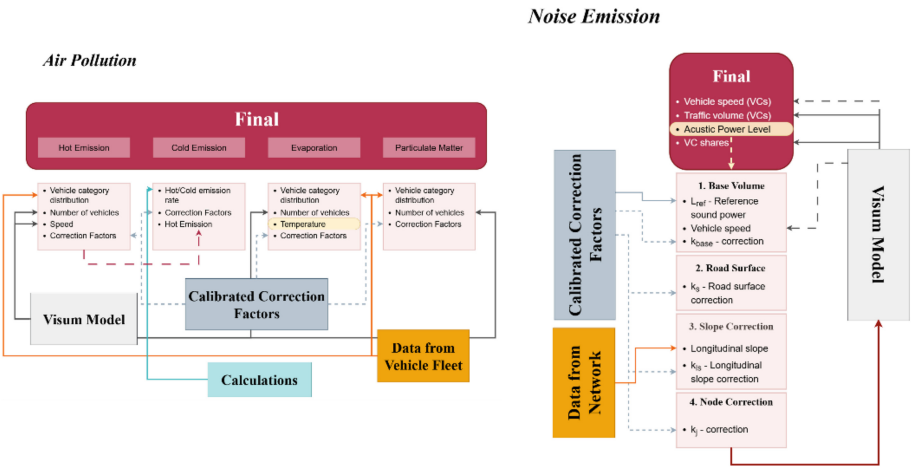


Fig. 1. Air and Noise Emission Calculation in the Emission Module

4.2 Applied Formulas

The module's methodology is based on COPERT formulas and logic, with necessary simplifications for practical use, as not all input parameters are available in typical traffic models. This change was based on the accessibility of the input data and was examined how it effects the results.

Emission calculations therefore rely on accessible data (such as speed, vehicle distribution, road gradient, and traffic volume) while maintaining consistency with COPERT. This balanced approach ensures scientifically sound results and allows flexible application across models with different levels of detail.

Hot Emission.

$$E_{HOT} = \sum_i \sum_k N \cdot share_k \cdot l \cdot \frac{\left(a \cdot v^2 + b \cdot v + c + \frac{d}{v}\right)}{\left(e \cdot v^2 + f \cdot v + g\right) \cdot (1 - k_{red})} \cdot (1 - cold_{rate}) \quad (1)$$

Where **N**: number of vehicles - from Visum, $\mathbf{share_k}$: share of "k" vehicle category, **l**: length [km] - from Visum, $\mathbf{e_{HOT,i,k}}$: hot exhaust emissions of the pollutant "i", produced

in the period concerned by vehicles of technology k driven on network element [g], **$\mathbf{cold_{rate}}$**: Calculated cold rate based on the trips on the network element. - imported from Visum, **a, b, c, d, e, f, g**: parameters of the speed dependency, **v**: speed of vehicles [km/h] - from Visum, **$\mathbf{k_{red}}$**: Reduction Factor [%].

Cold Start.

$$E_{COLD\ i,k} = \sum_i \sum_k N \cdot share_k \cdot l \cdot e_{HOT;i,k} \cdot cold_{rate} \cdot ((A \cdot v + B \cdot temp + C) - 1) \quad (2)$$

Where **$\mathbf{E_{COLD;i,k}}$**: cold-start emissions of pollutant i (for the reference year), produced by vehicle technology k, **A, B, C**: parameters of the speed and temperature dependency, **temp**: temperature at that location [°C] – from Visum.

Particulate Matter.

$$PM = PM_{tyre} + PM_{brake} + PM_{surface} \quad (3)$$

Where **$\mathbf{PM_{tyre}}$**: PM emission from tyre, **$\mathbf{PM_{brake}}$**: PM emission from brake, **$\mathbf{PM_{surface}}$**: PM emission from surface.

Noise Emission. The noise emission is calculation is based on RLS-19 method, for which the vehicles need to be separated into 3 categories and the vehicle speed is also necessary.

5 Results

5.1 Analysis and Importance of Calibration

The developed emission module was applied to a test network. Results showed that in sections where traffic intensity decreased, emission levels also fell significantly. This confirms the sensitivity of the model and its ability to reflect real traffic conditions. The magnitude of calculated pollutants can be assessed locally and also in relative terms across the network. The units of the calculated pollutants can be identified locally and analysed on a specific basis along individual sections of the network.

Accurate emission and noise modelling requires calibration with locally measured data. Vehicle fleets, driving styles and climatic conditions vary significantly between regions, and without calibration, even scientifically established models may produce biased results.

The model was run using both the current HBEFA and COPERT methodologies, with COPERT requiring more detailed input data. The results show that COPERT is more sensitive to small changes, as it allows modification of factors such as fleet Euro class composition. Uunlike HBEFA, where only predefined vehicle distributions can be applied leading to significant differences in future scenario outcomes.

5.2 Processing Script and Optimisation

To ensure reliability, a dedicated data-processing script was developed. This tool aggregates measured roadside emissions and traffic counts, then applies an optimisation algorithm to adjust model parameters within the emission formulas. In this way, pollutant and noise outputs are calibrated between the measured values and theoretical expectations.

The script ensures that hot emissions, cold-start effects, evaporative losses, non-exhaust particles and noise emission parameters are all fine-tuned to local conditions. This calibration process significantly increases the accuracy of results, enabling the model to be applied confidently for local, regional and national planning.

6 Conclusion

This study presents an emission calculation module that can be integrated into traffic models and provides detailed estimates of pollutants from road vehicles. The development builds on the COPERT methodology, covering not only exhaust emissions (CO_2, NOx, PM) but also non-exhaust sources such as brake, tyre and road wear, and evaporation. The calculation is structured along four components, ensuring flexibility, calibration and transparency.

The technical design considers practical limitations of traffic models. Equations and parameters do not follow COPERT in every detail but use an adapted version consistent with available data. This ensures applicability in diverse contexts without excessive input requirements.

The scientific relevance of this approach is underlined by several international studies [3, 11, 12], which showed how traffic conditions translate into emission estimates, especially under congestion. Tools such as SATURN, Aimsun and HERMESv3 reached similar conclusions: detailed inputs, accurate fleet data and sufficient spatial and temporal resolution are essential for reliable modelling.

The system's open architecture allows customisation and calibration with measured data, making it applicable not only in Europe but also globally, across varied fleets and environments. This strengthens the data-driven link between transport planning and environmental protection.

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References

1. Toşa, C., Antov, D., Köllő, G., Rõuk, H., Rannala, M.: A methodology for modelling traffic related emissions in suburban areas. Transport. **30**(1), 80–87 (2015)
2. Csikós, A., Tettamanti, T., Varga, I.: Macroscopic modeling and control of emission in urban road traffic networks. Transport. **30**(2), 152–161 (2015)
3. Rodriguez-Rey, D. et al.: A coupled macroscopic traffic and pollutant emission modelling system for Barcelona. Transp. Res. Part D: Transp. Environ. **92**, 102725 (2021)

4. De Nunzio, G., Laraki, M., Thibault, L.: Road traffic dynamic pollutant emissions estimation: from macroscopic road information to microscopic environmental impact. Atmos. **12**(1), 53 (2020)
5. Wang, L. et al.: Operational data-driven intelligent modelling and visualization system for real-world, on-road vehicle emissions—a case study in Hangzhou City. China. Sustainability. **14**(9), 5434 (2022)
6. Mądźiel, M.: Vehicle emission models and traffic simulators: a review. Energies. **16**(9), 3941 (2023)
7. Mayntz, S.P. et al.: Long-term road traffic noise, air pollution, and cardiovascular disease: AIRCARD prospective cohort study. JACC: Advances. **4**(6), 101787 (2025)
8. Augusto, B., Lopes, D., Rafael, S., Coelho, M.C., Ferreira, J.: Assessing the impact of different urban morphology scenarios on air pollutant emissions distribution. Sci. Total Environ. **950**, 175341 (2024)
9. Tordai, D., Munkácsy, A., Andrejszki, T., Hauger, G.: The real value of cycling. Transp. Res. Procedia. **72**, 2896–2903 (2023)
10. Li, Y., Kumar, A., Hamilton, S., Lea, J.D., Harvey, J., Kleeman, M.J.: Optimized environmental justice calculations for air pollution disparities in Southern California. Heliyon. **8**, e10732 (2022)
11. Nejadkoorki, F., Nicholson, K., Lake, I., Davies, T.: An approach for modelling CO_2 emissions from road traffic in urban areas. Sci. Total Environ. **406**(1–2), 269–278 (2008)
12. Liora, N., Kontos, S., Poupkou, D., et al.: Estimating road transport pollutant emissions under traffic-congested conditions with an integrated modelling tool. In: European Conference Series on Transport (ECST), pp. 137–146 (2021)

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Optimizing Tugboat Emissions within Port Areas Using Data Fusion

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Abstract. Maritime transport is essential for global trade but remains a major source of greenhouse gas and air pollutant emissions, especially near ports and coastal communities. Tugboats, which play a crucial role in vessel manoeuvres, are significant contributors but their emissions are poorly quantified due to the inadequacy of conventional estimation methods. This study develops a multidisciplinary approach to quantify and optimize tug-related emissions by integrating on-board field campaigns, interviews with tug crews, Automatic Identification System (AIS) data, and full-mission bridge simulation. Initial results from Spanish ports reveal that tugboats operate inefficiently, with more than half of their time spent below 25% engine load and extended waiting periods contributing to unnecessary fuel consumption. Logistic regression applied to AIS and observer data achieved 91% accuracy in identifying manoeuvre phases, while modified power–speed models outperformed the traditional cubic method for estimating engine power. These findings confirm that tug operations are oversized relative to their actual power needs, leading to avoidable emissions. The proposed methodology enables more accurate emission inventories and offers a framework for real-time monitoring and manoeuvre optimization, providing port authorities and policymakers with actionable strategies to mitigate local air pollution and improve sustainability in maritime operations.

Keywords: green house gas emissions · emission control · tugboats · coastal communities

1 Introduction

Maritime transport is the pillar of economic growth as 80% of worldwide freight is carried by vessels. However, it is a substantial source of greenhouse gas emissions (GHG) causing a noticeable impact on air, water and biodiversity and, generating a social alarm particularly in coastal communities. Greenhouse gas emissions from shipping

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increased worldwide by 9.6% from 2012 to 2018, amounting to some 1076 million tonnes, accounting for 2.9% of global GHG emissions. In global terms, the quantified SOx, NOx and PM2.5 emitted from shipping sector was 24%, 24% and 9% of worldwide emissions, respectively. A growth in global seaborne trade is forecasted in the near future because of the world's growing population, which will translate into an increase in air pollution from maritime transport. In parallel, the growth on maritime transport and the pollutants emitted has created a social alarm on coastal communities that has to be addressed. Major concerns are related to the consequences of emissions on human health affecting respiratory system among others. As a consequence of the actual and predicted paradigm, the International Maritime Organization (IMO) has developed and adopted over the years more stringent regulations aimed at dramatically abating emissions from vessels [1]. These air pollution regulations focus on the reduction of CO2, NOx, SOx and PM, since these are the main emissions from marine engines. Focusing on shipping emissions, the list of parameters to take into consideration when theoretically assessing their environmental impact is boundless. Since nearly 70% of ship emissions are emitted from within 400 km of coast with intensive ship traffic and in-harbour activities, where emissions from harbour operations add further to the air pollution generated by ships imposing a potential threat to the local ecosystem and residents' health. Exhaust from large marine diesel engines contributes significantly to the anthropogenic burden, thereby affecting the chemical composition of the atmosphere, global climate, and air quality in coastal areas [4]. Pollution emitted from ports comes from merchant ships constantly docking and undocking but also from other auxiliary port vessels working continuously throughout the year, like pilotage vessels, bunkering barges, vessel-generated waste collection services, mooring and unmooring services and port tugs.

There are extensive and multi-perspective ways to assess ship emissions based on methodologies that either combine fuel sales data with emissions (top-down methods) or are based on vessels' technical and operating conditions (bottom-up methods) [5]. Bottom-up approaches are widely used because they are ship-specific. [6] suggest a methodology for the evaluation of the exhaust emissions of marine traffic using the Automatic Identification System (AIS). The emissions are computed based on the relationship of the instantaneous speed to the design speed, and using the detailed technical information of the engines installed on-board. The estimation of fuel consumption (FC) is commonly based on the cubic speed–power relation as a bottom-up approach [7]. The need to emission-control policies and regulations at ports is widely acknowledged as an active policy issued by maritime port authorities. It is also considered an answer of international and European regulations and depends on an accurate estimation of emission inventory in close-to-land and in-port [8]. Port tugboats frequently sail between terminals (free sailing) and provide docking, undocking and removing merchant ships services. Port tugboats have powerful engines but they are not prepared for speeding and in most ports, between 40% and 70% of all free sailing is done at speeds where the fuel consumption is higher, often for no reason. [9] also reports that only 3.5% of the total time operation, tugs are required to give maximum power, and at only 0.5% of total manoeuvring time, the main engines have a maximum continuous rate of 81%, confirming that not as much propulsion power is needed during the manoeuvres of a tugboat, and smaller ones could be used. The traditional propeller-law-based method

is not applicable to estimate the emissions during pushing and pulling operations, even during free sailing phases in tug speeds due to the characteristic engines these vessels are designed with [2]. Very few researchers have considered port tugs emissions during pushing and pulling operations, while these two services may consume a large amount of energy [2, 10, 11]. [10] summarized the tug engine load during berthing and unberthing services, which provides empirical rules for emissions of port tugboats, but have not been systematically evaluated yet and therefore are not generally applicable. The empirical rules are based on the experiences of tug captains and operational guidelines, thereby providing a more accurate estimation of Main Engine (ME) load than the propeller-based method. However, these empirical rules face the emissions assessment considering real data of ME load during operations. An on-board analysis of each tug is expensive and inefficient for collecting ship emission data, being necessary to obtain a methodology to estimate the total emissions and characterize the spatial and temporal features of emissions distinguishing the operational modes of tugs and calculate the emissions according to the status of ship engines. In light of all the above, there is a need for urgent action on emissions mitigation and fleet technological and operational adaptation.

Our hypothesis is that the current methods to estimate emissions are not suitable for in-port manoeuvres and in particular for tugs activity. Thus, the main goal of the proposal is to assess port authorities to reduce tugs' emissions.

2 Methodology

The methodology follows a logical sequence of steps that are connected among themselves in order to optimize the usage of data: i) new multidisciplinary approach to define tug manoeuvres, ii) use of bottom-up approach to compute in-port fuel consumption and emissions through real-ship data, iii) multi-criteria assessment to identify the best methodology to estimate fuel consumption and tug-related emissions, iv) full mission bridge simulator use as a research tool to obtain tug manoeuvre characteristics and optimization.

- Intensive multi-disciplinary field campaigns: unprecedent on-board observations to spatio-temporally characterize emissions.
- AIS data to classify in-port manoeuvres: use raw AIS data to identify and classify tug in-port manoeuvres within a framework for high resolution spatial planning.
- Composite methodology to gather manoeuvres data: propose a composite methodology to systematically reproduce a manoeuvre through the full mission bridge simulator using AIS data.

The resulting data set (obtained from Jan 23 to Dec 25) enables a process based inter comparison of different data sources, improving the cross-validation among them (field campaigns and AIS data mainly). The data is processed according to resolution and accuracy to derive integrated indicators for the manoeuvres (e.g. mean length and duration, engine load interval phases), fuel consumption (e.g. daily consumption) and emissions (e.g. gr of pollutant per working condition). The fusion of near-real time AIS data (vessel trajectories, navigational status, ship type), manoeuvre simulator (full bridge) and field data (fuel consumption, engine orders, pollutants emissions) provides

a unique benchmark data set for demonstrating the capabilities of the shipping industry to reduce emissions with the appropriate available resources.

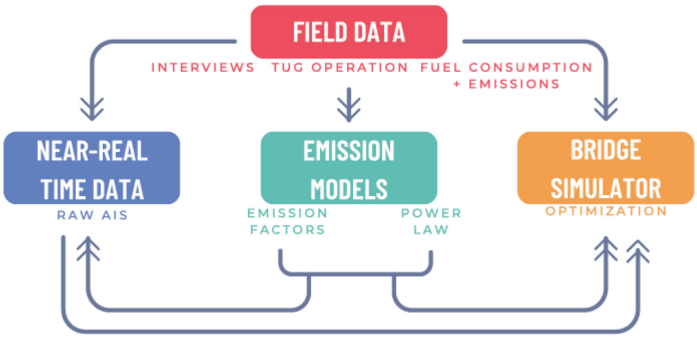


Fig. 1. Workflow sketch of the methodology

The workflow shown in Fig. 1 summarizes the methodology presented. Extensive field campaigns are designed to obtain data from real manoeuvres. The campaigns include a set of interviews to tugboat skippers and chief engineers, on-board field campaigns collecting data from operations (call time, start of manoeuvre, time pulling/pushing or accompanying, etc.…) combined with field campaigns including exhaust engines gas and engine load monitoring in Azabra tugboat. The data collected feeds i) the near-real time AIS data to produce models capable of distinguishing the different operational phases of a tug manoeuvre, ii) the calibration of new emission models including the power-law and the emission factors and iii) the bridge simulator campaign to optimize manoeuvres based on the results from near-real time data, emission models and interviews. At the same time, the emission models are also used to incorporate the new models to AIS data to estimate near-real time emissions and be able to reduce them, as well as the bridge simulator to propose new manoevures minimizing emissions. The data is fused in different steps of the methodology (e.g. on-board observers is fused with AIS trajectories to create a validated dataset)

3 Results and Discussion

Initial field campaigns conducted so far have yielded interesting results. 17 interviews were conducted to tugboat skippers and chief engineers from 11 different ports in Spain which yielded unexpected responses [12]. The interviewees emphasized the need to enhance traffic control to reduce unnecessary waiting times. They also pointed at the need to optimise manoeuvre planning to minimize the time spent with engines running at high power.

A first on-board field campaign was conducted between March and July 2024 with an on-board observer enrolled in a tugboat from the Port of Barcelona (Azabra, complying with TierIII), which included 55 different manoeuvres −58% departure, 38% arrival, 2% shifting berths and 2% false services-. In addition, most of the manoeuvres required 2

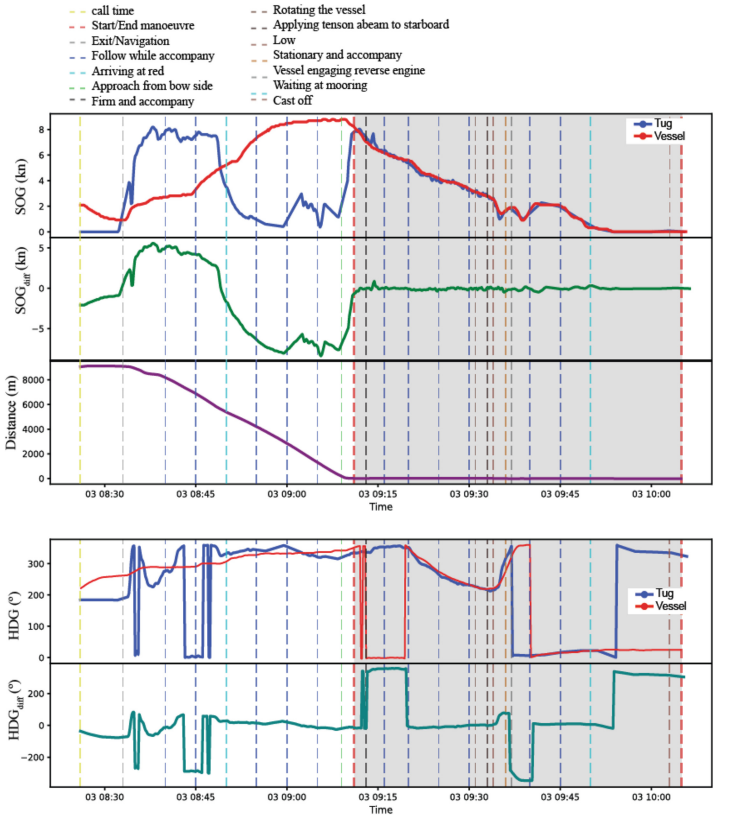


Fig. 2. Example of an arrival with AIS data combined with on-board observer. Gray area highlights the time between the start and the end of the manoeuvre. Yellow dashed line sets the call time for the service to start.

tugboats (71%), whereas only 20% required single tugboat assistance, with the remaining having more than 2 tugboats. This field campaign also allowed to better describe the sequence of any manoeuvre and the classification of tugboat manoeuvres into three service types: Arrival, Departure and Shifting, combined with the situation of the tugboat (free sailing, waiting, manoeuvre and escorting); the position of the tugboat with respect to the commercial vessel (pulling, pushing and stand-by,) and the engine order (idling, dead slow, slow, half and full).

The on-board field campaign was used to analyze AIS data in order to identify clear patterns [13]. Figure 2 shows an example of an arrival with time evolution of Speed Over Ground (SOG) AIS-data from the tug and the commercial vessel and their differences as well as the evolution of the distance between tugboat and commercial vessel. Heading (HDG) was also considered interesting for pattern purposes along with HDG difference between both vessels. An interactive visualization tool was developed in order to ease the process of visually analysing all manoeuvres. This interactive tool allows to plot at the same time the geo-spatial map position, along with the variables of interest shown in

Fig. 2 with a time bar to locate each instant in time and space. At the same time, historic raw AIS data collected from the antenna has been made publicly available through a portal.

On-board observers' data was used to feed a Logisitic Regression (Logit) algorithm in order to distinguish in geo-spatial data the real manoeuvre within the entire tugboat track. The accuracy of the model was 91%, and main errors occurred, as expected, during the transition phase that includes the waiting time, making fast the towing line, and the beginning of the manoeuvre, but also the last points of the manouevre -see Fig. 3- coincident with the final actions.

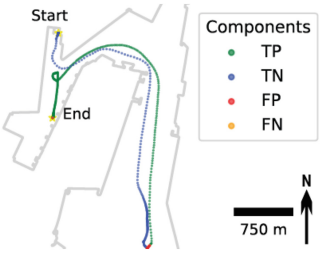


Fig. 3. Example of the geo-spatial results obtained with the logit methodology to identify the manoeuvre within the segment of the track (TP: true positive; TN: true negative; FP: false positive; FN: false negative).

Current methodologies, based on the classical cubic formulation, are appropriate for merchant vessels operating at speeds close to their design conditions, but they are inadequate for tugboats, which typically work at lower speeds and under highly variable operating conditions. To assess the applicability of the power–speed relationship with an adjusted exponent for estimating the instantaneous power of tugboats, real data from field campaign were analyzed. The current methodology for power estimation, was compared against four alternative models where the exponent n was adjusted: constant, linear, quadratic, and power-law. The results show that the classical cubic correlation cannot be applied in the context of a manoeuvre, including the free-sailing track segment and models with an adjusted exponent significantly improve the accuracy of power estimation. This improvement enables a more precise estimation of pollutant emissions, which is essential for progressing towards more sustainable port operations.

At the same time, the data analysis shows that the tugboat operates most of the time at low engine loads, while higher loads occur only residually. This indicates that the engine reaches maximum power only during very specific moments of the manoeuvre. In fact, 55.03% of the time the tugboat operates below 25% of engine load, and 26.36% below 10%, conditions that are particularly inefficient. The higher engine orders totally account only about 5% of the total manoeuvre time, confirming that the system is clearly oversized.

The full simulation bridge campaigns have been used to test the ability to reproduce AIS vessel tracks in order to obtain engine orders. The initial campaign included trials with 3 different experienced captains. First results using a reference vessel to reproduce manoeuvres show the clear need to use exactly the same model with exact ship particulars

and engine configuration. Still, with an initial model differing less than 5% of the LOA, with the same engine configuration yielded similar AIS track with a high sensitivity on engine orders at specific times of the manoeuvre. In order to optimize maneuvres from an emissions reduction perspective, the following campaigns in the full simulation bridge are designed to reproduce free sailing and manoeuvre segments of the exact tug that is being used in the field campaigns.

4 Conclusions

With the ongoing research and the results obtained so far, we can conclude that:

- Optimization from the tug manoeuvre to reduce pollutants emissions will have to tackle waiting times and maximum engine power, regardless of the compliance of the IMO regulation for tugboats.
- AIS data is useful to identify the different phases of the track without the need of highly complicated machine learning models.
- The traditional model to estimate engine power as a function of the cube of the SOG does not work for the in-port tugboat operations.
- Full bridge simulations must be performed using the exact vessel model.

Although the proposed research is based on a single port and using data of one specific tug, it aims to be applicable to other tugs and, most importantly, other ports. As far as the authors are concerned the main limitation of the results arose from the fact that only one tugboat was used for the field campaigns and, therefore, manouvres with more than one tugboat might be underlooked in terms of total emissions.

The needs to further develop the engine model, the AIS manoeuvre detection and the final emissions assessment require deep research that it is currently ongoing.

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References

1. Raza, Z.: Effects of regulation-driven green innovations on short sea shipping's environmental and economic performance. Transp. Res. Part Transp. Environ. **84**, 102340 (2020). https://doi.org/10.1016/j.trd.2020.102340
2. Chen, S., Meng, Q., Jia, P., Kuang, H.: An operational-mode-based method for estimating ship emissions in port waters. Transp. Res. Part Transp. Environ. **101**, 103080 (2021). https://doi.org/10.1016/j.trd.2021.103080
3. Tang, L. et al.: The impact of ship emissions on air quality and human health in the Gothenburg area – Part 1: 2012 emissions. Atmos. Chem. Phys. **20**, 7509–7530 (2020). https://doi.org/10.5194/acp-20-7509-2020

4. Capaldo, K., Corbett, J.J., Kasibhatla, P., Fischbeck, P., Pandis, S.N.: Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. Nature. **400**, 743–746 (1999). https://doi.org/10.1038/23438
5. Castells-Sanabra, M., Borén, C., van der Meer, R., Torralbo, J., Ordás, S.: Existing emission calculation methods applied to monitoring, reporting and verification (Mrv) on board. Nase More. **67**, 163–171 (2020). https://doi.org/10.17818/NM/2020/2.9
6. Jalkanen, J.P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., Stipa, T.: Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. Atmos. Chem. Phys. **12**, 2641–2659 (2012). https://doi.org/10.5194/acp-12-2641-2012
7. Otto, K.H.: Energy demand and exhaust gas emissions of marine engines. project no. 2016-108: update of decision support system for exhaust gas emission calculations report No. 05 (2017)
8. Yu, H., Fang, Z., Fu, X., Liu, J., Chen, J.: Literature review on emission control-based ship voyage optimization. Transp. Res. Part Transp. Environ. **93**, 102768 (2021). https://doi.org/10.1016/j.trd.2021.102768
9. Murcia González, J.-C.: Analysis and measurement of SOx, CO2, PM and NOx emissions in port auxiliary vessels. Environ. Monit. Assess. **193** (2021). https://doi.org/10.1007/s10661-021-09145-4
10. Xie, G.: Engergy savings in port pilot. China Water Transp. **6**, 6 (2014)
11. Lee, H., Pham, H.T., Chen, M., Choo, S.: Bottom-Up Approach Ship Emission Inventory in Port of Incheon Based on VTS Data. J. Adv. Transp. **2021**, 5568777 (2021). https://doi.org/10.1155/2021/5568777
12. Ribet, J.A., Castells-Sanabra, M., Boren, C., de Osés, F.X.M., Mujal-Colilles, A.: Characterization of tugboats activity within spanish ports. In: Marit. Transp. Conf. (2024). https://doi.org/10.5821/mt.13191
13. Niyazi, L., Vigo, M., Pla, N., Murcia, J.C., Castells-Sanabra, M., Colliles, A.M.: Characterizing the AIS data of Port Tugs in the Port of Barcelona. In: Marit. Transp. Conf. (2024). https://doi.org/10.5821/mt.13177

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Electrification and Alternative Fuels

Optimising Logistics for a Sustainable Hydrogen Economy: The DTI4HydroChains Framework

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Abstract. Logistics is the strategic backbone of a scalable hydrogen economy. It links renewable resources, industrial clusters and export corridors while determining cost, reliability and investment feasibility. This paper introduces DTI4HydroChains, a modular decision support framework that integrates techno-economic optimisation, scenario analysis and risk assessment to guide phased, multi-product infrastructure development. The framework is applied to a Finland-wide case study, informed by several months of exploratory research involving companies, technology developers and public sector actors. The analysis focuses on three near term value chains with strong market pull, biogenic CO_2, e-methane and e-SAF, and examines how their logistics requirements shape feasible siting, transport and export configurations. Results highlight that (i) biogenic CO_2 aggregation is a central constraint on synthetic fuel scale up, (ii) early export ready infrastructure is essential given limited domestic demand, and (iii) flexible, multi-product assets reduce lock in risks under uncertain market development. The study provides actionable policy insights and discusses the transferability of the framework to other national contexts.

Keywords: Hydrogen economy · Hydrogen derivatives · Logistics · Renewable energy · Biogenic carbon capture · Decarbonisation

1 Introduction

The EU's REPowerEU plan targets 20 Mt. of renewable hydrogen consumption by 2030 [1]. Finland aims to contribute at least 1 Mt., positioning itself as a significant supplier within Europe's emerging hydrogen economy [2]. Achieving this ambition requires more than production capacity – it depends on logistics systems that can reliably connect renewable resources, industrial clusters, and export markets. Pipelines, terminals and storage facilities form the backbone of such systems, and their design will determine whether Finland can scale hydrogen production into a sustainable, investable industry.

Hydrogen's physical properties pose major challenges: its low volumetric energy density makes transport and storage costly, while its handling requires specialised infrastructure. This is why hydrogen derivatives, particularly synthetic aviation fuel (e-SAF) and e-methane, are attracting attention. These carriers are not chosen solely because they are easier to move. They directly serve critical end-use applications in the regulation driven aviation, maritime and industrial sectors, creating demand signals that justify

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early infrastructure investments [3, 4]. For Finland, biogenic CO_2 logistics add another decisive layer: without efficient aggregation and transport of CO_2, large-scale e-fuel production cannot take place [5].

Finland's geography accentuates the challenge. Renewable energy resources are concentrated in the north and west, while demand centres and export ports lie in the south. At the same time, Europe's hydrogen infrastructure plans include the Nordic-Baltic corridor, linking Finland to Germany and beyond. Export readiness is therefore essential from the very beginning. Logistics solutions must serve domestic users while ensuring future compatibility with international corridors.

This study builds on several months of exploratory research involving discussions, interviews and workshops with companies, technology developers, infrastructure operators and public authorities active in Finland's emerging hydrogen and Power-to-X (P2X) ecosystem. These engagements provided practical insight into logistics constraints, market needs and feasible value-chain configurations. The work concentrated on three strategically relevant early pathways, namely biogenic CO_2, e-methane and e-SAF, reflecting both regulatory demand signals and the structure of Finland's industrial and renewable-energy system.

This paper introduces the DTI4HydroChains framework, which operationalises the principles of Decentralised Technical Intelligence (DTI) for hydrogen and P2X logistics. The framework integrates optimisation, scenario exploration, risk assessment and stakeholder insight into a single decision-support structure. The hydrogen case illustrates how DTI4HydroChains structures analysis under uncertainty and supports scalable infrastructure planning. By combining techno-economic modelling, scenario analysis and industry-informed assumptions, the study develops logistics configurations that reduce investment risk, support infrastructure phasing and clarify Finland's role as a scalable, interoperable node in Europe's hydrogen economy. The core contribution of this paper is not only the case study analysis but the demonstration of DTI4HydroChains as a generalisable framework for hydrogen-logistics decision-making under uncertainty.

2 Background and Related Work

Hydrogen logistics has emerged as a critical field of research and planning, driven by the need to connect renewable energy resources with industrial demand and international markets. While hydrogen is widely recognised as a cornerstone of the energy transition, its physical properties, such as low volumetric energy density, need for compression or liquefaction and high handling complexity, make logistics both technically demanding and economically decisive [6, 7].

2.1 Hydrogen Carriers and Their Logistics Profiles

Hydrogen can be transported directly via pipelines or as a compressed or liquefied gas, but each option involves high infrastructure costs and strict safety requirements [8]. For early market development, hydrogen-derived fuels with immediate demand signals, particularly sustainable aviation fuel (e-SAF) and synthetic methane (e-methane), are

central in the European context [9]. E-SAF is driven by the ReFuelEU Aviation regulation, which mandates increasing shares of sustainable aviation fuel in the EU kerosene mix starting in 2025, creating a strong, legally anchored demand signal. E-methane can utilise existing natural gas and LNG infrastructure in both industry and maritime transport, making it an attractive early-stage hydrogen-derived fuel with minimal additional logistics barriers.

In this study, only e-SAF, e-methane, and biogenic CO_2 were considered. Other hydrogen carriers discussed in the literature are not included, as they are not as relevant to the near-term pathways assessed for Finland.

2.2 Biogenic CO_2 as a Logistics Challenge

Producing e-fuels such as e-methane and e-SAF requires a steady supply of CO_2, ideally from biogenic sources to ensure climate benefits. Finland's forestry and bio-industry sectors generate substantial CO_2 volumes, but these are dispersed across regions and industrial sites [5]. Capturing, aggregating, and transporting CO_2 therefore becomes a decisive element of the hydrogen economy [10]. Dedicated CO_2 hubs and transport systems – whether short industrial pipelines, refrigerated tankers, or export terminals – are required. Without such logistics solutions, synthetic fuel production cannot scale

2.3 Comparative Context and Insights from Existing Studies

Finland faces distinct logistical conditions compared with central European hydrogen hubs. Renewable-energy resources (notably wind power) are mostly in the north and west, while demand from industrial clusters and ports is concentrated in the south, creating a structural north–south transport requirement even before exports are considered [11]. By contrast, continental hubs sit closer to large industrial areas and existing pipeline networks. Finland's position on the Baltic Sea, however, enables integration into the planned Nordic–Baltic hydrogen corridor, offering a strategic route for exporting e-fuels and biogenic CO_2 to Central Europe.

Techno-economic studies consistently show that pipelines become cost-effective only for large, continuous flows, while road, rail and maritime transport are already suitable for early markets. P2X supply chains introduce added complexity by linking variable green electricity with spatially dispersed CO_2 sources, making flexible infrastructure and buffering capacity important for reliability [9, 10]. Recent EU regulations for aviation and maritime fuels further reinforce the urgency of building such P2X logistics systems within this decade [3, 4].

3 Methodology

The methodology is structured around the DTI4HydroChains framework, which guides scenario construction, logistics modelling and stakeholder-informed interpretation throughout the study.

3.1 Objectives and Scope

The objective of this study is to develop logistics-driven strategies and decision-support tools that enable Finland's hydrogen economy to scale in a coordinated, cost-efficient and investable manner. Rather than focusing solely on cost-optimal configurations, the approach is demand-driven.

The scope of the analysis reflects the structure of Finland's emerging P2X sector and the immediate demand signals created by European regulation. The study concentrates on three strategically relevant pathways – biogenic CO_2, e-methane, e-SAF.

Hydrogen is considered primarily as an intermediate for these derivative products, reflecting the limited near-term domestic demand for pure hydrogen. The analysis covers both domestic logistics configurations (e.g. regional hubs and feedstock aggregation) and international corridor considerations, particularly Finland–Germany connectivity [3, 4].

The scenario inputs and value-chain assumptions are informed by several months of exploratory research, including interviews, company dialogues and stakeholder workshops with actors from energy, logistics, industrial and public-sector domains. These engagements helped identify realistic siting conditions, logistics constraints, and perceived risks and opportunities within Finland's hydrogen-economy development.

3.2 Scenario Planning and Selected Value Chains

Within the DTI4HydroChains logic, scenario design is a core mechanism for coordinating distributed insights and testing infrastructure strategies under uncertainty.

A backcasting scenario approach is adopted: the analysis starts from plausible end-use configurations and desired future market states in 2030–2045, then works backward to identify the infrastructure, logistics and supply chain arrangements required to reach those futures.

Scenarios include:

- Export-oriented setup where Finland supplies e-fuels and CO_2 to Europe.
- Domestic-oriented configurations that emphasise industrial clusters, regional hubs, and short-range CO_2 pipelines.
- Carrier-variant scenarios that test the implications of prioritising different products (e.g., e-SAF vs. e-methane).

The modelling focuses on three early value chains that consistently emerged from exploratory industry engagement and regulatory analysis:

- Synthetic Methane (e-methane): Produced by combining hydrogen and biogenic CO_2, e-methane benefits from compatibility with existing natural gas and LNG infrastructure. The logistics analysis concerns CO_2 aggregation and transport to methanation sites, and distribution options via pipeline or liquefied routes [10].
- Sustainable Aviation Fuel (e-SAF): Driven by EU ReFuelEU Aviation mandates, e-SAF represents a major early market for hydrogen-derived fuels in Europe. The value-chain analysis covers feedstock delivery (H_2 and CO_2), siting considerations relative to renewable-energy clusters, and distribution to domestic airports and export terminals [3].

- Biogenic CO_2: A critical feedstock for e-fuels, sourced from forestry and industrial processes. Logistics solutions include regional aggregation hubs, short pipelines, refrigerated tankers and potential export terminals [5].

These chains are analysed as an integrated system, with shared infrastructure constraints and interdependencies. Each scenario explores the siting of production facilities, feedstock transport requirements, infrastructure reuse potential, and export options. Stakeholder workshops are used to validate assumptions, test feasibility, and align findings with industrial priorities.

3.3 Analytical Framework: DTI4HydroChains

The analytical foundation of this study is the DTI4HydroChains framework, which operationalises the principles of Decentralised Technical Intelligence (DTI) [12, 13]. It is designed as a framework rather than a single model, allowing analysts and stakeholders to integrate insights from multiple tools, datasets and viewpoints into one coherent decision-support process. DTI is a paradigm for structuring complex decision-making in socio-technical systems by distributing intelligence across multiple tools, actors and datasets rather than relying on a single centralised optimisation model. In the context of hydrogen and P2X logistics, this approach is essential: no single model can capture the interacting uncertainties in renewable-energy availability, CO_2 supply, market development, regulation and infrastructure phasing.

Unlike single-model optimisation approaches, DTI4HydroChains builds a distributed intelligence ecosystem where models, expert insights and scenario tools interact. This is a direct implementation of DTI, which emphasises that in complex transitions, such as hydrogen, no single model can foresee all contingencies. Instead, system-level insight emerges from the structured combination of partial models, qualitative knowledge and reflexive scenario testing.

Accordingly, DTI4HydroChains consists of interoperable modules that collectively support coordinated planning under uncertainty (Table 1). These modules include (i) supply-chain optimisation, (ii) scenario-based ecosystem foresight, (iii) cost and business analysis, (iv) infrastructure phasing and corridor design, (v) safety and acceptance integration, and (vi) concepts for operational reliability. The framework is designed not as a static model but as an evolving system that incorporates new data and stakeholder insights over time, which is an essential property for hydrogen-economy development where learning, iteration and partial information dominate. This design reflects the DTI principle that system-level intelligence emerges not from centralisation but from the structured interaction of diverse analytical components and stakeholder knowledge.

Table 1. Illustrative functions of the DTI4HydroChains platform

Function within the platform	Purpose
Supply chain optimisation	Joint optimisation of production and logistics under uncertainty
Ecosystem foresight	Strategic exploration of scenarios and stakeholder engagement
Cost and business analysis	Identification of cost-efficient production and logistics configurations
Infrastructure planning	Phasing of investments and corridor design
Safety and acceptance integration	Incorporation of safety, regulation, and social license factors
Operational monitoring	Assessment of reliability and compliance in transport and storage systems

4 Risks and Policy Implications

Finland's P2X scenario analysis highlights a set of system-wide logistics risks that cut across biogenic CO_2, e-methane and e-SAF pathways. Dispersed CO_2 sources create aggregation challenges, while insufficient domestic demand makes the timing of export infrastructure critical. Electricity and siting constraints, driven by regional imbalances and variable renewables, further complicate project sequencing. Infrastructure also risks becoming locked into single products as markets evolve, and limited transparency on flows and outages undermines planning and investment. Addressing these risks requires regional CO_2 hubs, pre-permitted export terminals with offtake-linked support, prioritised grid access for electrolyser clusters, multi-product design standards, and stronger data-sharing mechanisms. Together, these factors set the boundary conditions for phased infrastructure development.

5 Discussion

The study shows that logistics, rather than production capacity, determines the feasibility and speed of Finland's P2X scale-up. Infrastructure for CO_2 aggregation, renewable-energy integration, and export readiness must be coordinated early, as even modest production volumes require reliable transport and storage solutions.

A phased approach is essential. Early markets depend on flexible options such as trucking of CO_2 and containerised fuels, while later stages justify pipelines, terminals and large-scale storage. Designing these assets for multi-product flexibility helps mitigate lock-in risks under uncertainty about future demand patterns.

The DTI4HydroChains framework proves sensible in understanding and structuring decisions under uncertainty by combining optimisation, scenario exploration and distributed stakeholder knowledge. This decentralised intelligence approach is well suited

to hydrogen-economy development, where interdependent actors, evolving technologies and uncertain markets complicate centralised planning.

Portable elements include the modular optimisation–scenario–risk toolchain, stakeholder co-creation and phased investment logic. Before projecting costs or performance, one must adjust for local realities. This includes evaluating infrastructure, regulations, CO_2 source proximity and public acceptance. The approach is thus transferable, but numerical outcomes are location- and regulation-dependent.

The logic of DTI4HydroChains is critical for capturing the system-level nature of Finland's P2X transition. Because the framework integrates optimisation, foresight, risk and stakeholder intelligence, it reveals interactions that traditional models typically overlook, such as the dependency between CO_2 aggregation pathways and export-terminal phasing, or the effects of multi-product flexibility on investment risk.

The DTI logic also enables iterative refinement of scenarios as technologies, regulations and markets evolve. This makes the framework suitable not only for the Finnish case but also for evolving hydrogen ecosystems where learning, data and stakeholder expectations change over time. In this sense, the case serves primarily as a demonstration of how DTI4HydroChains orchestrates diverse analytical components to produce robust, system-level insights.

6 Conclusions

The development of Finland's hydrogen economy will depend primarily on the design and sequencing of its logistics systems. Because near-term domestic demand for pure hydrogen remains limited, the transition will begin through hydrogen-derived products with clear market pull, i.e. e-SAF, e-methane and biogenic CO_2. The feasibility and scalability of these value chains are governed by three interrelated factors.

Three priorities stand out:

1. Export readiness from the start: Finland must develop export terminals and corridor connections in parallel with production capacity, since domestic demand alone will not justify large-scale investments.
2. Integration of biogenic CO_2 logistics: capturing, aggregating, and transporting CO_2 is both the central constraint and the key opportunity for scaling synthetic fuel production.
3. Flexible, phased infrastructure: early modular solutions must evolve into multi-product systems that remain interoperable with European standards and adaptable to shifting markets.

The DTI4HydroChains framework clarifies these priorities by revealing how infrastructure decisions interact across carriers, regions and time horizons under uncertainty. The framework supports this transition by operationalising the principles of DTI. Its modular structure integrates optimisation, scenario exploration, risk assessment and stakeholder insights into a coherent decision-support approach suited to complex, multi-actor energy systems. By structuring logistics decisions under uncertainty, the framework helps reduce investment risk and align infrastructure development with real market needs.

Together, these findings indicate that logistics is not a downstream operational issue but the strategic backbone of a sustainable, export-oriented hydrogen economy. Addressing the identified challenges will be essential for turning Finland's hydrogen ambitions into feasible, investable and internationally connected energy pathways.

References

1. European Commission: A hydrogen strategy for a climate-neutral Europe. Brussels (2020)
2. Government of Finland: Government resolution on hydrogen. Helsinki (2023)
3. European Commission: Regulation (EU) 2023/2405 on Ensuring a Level Playing Field for Sustainable Air Transport (ReFuelEU Aviation). Official Journal of the European Union, Brussels (2023) URL https://eur-lex.europa.eu/eli/reg/2023/2405/oj/
4. European Commission: Regulation (EU) 2023/1805 on the Use of Renewable and Low-Carbon Fuels in Maritime Transport (FuelEU Maritime). Official Journal of the European Union, Brussels (2023) URL https://eur-lex.europa.eu/eli/reg/2023/1805/oj
5. Cordova, S.S., Rasmussen, J., Gustafsson, M.: Barriers and drivers for biogenic CO_2 utilization: implications for the future market. Sustainable Prod. Consumption. **56**, 490–503 (2025). https://doi.org/10.1016/j.spc.2025.04.007
6. Bicer, Y., Dincer, I.: Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour. Conserv. Recycl. **132**, 141–157 (2018). https://doi.org/10.1016/j.resconrec.2018.01.036
7. Glenk, G., Reichelstein, S.: Economics of converting renewable power to hydrogen. Nat. Energy. **4**(3), 216–222 (2019). https://doi.org/10.1038/s41560-019-0326-1
8. Zhang, T., et al.: A systematic review of modelling methods for studying the integration of hydrogen into energy systems. Renew. Sust. Energ. Rev. **208**, 114964 (2025). https://doi.org/10.1016/j.rser.2024.114964
9. Kountouris, I., Bramstoft, R., Madsen, T., et al.: A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. Nat. Commun. **15**, 5517 (2024). https://doi.org/10.1038/s41467-024-49867-w
10. Wiltink, T., Ramirez, A., Pérez-Fortes, M.: Trade-offs in the integration of biogenic CO_2-based supply chains for storage and use in the transport sector. In: Proceedings of the 17th Greenhouse Gas Control Technologies Conference (GHGT-17). IEAGHG, Cheltenham (2024). https://doi.org/10.2139/ssrn.5076099
11. Sivill, L., et al.: Hydrogen economy: opportunities and limitations. In: Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2022:41. Helsinki (2022) URL https://urn.fi/URN:ISBN:978-952-383-068-4
12. Walter, S., Mikkola, M.: Advancing networked production through decentralised technical intelligence. In: Soldatos, J. (ed.) AI in Manufacturing. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-46452-2_16
13. Walter, S.: Collaborative digitalisation and the future of networked production: exploring decentralised technical intelligence in supply chains. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility Lecture Notes in Mobility. Springer, Cham (2026). https://doi.org/10.1007/978-3-032-06763-0_19

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Sharing Charging Infrastructure – Analysis of a Platform-Based B2B Network

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Abstract. The underutilisation of private charging infrastructure in business fleets represents both an economic inefficiency and a missed opportunity for accelerating electric vehicle (EV) adoption. This paper examines a platform-based business-to-business (B2B) model for sharing corporate charging stations, developed within the German research and innovation project FAMOUS. Two questions guide the study: (1) how do stakeholders exchange value within a platform model for reserving and sharing charging infrastructure, and (2) what benefits can emerge from this approach? Using 23 expert interviews, workshops with industry stakeholders, and analysis through the Business Model Canvas and Value Network Diagram, we identify 21 stakeholder-specific value flows (financial, operational, data) and 9 systemic values. Results show that the platform introduces a new coordinating actor and enables transparent financial redistribution, data-driven planning, and regulatory compliance. The findings suggest that sharing idle charging infrastructure can reduce the need for new installations, improve network accessibility, and create collaborations across the e-mobility ecosystem. These insights provide guidance for policymakers, charge point operators, and e-mobility providers seeking scalable solutions to Europe's electrification and decarbonisation goals.

Keywords: Electric Mobility · Sharing Infrastructure · B2B Charging Infrastructure · Stakeholder Analysis · Value Network

1 Overview and Motivation

The transition to electric mobility represents a cornerstone of climate action, particularly in Europe, where transport accounts for nearly 29% of greenhouse gas emissions [1]. In Germany, the transport sector contributes approximately 22% of total emissions, highlighting the need for targeted intervention [2]. Despite significant reductions in other sectors over the last two decades, transport remains stagnant in emission reductions. Businesses are increasingly adopting EV fleets as part of their sustainability strategies, but as our interview results (23 interviews; 2023–2024) reveal charging stations are often idle outside operational hours, representing potential to accelerate EV adoption while fostering collaboration [3].

Fleet electrification is gaining momentum due to legal mandates and European sustainability goals. The European Union's target of zero tailpipe CO_2 emissions for all

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newly registered passenger cars from 2035 [4] and the adoption of the Alternative Fuels Infrastructure Regulation [5] stress the urgency of increasing EV adoption and charging infrastructure. As of early 2024, approximately 1.4 million EV and 2.9 million hybrid vehicles were registered in Germany, with commercial owners accounting for a significant share of new registrations [6]. This growth emphasises the increasing demand for efficient charging solutions at company locations, supporting diverse mobility profiles and operational needs [7].

From an economic perspective, the feasibility of building and operating charging points within company sites is directly linked to utilisation. The higher the utilisation, the earlier the payback of investment costs. While some companies restrict charging access to internal stakeholders like employees, others are exploring external sharing models to maximise economic returns [8]. Sharing corporate charging stations with third parties offers financial and ecological advantages by improving resource efficiency and reducing the need for additional (public) infrastructure [9, 10].

Launched in 2023, the Hamburg (Germany) based project FAMOUS aims to address this topic by enabling companies to offer their charging stations for use during idle periods to authorised users, hence enhancing convenience and enabling better capacity planning for operators [11]. This is achieved by creating a new digital platform focusing on the two main challenges: reservation functionality and management of user-group authorisation, while also introducing a new actor – the platform operator – into the EV ecosystem [12]. However, several implementation challenges must be addressed to achieve the full potential of the new booking platform [13]. Technical integration across multiple stakeholder systems requires careful coordination and standardisation [14]. The reservation functionality introduces operational complexities around booking confirmation, cancellation policies, and enforcement procedures which must be carefully designed to balance user flexibility with infrastructure optimisation [7]. User group management represents another operational challenge, as CPOs may wish to limit access to their infrastructure based on various criteria such as corporate affiliations, vehicle types, or time windows. Moreover, the platform must provide user-specific access control mechanisms while maintaining a streamlined user experience. Payment processing and revenue distribution across multiple stakeholders require clear financial distribution processes and well-defined contractual frameworks [15]. The framework contract developed within the project provides a foundation for these arrangements, but operational implementation will require ongoing refinement as the ecosystem evolves. Data privacy and security considerations also present operational challenges, particularly given the sensitive nature of user data, payment information, and infrastructure access credentials [16, 17]. The platform must implement strong data protection measures without affecting the flow of data which underline the ecosystem benefits.

Even though being still in its development phase, this paper examines a platform-based business-to-business (B2B) model for sharing corporate charging stations, developed within the German research and innovation project FAMOUS. By applying a Value Network Analysis (VNA) stakeholder relations and value flows are mapped. Two questions guide the study: (1) how do stakeholders exchange value within a platform model for reserving and sharing charging infrastructure, and (2) what benefits can emerge from this approach?

2 Methodology

To develop the Value Network Diagram (VND) for the platform ecosystem, a structured five-stage approach was applied. The process began with 23 semi-structured expert interviews conducted within the FAMOUS project in 2023 and 2024, involving project, associated, and external partners. Interviewees represented the following actor groups: Charge Point Operators (CPO), E-Mobility Providers (EMP), Users, Public Authorities (PA), Grid Operators (GO), FAMOUS Platform operators (FP), and Energy Providers (EP). Insights from the interviews were analysed using the VNA, a method for mapping tangible and intangible value exchanges between actors in complex ecosystems [18]. This produced an initial network model identifying interactions between key stakeholders, and how tasks and responsibilities are distributed among them. In the next step, business models focusing on sharing ecosystems were developed in a collaborative workshop with participating CPOs, EMPs, and the FP operators using the Business Model Canvas method [19, 20], giving additional techno-economic insights. The project's framework contract, which outlines the stakeholders' expected deliverables and legal obligations, was also reviewed to identify and/or confirm additional value flows. Finally, the completed VND was discussed, reviewed, and validated in a workshop with the project partners, ensuring the best potential outcome.

The values are defined as follows:

- Stakeholder-specific values: The flow of financial, operational, and data-driven values between key stakeholders within the system.
- Systemic values: The emergent advantages for stakeholders, the environment, and society as a whole.

3 Results

The VND (Fig. 1) shows the FP as the central hub in an ecosystem that links key stakeholders, enabling mutually beneficial use of shared EV charging infrastructure. Drawing on findings from the first two project years, the analysis so far has focused on the conceptualisation of the platform, development of business models, and exploration of legal aspects. Although the network structure and anticipated advantages are presented in this stage, it is important to emphasise that practical testing and approval have not yet occurred and are expected in 2026.

As illustrated in Fig. 1 stakeholders interact through multiple value flows that generate both individual and systemic benefits. Each stakeholder serves a distinct role: PA provide the regulatory framework and financial support that enable platform development, while the FP acts as the central coordinating entity, managing bookings and facilitating information exchange. EMPs deliver the user interface, handle customer relationships, payment processing, and service delivery. GO maintain electricity network stability through capacity planning and load management, whereas CPOs manage and operate the physical charging infrastructure, including access policies and pricing. Users represent the demand side, paying for services and generating valuable usage data. Energy Providers supply the electricity and pricing information that underpin the entire system.

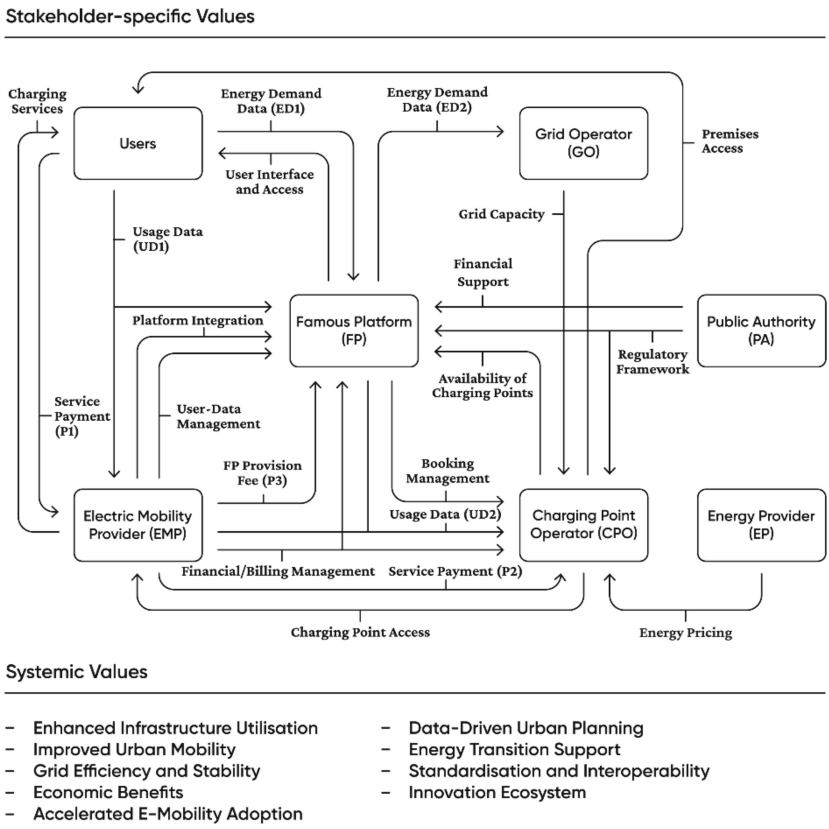


Fig. 1. FAMOUS Value Network Diagram (own depiction)

The VND showcases distinct value flows that can be categorised into three primary types: financial flow, data flow, and operational/service flow. These value flows outline the core responsibilities and tasks for each stakeholder, creating a guide on which the shared charging ecosystem operates. As a result, the platform could potentially offer better coordination between charging demands and charging capacities, creating a more efficient and accessible charging ecosystem for fleet operators and other business users.

3.1 Stakeholder-Specific Values

Financial Value Flow

The primary financial flow originates with Users who make service payments (P1) to their respective EMPs. This payment includes the complete service value, which is then divided and distributed by the EMPs. After receiving their service payment, the EMPs give the CPOs and FP their service payments (P2, P3) respectively, creating a streamlined system that rewards stakeholders proportionally to their value addition and ensures transparency. The PA also contributes financially through research and development funding, supporting infrastructure development and improvement. This public

investment has societal benefits of optimised charging infrastructure utilisation, which includes reduced public spending on unnecessary infrastructure and accelerated adoption of sustainable transportation options.

Data Value Flow
Data is a key currency within the ecosystem, driving efficient operations, informed decision-making, and continuous improvements. The platform facilitates numerous data exchanges which create value for the involved stakeholders. Users provide energy demand data (ED1) and usage patterns (UD1) through the platform to EMPs, which is then processed and shared with CPOs (UD2) and GOs (ED2). This data sharing enables critical functions such as accurate demand forecasting, infrastructure planning, and service optimisation. The bi-directional flow of availability information from CPOs to the platform, combined with booking data from Users, creates a real-time operational awareness that boosts infrastructure utilisation. GOs benefit from energy demand forecasts, enabling them to anticipate load patterns and ensure grid stability—an important aspect as EV adoption accelerates and places additional demands on existing electrical infrastructure.

Operational and Service Value Flow
The operational side includes service delivery, access management, and technical integration. CPOs share information about the availability of charging points and the designated user group with the FP via a booking calendar. Furthermore, CPOs grant EMPs charging point access by connecting their charging stations to their EMP product. At the same time, CPOs provide users with premises access, enabling physical access to their charging infrastructure. The EMP contributes to the system by providing platform integration and user-data management services to the FP, allowing the FP to function as an extension of the EMP's platform ecosystem and ensuring the management and authorisation of user accounts through a verified EMP according to the framework contract requirements. In addition, EMPs deliver the digital interface and authorisation mechanisms (charging services) which enable Users to access the facilities. Moreover, EMPs manage financial and billing processes for both CPOs and the FP. The platform manages booking coordination, user interfaces, and access permissions that bridge physical and digital dimensions. EPs contribute operational value through pricing information which enable CPOs to optimise their service offerings and pricing structures. GO provide CPOs with information about grid capacity and peak-load time windows, enabling them to manage charging stations and adjust pricing accordingly. PAs deliver regulatory frameworks that provide operational certainty for all stakeholders, while also receiving compliance and impact data, supporting future policy development. This integration of operational capabilities across stakeholders creates a better user experience, improving the efficiency of existing stations and reducing system complexity.

3.2 Systemic Values

The FP is assumed to create systemic benefits that extend beyond the individual stakeholder level. First, it enhances infrastructure utilisation by connecting existing charging demand with unused charging capacity, allowing the current charging infrastructure to be

used more efficiently. This reduces the need to build additional private or public charging stations, thereby lowering space requirements and material use. Second, the FP improves mobility by creating a denser network of accessible charging stations, enabling registered users to travel shorter distances for charging and reducing unnecessary journeys and traffic.

Furthermore, the reservation system supports grid efficiency and stability, as GO can more accurately forecast expected energy demand, prepare for sudden peaks, and manage consumption more effectively. The platform also creates economic benefits for all stakeholders through time savings, potential new income streams, and the use of collected data. By bringing different stakeholders together, the FP also enables synergy effects such as the development of strategic partnerships.

In addition, the FP accelerates e-mobility adoption by lowering barriers to electric vehicle use. Expanding access to charging points and enabling businesses to share infrastructure increases trust in charging availability, encouraging companies to transition to electric mobility and reducing fossil-fuel emissions. The platform also supports data-driven urban planning by providing insights into charging behaviour, energy consumption, and high-demand locations, allowing infrastructure planners to make more objective and strategic decisions regarding the expansion of public charging networks.

Finally, the FP contributes to the energy transition by promoting renewable energy use through the support of electric vehicle fleets and by improving the accessibility and efficiency of existing charging infrastructure. It also enables standardisation and interoperability by functioning as an extension to multiple EMP interfaces, creating a standardised framework for sharing corporate charging infrastructure and allowing seamless charging across providers. At the same time, the FP fosters an innovation ecosystem by encouraging collaboration among stakeholders from different sectors and enabling new sustainability-oriented business models and technologies.

4 Conclusion and Future Outlook

In conclusion, the FAMOUS platform represents a promising approach to improving the utilisation and accessibility of corporate charging infrastructure by linking economic, technological, and environmental objectives within a shared ecosystem. As such the platform represents a resource efficient approach to supporting EV adoption. The VNA reveals that value co-creation among diverse stakeholders—ranging from charge point operators to public authorities—can enhance both financial efficiency and systemic sustainability and address infrastructure bottlenecks. By establishing a digital platform that integrates booking, authorisation, and data management, the project lays the groundwork for new governance and business models that extend beyond traditional charging use cases. As upcoming field tests in 2026 validate the conceptual framework, future work will need to examine scalability, user acceptance, and regulatory alignment to ensure the platform's long-term contribution to e-mobility and energy transition goals.

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References

1. European Environment Agency: https://www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobility-systems/climate. Accessed 19 Mar 2025
2. Umweltbundesamt: https://www.umweltbundesamt.de/daten/verkehr/emissionen-des-verkehrs. Accessed 19 Mar 2025
3. Jahic, A., Eskander, M., Schulz, D.: Charging schedule for load peak minimization on large-scale electric bus depots. Appl. Sci. **9**(9), 1748 (2019). https://doi.org/10.3390/app9091748
4. European Commission: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/cars-and-vans_en. Accessed 19 Mar 2025
5. Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (2023)
6. Kraftfahrtbundesamt: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Jahrebilanz_Bestand/fz_b_jahresbilanz_node.html?yearFilter=2024. Accessed 19 Mar 2025
7. Meinert, M., Vladova, G.: Entwicklung einer Sharing-Plattform zur koordinierten Auslastungssteigerung von betrieblicher Ladeinfrastruktur. In: Hamburger Energieinfrastruktur – Anforderungen, Problemstellungen und Lösungsansätze, pp. 13–17 (2025). https://doi.org/10.24405/17157
8. Barbu, C.M., Bratu, R.Ș., Sîrbu, E.M.: Business models of the sharing economy. RMCI. **19**(2), 154–166 (2018). https://doi.org/10.24818/RMCI.2018.2.154
9. Chávez, C.A.G., et al.: Using digital platforms for value chain sustainability – cases from the Digitala Stambanan project. Procedia CIRP. **120**, 1137–1142 (2023). https://doi.org/10.1016/j.procir.2023.09.138
10. Melander, L., Wallström, H.: The benefits of green horizontal networks: lessons learned from sharing charging infrastructure for electric freight vehicles. Bus Strat Env. **32**(4), 1835–1846 (2023). https://doi.org/10.1002/bse.3222
11. Pfeiffer, Z., Al Sabouni, A., Appel, A., Hertel, J., Weber, A., Vladova, G.: Factsheet FAMOUS. IKEM (2024) https://www.ikem.de/famous-factsheet/
12. Hysolutions: https://www.hysolutions.de/projekte/innovationen-fuer-ladestations-sharing/. Accessed 19 Mar 2025
13. Chatterjee, S., Chaudhuri, R., Vrontis, D., Mahto, R.: Bright and dark sides of adopting a platform-based sharing economy business model. R&D Manag. **54**(5), 1145–1165 (2024). https://doi.org/10.1111/radm.12650
14. Hijazi, A.A., Kang, M., Moehler, R.C., Maxwell, D.: A roadmap to a shared vision for platforms: the motivations and roles of stakeholders in the transformation from projects to platforms. In: Proceedings of the Creative Construction Conference 2023, pp. 185–193. Budapest University of Technology and Economics, Keszthely (2023). https://doi.org/10.3311/CCC2023-025
15. Marth, S., Hartl, B., Penz, E.: Sharing on platforms: reducing perceived risk for peer-to-peer platform consumers through trust-building and regulation. J. Consum. Behav. **21**(6), 1255–1267 (2022). https://doi.org/10.1002/cb.2075
16. Schawe, N.: It's all about data: time for a data access regime for the sharing economy? IP. **25**(2), 177–195 (2020). https://doi.org/10.3233/IP-190206

17. Yan, K., Shen, W., Jin, Q., Lu, H.: Emerging privacy issues and solutions in cyber-enabled sharing services: from multiple perspectives. IEEE Access. **7**, 26031–26059 (2019). https://doi.org/10.1109/ACCESS.2019.2894344
18. Allee, V.: Value network analysis and value conversion of tangible and intangible assets. J. Intellect. Cap. **9**(1), 5–24 (2008). https://doi.org/10.1108/14691930810845777
19. Hein, A., Weking, J., Schreieck, M., Wiesche, M., Böhm, M., Krcmar, H.: Value co-creation practices in business-to-business platform ecosystems. Electron. Mark. **29**(3), 503–518 (2019). https://doi.org/10.1007/s12525-019-00337-y
20. Osterwalder, A., Pigneur, Y.: Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. Wiley, New York (2013)

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Where and How? Analysis of the Usage Behaviour of Public Charging Stations

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Abstract. Forecasting user behaviour at public charging stations is a relevant factor in planning a network of charging stations. A common variable in analysing the user behaviour is the number of points of interest around a charging station. The assignment of urban areas into neighbourhood archetypes could simplify this process. To examine this hypothesis, we used four self-defined neighbourhood archetypes. Based on a data set containing charging information for all public charging stations operated by Stadtwerke Stuttgart GmbH in Stuttgart, Germany, we analysed the users' charging behaviour both regarding neighbourhood archetypes and points of interests. Both of these aspects are able to explain the charging behaviour at charging stations to a certain extent. While the neighbourhood archetype that we call inner city neighbourhood shows a unique profile of points of interests, the remaining neighbourhood archetypes do not. Results indicate, that for inner city neighbourhoods with a large number of point of interests a large number of charging processes as well as short charging durations and low energy outputs are to be expected.

Keywords: Transportation planning · electric mobility · charging stations · mobility behaviour · neighbourhoods

1 Introduction

In the upcoming years local electricity grids will face challenges through the ramp-up of three technologies: Electric mobility, heat pumps and photovoltaics are each used as tools to combat climate change, while parallel influencing the local electricity demand and supply. The ramp-up of these technologies is expected to vary in its speed in different neighbourhoods. For example, in neighbourhoods consisting of one- or two-family-homes, people are more likely to be able to install private charging stations and to operate them with energy from their own photovoltaic systems, than in other neighbourhood types [1].

This study is part of the project SektorSim^3, which focuses on the holistic ramp-up of said technologies in different neighbourhood types and the resulting influence on local electricity grids. In former work, we defined seven so called neighbourhood archetypes (NAT) [2]. This study focuses on the subsidiary aspect of public charging stations (PCS).

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We hypothesize that for different neighbourhood types, different charging behaviour at PCS is to be expected. On the other hand, the expected charging behaviour is a vital criterion for PCS planning [3]. As the selection of NATs was based mostly on spatial and structural criteria, it is so far unclear which differences in charging behaviour exist between NATs. The aim of this explanatory study is to analyse whether the NAT in which a PCS is placed can predict the user behaviour at this PCS. Time-related analyses are beyond the scope of this study and will be presented in a separate paper.

One method used in the planning of PCSs is the analysis of points of interest (POI). It can be assumed that people charge their vehicle while visiting a POI [4] [5]. develop a model to predict spatial charging demand through a POI analysis. Yang et al. analyse the influence of POIs on PCS network planning [6] [7]. analyses data from PCSs and classifies neighbourhoods based on this. While this is an appropriate method to analyse PCS data, it reaches its limits, when using pre-defined neighbourhood types. Based on literature, we hypothesize, that the user behaviour of a PCS is dependent from its surrounding POIs and that each NAT has a unique profile of POIs. If this is true, user behaviour at PCSs could be predicted solely by identifying its NAT. Our research questions are whether the user behaviour at PCSs can be predicted by the NAT and whether this prediction shows differences to a prediction through surrounding POIs.

2 Methodology

2.1 Neighbourhood Types

We understand neighbourhood types as urban areas that consist of comparable structures regarding their built environment. Currently, there is no widely accepted standard for classifying neighbourhood types [8]. define ten types of so called ESTs (Energetische Stadtraumtypen, “energetic city quarter types”). The ESTs stem from an energetic perspective and enable neighbourhoods to be assigned to neighbourhood types by means of their predominant building type [9]. define twelve urban structural types based on the similarity of building typologies. For this project both works cited were used as foundation. To reduce complexity and therefore to minimize the challenges of identifying the neighbourhood types in field, we reduced the number of categories. This led to a total of seven NATs [2]. The scope of this study focuses on the four NATs, that mainly consist of housing:

- One/two-family house neighbourhood (OTF)
- Multi-family house neighbourhood (3–6 residential units) (MFH)
- Inner city neighbourhoods (ICN)
- Large multi-family house neighbourhoods (> 6 residential units) (LMF)

2.2 Data Basis

The data basis for this study was provided by Stadtwerke Stuttgart GmbH (SWS), the public utilities company in Stuttgart, Germany. The data set contains data from all public PCSs operated by SWS. All PCSs examined are located within the city of Stuttgart. All PCSs offer two charging connections, with a power output of 22 kW each. The PCSs

are located in public road space and are designed for either parallel or perpendicular parking. The data set contains data on every charging process (CP) that took place at one of the PCSs between 8 October 2023 and 8 October 2024. The following data is available for each charging process:

- CP identification number
- Location name of the PCS
- Information about the charging point used
- Start time of the charging process
- End time of the charging process
- Amount of energy output [kWh]

Within the SektorSim[3] project, all PCSs were assigned a NAT manually, by viewing their surroundings on Google Street View.

2.3 Analysis of NATs

To analyse whether there are differences in charging behaviour between NATs, we analysed the data set provided, beginning with a descriptive analysis, displaying main values for the amount of charging processes, the charging duration and the energy output per NAT. Further, we conducted two ANOVAs to compare the effect of NAT (independent variable) on charging duration and energy output (dependent variables) respectively. For the ANOVAs, a Bonferroni correction was applied to adjust the error level. The original alpha was set to 0.05.

2.4 POI Analysis

The second analysis was performed to evaluate the influence of POIs. For each PCS the number of POIs within a 300 m radius around the PCS was determined. The radius was selected to correspond with the catchment area of urban bus stops in Germany [10]. The POIs were taken from OpenStreetMap, through use of the Overleaf API. For this, we developed a python-based script, which collects all POIs within the given radius around the PCSs. The script can be found in the digital appendix.

The POIs were grouped into three categories, depending on the expected length of stay. The categories were POIs with an expected length of stay <1 h (e.g. Retail, Take-away, Hairdressers), 1 to 2.5 h (e.g. Restaurants, Churches, recreation) and > 2.5 h (e.g. Hotels, museums, park & ride). The categories were selected based on discussions with urban planning experts at the Stuttgart University of Applied Sciences. A list of all types of POIs can be found in the digital appendix. To examine the influence of POIs on charging behaviour, several linear regressions were performed. First, a simple linear regression with the total number of POIs as independent and the number of CPs per PCS as dependent variable was performed. Second, three multiple linear regressions were performed with the categories of POIs as independent variables. The dependent variables were the number of CPs, the mean energy output per PCS and the mean charging duration per PCS respectively. A MANOVA was performed to analyse whether there is a significant association between NAT and POIs. For all tests we chose an $\alpha = 0.05$.

3 Results

3.1 NATs

The data set contributed by SWS contains data on 244 public PCSs within the municipality of Stuttgart, Germany. 39 PCS were removed from the data set, as their operation started later than October 2023. From the remaining PCSs, 35 PCSs were located in OTF, 108 in MFH, 28 in ICN, 10 in LMF and 24 in other neighbourhood archetypes. The latter were not taken in to the analysis. A total of 181 PCS were analysed. The descriptive analysis is displayed in Table 1.

Table 1. Descriptive analysis of PCS and CP

Category	OTF	MFH	ICN	LMF
n	35	108	28	10
Charging processes				
$\sum$ CP	24,809	80,748	40,745	7,478
Ø CP/PCS	708.8	747.7	1,455.2	747.8
Ø CP/PCS & day	1.94	2.04	4.0	2.04
Charging duration [h]				
Ø Charging duration/PCS	2,376.1	2,462.5	4,388.3	2,178.6
Ø Charging duration/CP	3.35	3,29	3.02	2.91
Energy output				
$\sum$ Energy output [MWh]	494.3	1,411.5	628.1	124.8
Ø Energy output/CP [kWh]	19.9	17.5	15.4	16.7

For the performed ANOVAs we included a Bonferroni correction to account for multiple comparisons. With an original alpha of 0.05 and two tests, the adjusted alpha was 0.025. A one-way ANOVA was performed to compare the effect of NAT on charging duration. The ANOVA revealed that there was a statistically significant difference in charging duration between at least two groups ($F(3, 153{,}776) = 90.6$, $p < .001$). Tukey's HSD Test for multiple comparisons found that the mean value of charging duration was significantly different between OTF and ICN ($p < .001$), OTF and LMF ($p < .001$), MFH and ICN ($p < .001$) as well as MFH and LMF ($p < .001$). No significant differences were found between OTF and MFH ($p = 0.092$) as well as ICN and LMF ($p = 0.088$). The effect size was $\eta^2 = 0.002$, which is considered a small effect.

A one-way ANOVA was also performed to compare the effect of NAT on energy output. The ANOVA revealed that there was a statistically significant difference in charging duration between at least two groups ($F(3, 153{,}776) = 461$, $p < .001$). Tukey's HSD Test for multiple comparisons found that the mean value of charging duration was significantly different between all NATs ($p < .001$). The effect size was $\eta^2 = 0.009$, which is considered a small effect.

3.2 Surroundings

For the following analysis further six PCSs had to be removed from the data set, as there were issues during the POI analysis. 175 PCS remained. Simple linear regression was used to test whether the total number of POIs significantly predicted the number of CPs per PCS. The fitted regression model was Number of CPs = 543.66 + 5.72 x Number of POIs. The overall regression was statistically significant (R2 = .319, Adjusted R^2 = .315, F(1, 173) = 81.19, p < 0.001). The POIs were then broken down into three categories. The overall multiple linear regression with these categories as predictor values was statistically significant (R^2 = .339, Adjusted R^2 = .328, F(3, 171) = 29.23, p < .001). The number of POIs (< 1 h) and POIs (1–2.5 h) significantly predicted the number of CPs per PCS, while Number of POIs (> 2.5 h) did not (see Table 2a).

Table 2. Regression coefficients

(a) Regression cofficients for number of CP				
Predictor	**Estimate**	**Std. error**	**t**	**p**
Intercept	501.549	54.54	9.196	< 0.01
POIs (< 1 h)	4.714	1.92	2.451	.015
POIs (1–2.5 h)	12.950	3.56	3.634	< 0.01
POIs (> 2.5 h)	0.649	3.42	0.190	.85
(b) Regression coefficients for mean energy output				
Predictor	**Estimate**	**Std. error**	**t**	**p**
Intercept	19.6316	0.4701	41.761	< 0.01
POIs (< 1 h)	−0.0396	0.0166	−2.388	.02
POIs (1–2.5 h)	−0.0182	0.0307	−0.594	.55
POIs (> 2.5 h)	−0.0354	0.0295	−1.200	.23
(c) Regression coefficients for mean charging duration				
Predictor	**Estimate**	**Std. error**	**t**	**p**
Intercept	209.0540	6.201	33.714	< 0.01
POIs (< 1 h)	−0.5395	0.219	−2.467	.02
POIs (1–2.5 h)	0.0436	0.405	0.108	.91
POIs (> 2.5 h)	−0.0001	0.389	0.000	.99

A multiple linear regression was used to test whether the values for each category of POIs significantly predicted the mean energy output per CP. The overall regression model was statistically significant (R^2 = .184, Adjusted R^2 = .170, F(3, 171) = 12.85, p < .001). The number of POIs (< 1 h) significantly predicted the mean energy output per PCS, while the number of POIs (1–2.5 h) and POIs (> 2.5 h) did not. The results are shown in Table 2b. A multiple linear regression was used to test whether the values for each category of POIs significantly predicted the mean charging duration per CP. The

overall regression model was statistically significant ($R^2 = .088$, Adjusted $R^2 = .072$, $F(3, 171) = 5.47$, $p < .001$). The number of POIs (< 1 h) significantly predicted the mean energy output per PCS, while the number of POIs (1–2.5 h) and POIs (> 2.5 h) did not. The results are shown in Table 2c. A MANOVA showed that there is significant association between NAT and different categories of POIs ($F(3, 171) = 11.0$, $p < .001$, Wilk's $\Lambda = .591$). The effect size was $\eta^2_p = .16$, indicating a large effect. Post-hoc-Tests (Tukey HSD) showed for all categories of POIs that significant differences occurred only between ICN and the other NATs ($p < .001$ each, except POI 1–2.5 h, ICN/LMF, $p = .002$). Figure 1 shows the mean number of POIs per NAT.

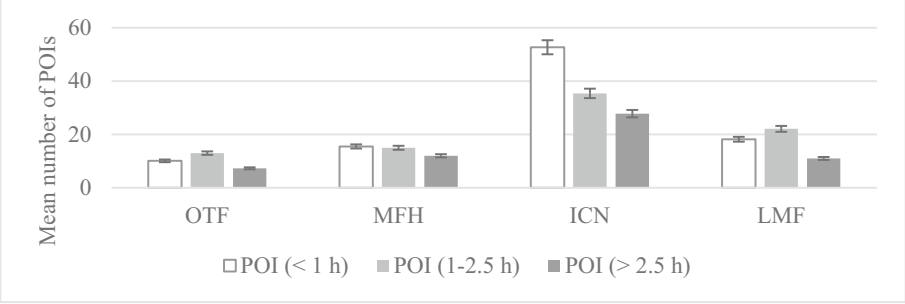


Fig. 1. Mean number of POIs per NAT. Error bars indicate 95% confidence intervals.

4 Discussion

Descriptively, the mean number of CPs per PCS seems to be consistent between most NATs. The exception is ICN, with a value that is almost twice as high. The same result is apparent for the mean number of CPs per PCS and day. ICN shows a mean of 4.0 CP per PCS and day, which is around twice as the values for the other NATs. The conducted ANOVAs showed, that for charging duration NATs could be classified into two groups. With OTF and MFH on one side and ICN and LMF on the other side, the latter group showed significantly shorter charging durations. For energy output, significant differences could be shown between all NATs. Thus, the classification of urban areas into NATs can be a predictor for the expected user behaviour at PCSs. However, as the effect sizes were small, we assume that the differences have almost no practical effect.

Statistical analysis of the raw data showed, that user behaviour at PCSs can also be predicted by the surrounding POIs. The more POIs surround a PCS, the more CPs can be expected. A deeper analysis showed that this prediction can be based upon the number of POIs with expected length of stays below 2.5 h. To a lesser extent the mean energy output per CP can be predicted by the number of surrounding POIs with expected length of stays below 1 h. The same to an even lesser extent, is true for the mean charging duration of CPs. The results indicate, that user behaviour at PCSs might be mostly shaped through surrounding POIs with short expected lengths of stay. We can interpret this, as POIs with short expected lengths of stay result in a high turnover ratio. While the number of CPs

increases, the mean duration and energy output decrease. While a MANOVA showed a significant association between NAT and the three categories of POIs, post-hoc tests could only confirm this for differences between ICN and the other NATs. ICN is the NAT with the highest amount of POIs, while the remaining three NATs share a similar, lower number of POIs. This explains some of the results from the NAT analysis in chapter 3.1. Still, the performed ANOVAs showed some results that can't be explained by the number of POIs. For example, LMF neighbourhoods show different charging durations than OFT and MFH neighbourhoods, even though their average number of POIs does not differ. We can conclude, that a classification of CSs into NATs can help to gain insights on users' charging behaviour.

5 Conclusion

In this study, we conducted two analyses with a data set containing information on CP of PCS in Stuttgart, Germany. We could show that the NAT in which a PCS is located as well as its surrounding POIs influence its users' charging behaviour. We also showed, that the number of POIs depends on the NAT. Still, both analyses did not have exactly the same results. The given NAT explains parts of the user behaviour, that the number of POIs can't explain. While the effect size for NAT is small, this analysis shows a potential to use NATs as a simple forecasting method for PCS' user behaviour. Still, in the current state more variables than NAT need to be considered for forecasting user behaviour. Future research should focus on a more granular definition of NATs, to strengthen the results of this method and to allow its use in CS planning.

Limitations of this study result from an automated POI analysis, based on open data. A deeper, manual collection of POIs could show different results and allow better analyses. The data is limited to the city of Stuttgart, which might limit results. The assignment of PCS to NATs was performed manually and should be interpreted cautiously. Different types of vehicles and their technological differences could not be integrated in the study. The descriptive analysis of user behaviour is based on few variables, ignoring temporal and seasonal influences. The latter will be part of the authors future work. Finally, the analysis evaluates an existing PCS network. Possible effects and interdependences appearing through the addition of newly built PCSs are not part of the analysis. Future work could introduce station-level or multilevel models and additional control variables to deepen the analysis.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process ChatGPT was used to program the Python script for the data analysis. Nevertheless, spot checks were carried out manually in to validate the correctness of the results.

Data Availability. Due to restrictions from Stadtwerke Stuttgart GmbH, the raw data used in this study is not publicly available. Supplementary data is provided at: https://transfer.hft-stuttgart.de/katalog/dataset/tra2026

References

1. Damianakis, N., Mouli, G., Bauer, P., Yu, Y.: Assessing the grid impact of electric vehicles, heat pumps & PV generation in Dutch LV distribution grids. Appl. Energy. **352** (2023). https://doi.org/10.1016/j.apenergy.2023.121878
2. Otto, R. et al.: Projections for the deployment of heat pumps, photovoltaics, and electric vehicles in German urban Neighborhoods by 2045. Energy Rep. **15** (2026). https://doi.org/10.1016/j.egyr.2026.109118
3. Patil, P., Kazemzadeh, K., Bansal, P.: Integration of charging behavior into infrastructure planning and management of electric vehicles: a systematic review and framework. Sustain. Cities Soc. **88** (2023). https://doi.org/10.1016/j.scs.2022.104265
4. Hummler, P., Naumzik, C., Feuerriegel, S.: Web mining to inform locations of charging stations for electric vehicles. In: Laforest, L., Troncy, R., Médini, L., Herman, I. (eds.) Companion Proceedings of the Web Conference 2022 (WWW '22). Association for Computing Machinery, 166–170. NY, USA, New York (2022). https://doi.org/10.1145/3487553.3524264
5. Zhou, H., Liu, F., Chen, H., Ni, Y., Yang, S., Xu, W.: Predicting electric vehicle charging demand in residential areas using POI data and decision-making model. IEEJ Trans. Elec. Electron. Eng. **20**, 504–513 (2025). https://doi.org/10.1002/tee.24220
6. Yang, H., Liu, M., Zou, J., Xu, R., Huang, J., Geng, P.: Intelligent layout and optimization of EV charging stations: initial configuration via enhanced K-means and subsequent refinement through integrated GCN. Radioengineering. **34**, 79–91 (2025). https://doi.org/10.13164/re.2025.0079
7. Kwon, K.: Investigating the characteristics of public electric vehicle charging station: a case study of California. Transp. Policy. **166**, 101–107 (2025). https://doi.org/10.1016/j.tranpol.2025.03.004
8. Dettmar, J., Drebes, C., Sieber, S.: Energetische Stadtraumtypen. Strukturelle und energetische Kennwerte von Stadträumen. Fraunhofer IRB Verlag, Stuttgart (2020)
9. Beermann, B., Berchtold, M., Baumüller, J., Gross, G., Kratz, M.: Städtebaulicher rahmenplan klimaanpassung für die stadt karlsruhe (Teil 1) ["Urban development framework plan for climate adaptation in the city of karlsruhe (Part 1)"] (2013).https://doi.org/10.13140/RG.2.1.3492.0162
10. Verband Deutscher Verkehrsunternehmen e. V. (VDV): Linienbedarfsverkehr: zukunftsgerecht, integriert und nachfragegesteuert. Positionspapier. https://www.vdv.de/positionspapier-linienbedarfsverkehr-maerz23.pdfx (2023)

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ZeroFlex - A New Innovative Approach for Mobility Stations in Austria

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Abstract. The goal of the ZeroFlex project (https://zeroflex.at/), funded by the Austrian Initiative for Emission-Free Mobility, is the systematization and economic viability of mobility hubs – both at the level of individual stations and as a system innovation with an integrated overall offering for all stations. ZeroFlex aims to make each station economically viable, which is essential for the widespread adoption of mobility hubs – only then will they become attractive to customers such as municipalities, businesses, the tourism sector, etc. The ZeroFlex project comprises (1) the overall concept of modular, highly flexible, high-quality, and cost-effective mobility hubs that primarily offer electrically powered, single-track vehicles. Energy efficiency through photovoltaics and energy storage is a central component of the solution, as are (2) the technical and organizational development of the stations, (3) a large-scale field test under real conditions (city of Klagenfurt, Austria) including monitoring and evaluation, (4) the modelling of an optimized system as the sum of all ZeroFlex stations with regard to spatial structure and aspects of mobility behavior, (5) the development of a highly flexible business model and (6) the modelling of the climate impact or the realistically possible contribution to climate neutrality.

Keywords: mobility stations · e-bike sharing · field test · business models · project evaluation

1 Introduction

Mobility hubs link various mobility options in one location, thus enabling sustainable and diverse mobility provision without private cars [1, 9]. Numerous approaches to the design of mobility hubs exist, particularly at the international level [2, 4, 6, 8]. However, almost all share the common feature that the realization of a high-quality mobility hub is currently very costly and inflexible [5, 13]. The decision by, for example, a municipality or transport company to establish or operate a mobility hub must therefore be carefully considered, as it requires the selection of a specific, primarily structural design that is then fixed or virtually unchangeable for many years [7, 11]. This problem is exacerbated by the current need to involve several different manufacturers for each site-specific solution, leading to additional costs and often inadequate integration of the various components [3, 10]. The ZeroFlex project aims to systematize and cost-effectively design mobility

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hubs – both at the level of individual hubs and as a system innovation with an integrated overall offering for all hubs [12]. The modular design of the ZeroFlex stations, including a cooperative system among all operators, allows for optimal adaptation to the respective regional needs and potential, thus significantly improving access to the multimodal transport system. Furthermore, ZeroFlex aims to make each hub economically viable, as this is essential for the rapid expansion of mobility hubs – only then will it be worthwhile for customers such as municipalities, companies, and tourism organizations to invest on a large scale. ZeroFlex represents an innovative technological development with the potential for rapid implementation and high added value for Austria, as all key components (including the vehicles) are produced in Austria and sourced from a single provider. Implementing the ZeroFlex system involves the detailed preparation and design of the elements required for the service: the vehicle itself, the docking stations, and the booking app for rentals via smartphone or at the docking stations. Additionally, the interfaces between all these elements must be defined. A prototype with all relevant functions is developed for each station to test and evaluate the solutions. The design already considers scalability, enabling the expansion of a standardized system to an entire city/region (with the option to return the vehicle to a different ZeroFlex station) or the creation of customized solutions for individual operators/providers of the ZeroFlex system (e.g., hotel owners for their guests) with a high degree of individualization (e.g., branding), operating as standalone solutions (vehicles are always returned to the same location). The design of the elements was developed taking into account the needs identified in interviews with experts, potential operators/hosts, system partners, and potential end users. Gender aspects and framework conditions for different user types were discussed through the definition of personas and the simulation of their needs in workshops.

2 Project Implementation

First, suitable materials were tested. These tests were conducted using CAD design and static calculations on the computer to ultimately obtain two to three functional versions of the individual modules. Crucial to this process was the precise selection of materials with regard to material type, thickness, weight of the individual components (for easy transport and assembly), stability in relation to legal requirements such as wind pressure, snow load, etc., and of course, the potential price of the hardware. The following components were developed: a charging station with a charging system, suitable for all vehicle types and largely vandal-proof; a roof structure suitable for photovoltaics as an “Easy-Fix System” (easy transport and assembly); the individual modules as a plug-and-play variant (flexible configuration); ground anchoring systems for various surfaces; an energy unit as an additional module for each configuration, easy to install; as well as the corresponding assembly instructions and transport boxes for the individual modules. The methodology employed included advanced CAD design, 3D printing, and testing the selected solutions for their usability. The direct involvement of developers and manufacturers as project partners minimized the technical risks. Particular attention was paid to ensuring that the suppliers were from the EU, so that it is a European product.

Prototypes of the vehicles for this project already existed before the project began, but they were not designed for stationary public rental. The existing platform saves

resources in development costs and reduces the necessary development effort to areas such as charging stations on the vehicle, sensor technology, software adjustments, as well as testing and certification. In principle, four vehicle variants were developed: the e-cargo bike according to the Austrian definition (riding without pedalling), an e-moped (L1e), and a small motorcycle variant (L3e). This covers speed ranges from 25 km/h (bike path) to almost 100 km/h (urban motorway). As a possible fourth variant, a vehicle with a roof and windshield including wipers (and optionally with doors) can be used as a three-wheeled model (L5e) and serves as a full-fledged car replacement, especially in bad weather. In the area of sensor technology, the project focuses on weight sensors to prevent overloading, etc. The vehicle can be used by multiple people simultaneously and features GPS tracking including accident detection and an emergency call function, tire pressure and temperature sensors with data transmission to the maintenance system to minimize downtime due to repairs, Bluetooth and CAN bus (L3e) for vehicle certification for the coming years, and a sound module for audible warning signals at low speeds (a safety measure already mandatory for electric cars, so it's only a matter of time before two-wheelers follow suit). After extensive testing, the vehicles will be certified accordingly and can be used throughout Europe. Software for operators and an app for end users were developed. The necessary steps to ensure optimal interaction between the software and the app were examined. The goal is compliance with interface standards that enable the integration of all ZeroFlex system components into Mobility-as-a-Service (MaaS) ecosystems. ZeroFlex hardware and software are designed as an open system, thus enabling bidirectional integration (third-party integration into ZeroFlex, integration into existing national mobility services such as WienMobil, Tim, Whim, etc., as well as white-label services such as VAO, EVIS AT, etc.). International interface standards and the European framework (European Delegated Regulations 2015/962 and 2017/1926) were also taken into account. Another aspect of the ZeroFlex stations is the financing model. Customers can either purchase or lease the system. In both cases, maintenance will be handled by a certified partner after the research project is completed. This means that the operator of the ZeroFlex stations (e.g., a hotel resort, a business park, a municipality) simply provides the space and the power supply and doesn't have to worry about anything else; the rental system runs smoothly. The pricing model for end users can be agreed upon with the operator (in the case of standalone ZeroFlex station setups). This can include free use for guests, employees, etc. (e.g., with a token) or various pricing models, from single tickets to time- and distance-based billing to flat rates over a defined period. All developed components and modules will be combined to form a ZeroFlex station and will undergo comprehensive field testing under real-world conditions in Klagenfurt starting in July 2025, over a period of approximately 12 months. Klagenfurt takes into account the usage requirements of an urban environment with approximately 100,000 inhabitants and tourist activity. Klagenfurt is the only Austrian city participating in the EU's City Mission, which aims for climate neutrality by 2030. Thanks to the city administration's clear commitment, close collaboration is ensured. For the monitoring and evaluation (M&E) of the ZeroFlex stations' impacts, field-test-specific M&E frameworks are being developed in cooperation with the test partners. These frameworks include indicators for outputs (implementation results), outcomes (e.g., acceptance, customer and provider satisfaction), and impacts (e.g., energy consumption) of the stations. Data for these

indicators are collected during and after the implementation phase. To ensure a smooth monitoring and evaluation process, regular feedback is provided to the test partners regarding the availability and practicality of the evaluation framework. Therefore, the development of the M&E framework and its application go hand in hand. A feedback questionnaire is integrated into the car rental app. Trip distances and timestamps are recorded during use and linked to the questionnaire. Finally, the data are analyzed, particularly with regard to their extrapolation potential. Furthermore, the implementation process is evaluated through a qualitative group modelling process to identify factors for a potentially successful future implementation and a successful business model.

3 Location of the Pilot ZeroFlex-Station

The ZeroFlex station in Klagenfurt is located directly at the entrance/exit of Klagenfurt West train station, west of the city centre of Klagenfurt, the capital of Carinthia. Within the overall urban context, the ZeroFlex location can be classified as a suburban or peripheral area. The station is served by S-Bahn (suburban train) and regional trains connecting Klagenfurt with the entire Carinthia region. For long-distance trains, a transfer at Klagenfurt Central Station is required. The city centre is accessible from the station via S-Bahn and regional buses. Furthermore, city bus lines connect the station directly to other important points in the city, such as the main train station, Heiligengeistplatz (central city bus station), and several northern and western outskirts. Thus, the ZeroFlex station is directly integrated into the public transport network and meets the criteria of a multimodal hub. Local attractions (such as the miniature world exhibition "Minimundus" and the reptile zoo) are a three-minute bike ride from the ZeroFlex station. Lake Wörthersee, a popular recreational area, is about five minutes away, the Europapark shopping centre six minutes, and the Wörthersee-Klagenfurt campsite seven minutes. Klagenfurt city centre is approximately twelve minutes away by bike. The ZeroFlex station is therefore also ideal as a park-and-bike location for tourists who want convenient access to their leisure activities. The ZeroFlex station is surrounded by residential buildings. The new "SEENAHWOHNEN III" residential building is within walking distance and borders a residential area to the south and east of the station. Parking spaces, electric vehicle charging stations, and shopping facilities are located nearby. A parcel locker is situated directly next to the ZeroFlex station. This makes the ZeroFlex station accessible to various user groups – commuters traveling to and from the station, residents of the adjacent neighbourhoods, and recreational users of the nearby leisure facilities. Figue 1 shows the location of the ZeroFlex station, and Fig. 2 shows a photograph. The pilot station opened in July 2025 and has been operational for a year. During this time, the feasibility of the hardware and software, as well as the user-friendliness and comfort of the ZeroFlex station, are being tested.

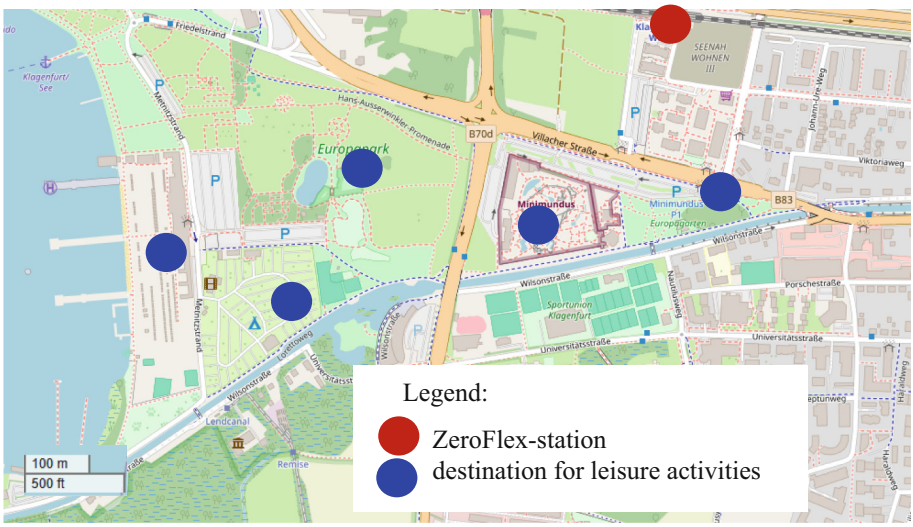


Fig. 1. The ZeroFlex-station in the city of Klagenfurt (based on openstreetmap)



Fig. 2. The ZeroFlex-station at the pilot location for testing

4 Components of the ZeroFlex Pilot Station

The **charging station** is protected from rain and sun and equipped with an information screen. All modules are designed as a plug-and-play solution for flexible setup. Installation instructions and a transport box for the modules are included. The roof is equipped with a solar panel for power supply. This photovoltaic-compatible roof structure is designed as an "easy-fix system" and is therefore easy to transport and install. An external power supply is also installed to support vehicle charging and screen operation. The **station** has an integrated buffer storage system that temporarily stores solar energy. This storage system allows for various storage capacity configurations and is easy to

install or modify. The charging station is equipped with sensors that initiate the charging process, ensure locking, and provide information about vehicle availability and status. The information screen (27-in. touchscreen) is integrated into the station and is used for booking and returning vehicles (as alternative to using the smartphone app). The station is designed for complete assembly by two people who secure the components to the ground and connect them to the power supply. The ground anchors are suitable for various surfaces. The entire ZeroFlex station can be quickly disassembled and reassembled at a different location. This allows for flexible use of the components as needed and cost-effective hardware deployment. The station accommodates five vehicles. Thanks to a standardized docking station, all common vehicle types can be used. The docking stations are vandal-proof. Only one vehicle type is used in the pilot project. The vehicles can be pushed into the docking station without lifting. The spacing between the vehicles in the row allows for convenient maneuvering when parking and returning them. **Bicycles** with a maximum speed of 25 km/h and pedals are used for the pilot station. The bicycles have either electric drive, pedal assist, or a combination of both (see Fig. 3). They are equipped with two baskets (one at the front and one at the rear) for carrying items. A display on the handlebars provides information about the bicycle (e.g., speed, remaining battery power). The rider can adjust the level of battery assistance via this display. All components of the vehicle are vandal-proof, so no major damage will occur if it falls over. The bicycle is equipped with a sturdy stand to securely park it outside the ZeroFlex station while customers are using it.



Fig. 3. The ZeroFlex-bike Rock-E

The **app and web software** were developed as the third pillar of the system. The app was made available for download and installation in the app stores. The user interface (available as either a web or mobile version) manages all rentals and pricing for customers. Payment can be made by credit card. Various pricing models were implemented: discounted trial rates with tokens, a ride fare, and a second, lower price for parking the vehicle at the ZeroFlex station. A backend interface was developed to enable system maintenance by the operator. In the future, this maintenance can be carried out either

by the ZeroFlex station operators themselves or by certified ZeroFlex system partners under a service agreement.

5 Demand Expectations

End-user demand for the stations varies depending on the use case. ZeroFlex stations can be operated in tourist areas for tourists and visitors (e.g., in front of hotels or public transport stops at tourist destinations to serve the last mile). Another use case is everyday mobility, for example, in residential areas in cooperation with property management companies or municipalities for public spaces. All ZeroFlex stations are designed and built as a standardized ZeroFlex system. This approach offers the advantage that the individual modules within the overall system (ZeroFlex stations in cities, municipalities, tourist facilities, businesses, etc.) can change location, thus ensuring optimal service at each location. Local branding is, however, possible. The pilot phase will be accompanied by an online survey to gather feedback on user experiences, attitudes, and use cases. Additionally, kilometres travelled and rental duration will be recorded and incorporated into the survey results. Data collection will continue until summer 2026.

6 Conclusion and Outlook

The commissioning of the first ZeroFlex station in real-world operation marks a significant milestone. The pilot project will run for at least one year, starting in July 2025, to test the hardware and software components and further improve existing solutions. During this time, visitors and residents can rent, test, and use vehicles. The integrated feedback questionnaire covers topics such as user-friendliness, reasons for renting, the clarity of the rental process, vehicle operation, mobility behavior, sociodemographic data, and other suggestions for improvement from the user's perspective. The completed questionnaires will be combined with vehicle data collected during use (e.g., kilometres driven, duration of renting). Furthermore, the ZeroFlex station serves as a showcase project for potential contractors or buyers of the system. Interested parties are invited to test the system, and discussion sessions will be organized with them. Based on these results, a scaling analysis and a projection of the potential market penetration of the ZeroFlex system will be conducted. The potential impacts of the entire mobility systems are being assessed (e.g., regarding space requirements and emissions; compare with [14]. Project development can be followed on the project website https://zeroflex.at/.

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References

1. Bieliński, T., Dopierała, Ł., Tarkowski, M., Ważna, A.: Lessons from implementing a metropolitan electric bike sharing system. Energies. **13**(23), 6240 (2020). https://doi.org/10.3390/en13236240
2. Bieliński, T., Kwapisz, A., Ważna, A.: Electric bike-sharing services mode substitution for driving, public transit, and cycling. Transp. Res. D: Transp. Environ. **96**, 102883 (2021). https://doi.org/10.1016/j.trd.2021.102883
3. Boez J.-M.: Bike-sharing muss ernst gemeint sein (2024). https://background.tagesspiegel.de/verkehr-und-smart-mobility/briefing/bike-sharing-muss-ernst-gemeint-sein. Accessed 9 Dec 2024
4. Chen, Z., Hu, Y., Li, J., Wu, X.: Optimal deployment of electric bicycle sharing stations: model formulation and solution technique. Netw. Spat. Econ. **20**(1), 99–136 (2020). https://doi.org/10.1007/s11067-019-09469-2
5. Genikomsakis, K.N., Galatoulas, N.-F., Ioakimidis, C.S.: Techno-economic assessment of a hotel-based e-bike rental service using stated preference modelling. Energy. **237**, 121586 (2021). https://doi.org/10.1016/j.energy.2021.121586
6. Julio, R., Monzón, A.: Long term assessment of a successful e-bike-sharing system. Key drivers of sustained growth. Case studies on. Transp. Policy. **10**(2), 1299–1313 (2022). https://doi.org/10.1016/j.cstp.2022.04.019
7. Liu, Y., Tian, Z., Pan, B., Zhang, W., Liu, Y., Tian, L.: A hybrid big-data-based and tolerance-based method to estimate environmental benefits of electric bike sharing. Appl. Energy. **315**, 119155 (2022). https://doi.org/10.1016/j.apenergy.2022.119155
8. Munkácsy, A., Monzón, A.: Impacts of smart configuration in Pedelec-sharing: evidence from a panel survey in Madrid. J. Adv. Transp. **2017**, 4720627 (2017). https://doi.org/10.1155/2017/4720627
9. Pan, L., Xia, Y., Xing, L., Song, Z., Xu, Y.: Exploring use acceptance of electric bicycle-sharing systems—refined similarity measures based on sensor data. Sensors. **22**(18), 7057 (2022). https://doi.org/10.3390/s22187057
10. Phillips S., Venkatesh C.: White paper neighbourhood mobility station (2023). https://movmi.net/materials/neighbourhood-mobility-station/. Accessed 6 Aug 2025
11. Song, J., Li, B., Szeto, W.Y., Zhan, X.: A station location design problem in a bike-sharing system with both conventional and electric shared bikes considering bike users' roaming delay costs. Transp. Res. E: Logist. Transp. Rev. **181**, 103016 (2024). https://doi.org/10.1016/j.tre.2023.103016
12. ZeroFlex-consortium: ZeroFlex - Flexible Mobility Point as a Module for Climate Neutrality, Factsheet Projekt ZeroFlex, Gefördert durch die Österreichische Forschungsförderungsgesellschaft - FFG (2023)
13. ZeroFlex-consortium: ZeroFlex report, wirtschaftliche und rechtliche rahmenbedingungen, kooperations und finanzierungssystem, projekt zeroflex, gefördert durch die österreichische forschungsförderungsgesellschaft – FFG (2024)
14. Zhou, H., Li, Z., Liu, L., Kurisu, K., Han, H., Zhang, Y., et al.: Do shared E-bikes reduce urban carbon emissions? Transp. Res. D: Transp. Environ. **118**, 103810 (2023). https://doi.org/10.1016/j.trd.2023.103810

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High-Efficiency Hybrid Powertrain Systems for Challenging Commercial Vehicle Applications to Meet Upcoming Market Expectations

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Abstract. The continuous minimization of GHG emissions and the successful reduction of pollutants from vehicle exhaust represent the key development tasks for the automotive industry. In this context, it is crucial to comprehensively meet the real-world requirements of the end-users. Continuously strengthened norms w/ extended boundaries of emission regulations regarding emissions and corporate CAFE regulations drive the development of new propulsion system layouts. Since the move towards electrification faces some challenges from the end customer view, existing policies are putting pressure on manufacturers, as non-compliance could result in massive penalties. In addition, environmental zones are established for urban areas, which represent a hurdle for many companies. For engineering technical solutions for the above-mentioned critical situation, propulsion system with highest FE and near-zero emission behavior needs to be developed, which can maintain the versatility of today's drive systems. This study delves into various strategies for hybridized powertrains in CV applications, offering a comprehensive comparative analysis of different hybrid concepts. The analysis focuses on two cornerstone cases: LCV and HD LH truck. It evaluates the CO_2 reduction potential and a comparison in financial figures across application-specific mission profiles.

Keywords: GHG reduction · Highly Efficient Engine; Hybrid Powertrain · Electrification · Low Carbon Footprint

1 Introduction and Background

1.1 Background

The global initiatives regarding sustainability and carbon neutrality from the overall vehicle segment and the associated change in the primary propulsion systems accomplish automatically in a vital modification of the vehicle layouts, affecting the vehicle body structure for all kinds of applications. In this context, the acronym "Hybrid BEV" is hereby especially considered for a layout, which is based on the electric traction as prime mover, but incorporates an ICE as well, as clear contrast to the classical hybrid layouts, where the electrical support system is added to an ICE in the existing vehicle configuration.

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Considering the current market situation and the coupled mid-term market development prognosis, the demands for the next generation of propulsion systems for light commercial vehicles (LCVs, <3.5 to) can be described as follows:

- Diesel-like versatility in a broad spectrum of applications
- Local emission-free operation
- Electric driving range of ~200+ km to ensure unlimited access to city centers, anticipating major access rules for ZEVs, probably demanding significant electric driving
- Significant Fuel Economy (FE) improvements and CO_2 reductions
- Full compliance with EU-7 emission legislation under all driving conditions
- Attractive total cost of ownership (TCO) to ensure market acceptance
- Compatibility with all fuels specified under DIN EN 590, incl. (HVO)

For HD LH applications, the market demand can be considered to be very comparable, definitely with less impact on inner-city requirements, but with much higher focus on TCO/TCU.

2 Conceptual Approach

The leading objective for the new powertrain definition, mainly for commercial applications, is to continue the given level of highest versatility of the currently dominating Diesel powertrains, which meet the wide range of different installations in the commercial market today very well.

To cover the extremely broad spectrum of multi-facial system configurations and topologies within this study, the following corner-point layouts are analyzed in more detail for both selected vehicle applications, the LCV type and the HD LH truck case.

1. A serial-hybrid layout with a small, moderately efficient gasoline engine; providing in general acceptable efficiency for battery charging with a highly cost-attractive approach. Weaknesses and shortages are mainly identified regarding engine lifetime and durability and different fuel types, as this concept forces big fleet owners with own fuel stations at the depot to invest in additional fueling infrastructure. Furthermore, an efficient, direct drive, e.g. for longer motorway operation – w/or w/out trailer - under steady-state conditions, is also not foreseen.
2. A parallel-hybrid powertrain set-up, featuring an advanced, class-leading LD Diesel engine with highest efficiency and quite powerful electric drive system. This compound bears the burden of high costs, incl. aftertreatment system, but offers the potential to combine the known Diesel-like versatility incl. highly efficient long-distance driving with local emission-free operation, and limiting the depot stored fuel to one type, incl. the usage of HVO.

The system allows the vehicle in general to operate primarily as a pure electric vehicle, with the ICE serving as a backup to provide additional range, when needed, eventually also more power, depending on the operation mode. In such a propulsion topology, the features and specifications of the electric traction system in the vehicle architecture are leading and superior. The add-on ICE can be integrated into a purely hybrid range extender as well as into a serial-parallel add-on architecture. [1][2]

Since purchase and tax incentives are highly dependent on local regulations [6], they have not been considered in this study. Additionally, despite significant consumer concerns about electric vehicles, depreciation and residual value were not considered because they are difficult to quantify. For a comprehensive assessment of TCO, various customer profiles have been considered, detailed and described as follows for the LCV sector:

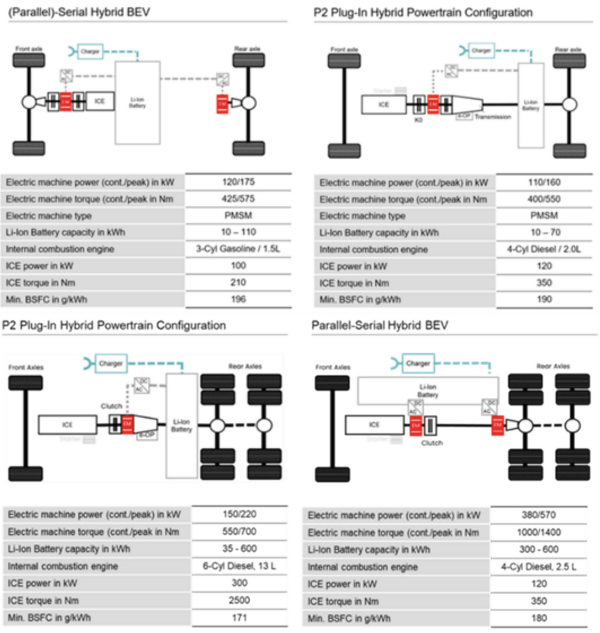
- "Parcel delivery" with a driving distance of 100–300 km between two consecutive "comfortable" charging stops (referenced as Scenario #1 in the LCV chapter)
- "Craftsmen" profile with a comparably large operating radius of 200–800 km driving distance
  (referenced as Scenario #2 in the LCV chapter)
- "Express logistics" drive pattern with a driving distance of 300–1200 km between two "comfortable" charging stops. (referenced as Scenario #3 in the LCV chapter)

Like the selected use case clustered for the LCVs, also distinct customer categories were created for heavy-duty long-haul trucks. Here, according to the more condensed usage, only two specific customer groups were established:

- Long haul truck with a "comfortable" intermediate charging stops during the day (referenced as Scenario #1 in the HD LH chapter)
- Long-haul truck with only overnight charging (once per day)
  (referenced as Scenario #2 in the HD LH chapter)

One representative example in this direction for heavy-duty applications is already today given by the Scania EREV prototype vehicle in trial operation, that is currently being tested by DHL group for main carriage transport between the cities of Berlin and Hamburg [5]. The truck symbolizes a series hybrid configuration with an electric motor of 230 kW / 295 kW (peak), linked to a battery with a net capacity of 416 kWh. The engine in this example is represented by a 120 kW gasoline engine, planned to be mirrored in a 2nd vehicle, but featuring then a light-duty Diesel engine as power plant.

In all layouts, the ICE runs – as consequence of the operational strategy - mostly in the sweet spot area, enhancing fuel economy and simultaneously lowering tailpipe pollutant emissions. In addition, on demand, some extra operating modes can be applied, e.g. a rapid emission control conditioning mode or a power boost mode. The generic "Hybrid BEV" platform offers the advantage to fund both - pure electric and hybrid - variants, allowing car makers to produce highly flexible with cost-effective and adaptable solution for various market and requirements. Utilizing this platform, manufacturers can reduce development and production costs while the approach streamlines the manufacturing process and allows for economies of scale, making it a financially viable option for producing a diverse range of vehicles. For passenger cars one can observe the trend towards a Hybrid BEV powertrain concept for multiple years. The full benefits of the Hybrid BEV can be leveraged especially with view on numerous applications and different installations in commercial vehicle types (Fig. 1). [2][4]



Electric machine power (cont./peak) in kW	120/175
Electric machine torque (cont./peak in Nm	425/575
Electric machine type	PMSM
Li-Ion Battery capacity in kWh	10 – 110
Internal combustion engine	3-Cyl Gasoline / 1.5L
ICE power in kW	100
ICE torque in Nm	210
Min. BSFC in g/kWh	196

Electric machine power (cont./peak) in kW	110/160
Electric machine torque (cont./peak in Nm	400/550
Electric machine type	PMSM
Li-Ion Battery capacity in kWh	10 – 70
Internal combustion engine	4-Cyl Diesel / 2.0L
ICE power in kW	120
ICE torque in Nm	350
Min. BSFC in g/kWh	190

Electric machine power (cont./peak) in kW	150/220
Electric machine torque (cont./peak in Nm	550/700
Li-Ion Battery capacity in kWh	35 - 600
Internal combustion engine	6-Cyl Diesel, 13 L
ICE power in kW	300
ICE torque in Nm	2500
Min. BSFC in g/kWh	171

Electric machine power (cont./peak) in kW	380/570
Electric machine torque (cont./peak in Nm	1000/1400
Li-Ion Battery capacity in kWh	300 - 600
Internal combustion engine	4-Cyl Diesel, 2.5 L
ICE power in kW	120
ICE torque in Nm	350
Min. BSFC in g/kWh	180

Fig. 1. Illustrations of the investigated Hybrid BEV configurations.

3 Results

3.1 Light Commercial Vehicle/Light Duty Truck

The selected propulsion system types, containing Hybrid BEV, PHEV, and EV, were thoroughly analyzed and delivered, by neglecting eventual subsidies or other temporary purchasing benefits, all higher total system costs, but significantly lower OPEX compared to today's pure Diesel applications, which is for sure mainly fuel tax-related, as here increasing tariffs are given. Obviously, across all investigated scenarios and customer groups, the variations in both - propulsion system costs and OPEX – showcase very moderate differences. [3, 7]

In summary, both electrified topologies - PHEV and Hybrid BEV (REX) - provide at the end in contrast to pure electrical drive systems, a substantially higher degree of versatility for the broad spectrum of end users, fully comparable to today's known and accepted solutions with Diesel powertrains. The lower flexibility of BEVs in daily use was quantified by inserting an additional financial drawback for frequent "uncomfortable" charging stops at public DC charging stations. A cost figure resp. a loss of sales of €50/h was accordingly considered during the downtime of the vehicle at the charging point (Fig. 2). [4, 8, 10]

For a more comprehensive evaluation of the conceptual approach for a Hybrid BEV, it is crucial to understand the integrational effort in detail as well as the commonalities and differences in the core powertrain components. The installation space made available by the removal of battery modules is typically fully sufficient to accommodate a compact range extender module including all necessary sub-systems.

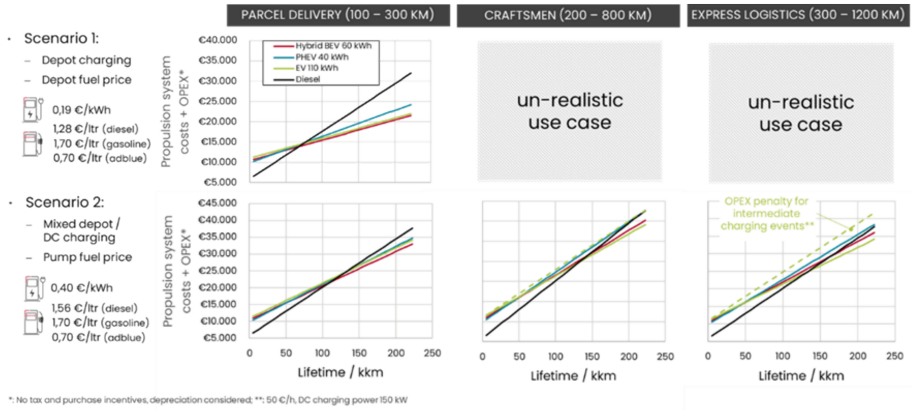


Fig. 2. Indicative Purchasing and Operational Costs (excl. purchase and tax incentives) for different electrified powertrain concepts across the investigated LCV/LDT customer groups.

However, spatial integration challenges become more significant when considering the available space in a typical LCV. Today's LCV battery electric vehicles (LCV-BEVs) are typically based on existing ICE platforms. In these BEVs, the battery is usually integrated into the vehicle floor. An electric axle module is typically installed on one axle. Auxiliary systems, such as air conditioning compressors, cooling packages, high-voltage electronics, and, in the case of front-wheel drive, a front electric drive unit (EDU), are packaged in the former engine compartment and vehicle front end. Integrating a range extender module into the battery compartment — typically a very flat structure located in the underbody — presents significant challenges and would generally require a complete powertrain redesign or new engine development.

3.2 Heavy-Duty Long-Haul Truck

For the before schematically displayed Hybrid BEV and PHEV layouts in the HD LH truck case a similar, full evaluation of the propulsion system costs, and operational costs (OPEX) were conducted over the defined entire vehicle lifetime with equal boundaries and assumptions, as already considered for the LCV matrix study, and depicted subsequently in Fig. 3. With a battery capacity of 400 kWh, nearly all trips involving intermediate charging during the day can be driven electrically, while still accommodating the use case of overnight charging only. This battery capacity enables the Hybrid BEV to achieve combined electricity and fuel costs comparable to those of a pure BEV truck. [5, 9]

For the configured Hybrid BEV and PHEV, a more comprehensive evaluation of the propulsion system costs and OPEX was performed over the vehicle lifetime for the same scenarios, that were considered for the LCV customer groups, The OPEX (excl. road tolls) for Scenario 1 is significantly lower for the BEV, Hybrid BEV, and PHEV compared to the long-haul diesel truck. Conversely, for Scenario 2, the outcome is different. The highest OPEX is here observed for the BEV, followed by the Hybrid BEV and PHEV. The lowest OPEX is achieved with the diesel truck, highlighting the sensitivity of OPEX

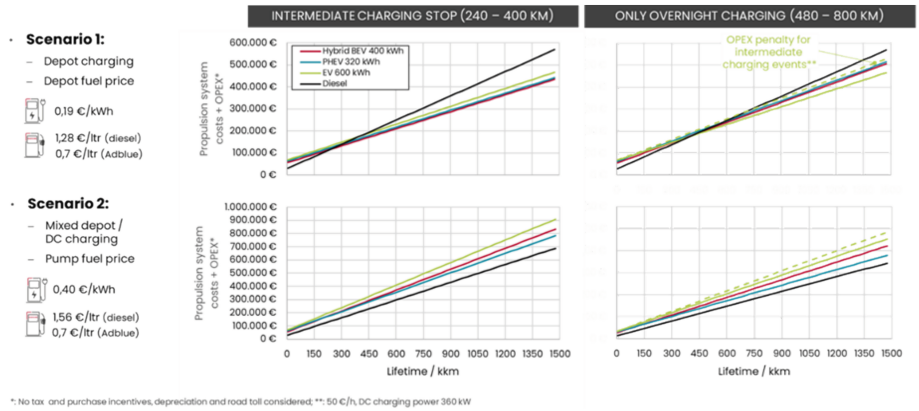


Fig. 3. Indicative Purchasing and Operational Costs (excl. purchase and tax incentives) for different electrified powertrain concepts across the investigated HD long-haul customer groups.

to fuel and electricity prices. In the "only overnight charging" use case, the BEV truck must make an intermediate charging stop at a DC charging station, where electricity prices are higher, resulting in increased operational expenses (OPEX). Considering the reduced flexibility of BEVs, an indicative cost penalty between €20 and €50 per hour is applied for these intermediate charging events. Consequently, a delta in OPEX of €65,000 is accumulated over the full distance of 1.5 million kilometers.

The OPEX (excl. road tolls) for Scenario 1 is notably lower for the BEV, Hybrid BEV and PHEV, compared to the classical diesel-powered long-haul truck. However, for Scenario 2, the situation is quite unlike. The highest OPEX is here observed for the BEV vehicle case, followed by the Hybrid BEV and PHEV. The lowest OPEX is still attained with the diesel truck w/out consideration of on-going improvements, highlighting the pronounced sensitivity of the OPEX to the energy prices. In the "only overnight charging" use case, the BEV truck must make an intermediate charging stop at a DC charging station, where electricity prices are assumed substantially higher in comparison to the attractive depot charging case.

4 Summary and Conclusions

The study in hand intends to deliver a full and wide-ranging assessment of the propulsion system costs and corresponding operational expenditures (OPEX) for different propulsion system layouts, covering today's highly accepted Diesel powertrains besides "bridge solutions" like Hybrid BEVs and PHEV configurations up to fully electrically operated systems over the entire vehicle lifetime. The in-depth analysis across different boundary settings and representative customer categories reveals that on one hand semi-electrified systems, like Hybrid BEVs (REX) and PHEVs, suffer also higher initial propulsion system costs, but on the other hand offer significantly lower OPEX in most use cases compared to standard Diesel powertrains, while ensuring the crucial high grade of versatility. The high flexibility of PHEVs and Hybrid BEVs (REX) further increases their

particular pull for the end users in comparison to pure BEVs, despite a marginal delta in total costs.

Both electrified versions, Hybrid BEV and strong PHEV solutions, enable during operation the potential of a high electrification share within a compressed timeframe, leading to corresponding CO_2 savings without major operational limits or functional shortcomings. The original well-known and crucial versatility in the commercial vehicle market is kept high on the same level as today's applications, regardless of the specific use case and driving profile. These technologies feature the capability to serve as a valuable and convincing bridge, offering high versatility until a widespread and attractive charging infrastructure becomes available for fully electrified solutions, offering the ultimate versatility in contrast to highly efficient Diesel powertrains.

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References

1. https://autovista24.autovistagroup.com/news/strong-growth-for-the-eu-lcv-market-in-2024/. Accessed 8 May 2025
2. Menne, C., Uhlmann, T., van der Put, D., Körfer, T., Thewes, M., Busch, H.: Hybrid BEV for light commercial vehicles, 16. In: Internationaler ATZ Kongress Antriebe und Energiesysteme von Morgen (2022)
3. Shoman, W., Yeh, S., Sprei, F., Plötz P., Speth, D.: Public charging requirements for battery electric long-haul trucks in Europe: a trip chain approach, Working Paper Sustainability and Innovation, No. S 01/2023. Göteborg, Karlsruhe: Chalmers University of Technology, Fraunhofer IS
4. https://group.dhl.com/en/media-relations/press-releases/2025/dhl-and-scania-to-test-electric-truck-with-fuel-powered-range-extender.html. Accessed 6 May 2025
5. https://www.acea.auto/files/Zero-emission-commercial-vehicles-Tax-benefits-purchase-incentives_2024.pdf. Accessed 8 May 2025
6. Schaub, J. et al.: Electrified efficiency – diesel hybrid powertrain concepts for light commercial vehicles. In: Internationaler Motorenkongress 2020, Proceedings. Springer Fachmedien Wiesbaden GmbH and Springer, Vieweg, Wiesbaden (2020)
7. Muthyala, P., Schaub, J., Badalian, K., Pischinger S.: Build your hybrid - a novel approach to test various hybrid powertrain concepts (2023). https://www.sae.org/publications/technical-papers/
8. Muthyala, P., Wessel, F., Schaub, J. Pischinger, S.: Cloud-based SOC optimization for predictive energy management and zero emission zone compliance in PHEVs Available SSRN: https://ssrn.com/abstract=5010588 or https://doi.org/10.2139/ssrn.5010588
9. Körfer, T., Schaub, J., Zwar, P., Ehrly, M., Müller, A., Vosshall, T.: Hybridized propulsion systems for challenging commercial vehicle applications, VDI Conference 07-2025_VDI_Antriebsstrangloesung_NFZ
10. Hui, D., Chao, M., Korfer, T., Liu, X., Li, J., Grütering, U.: An all-new 2,5L diesel engine platform to power global LD applications under upcoming challenging market requirements. In: FISITA Conference 2025, Barcelona

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The New CEN E20 Petrol Specification

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Abstract. CEN fuel standards in Europe have developed to enable the simultaneous advancement of engine technology and reduction of pollutant and GHG emissions, through the close collaboration of cross-industry stakeholders and European National Standardisation Bodies. The current European petrol standard 'EN 228:E10' permits up to 3.7% oxygen by mass from oxygenated components, including alcohols and ethers which help to reduce vehicle emissions by substituting high-carbon aromatic components and introducing renewable content. A task force within CEN, comprising experts from industry stakeholders, has developed a new 'E20' specification which increases the allowed oxygenate content to 8% mass oxygen equivalent and bioethanol up to 20% volume, further increasing decarbonisation potential.

Keywords: CEN · Technical Specification · E20

1 Introduction

1.1 Background

Decarbonisation is moving at pace in Europe, driven by the aim of mitigating global warming. Road transport currently accounts for almost a fifth of GHG emissions in Europe, of which, around 60% is attributable to cars [1]. BEVs are supplanting cars with ICEs, but that leaves huge scope to decarbonise ICE-powered cars that will remain on the road for decades, with around 250 million cars on the road today in the EU, more than half having a petrol-fuelled engine [2]. The current CEN standard for petrol fuel: 'EN 228:E10' [3] permits up to 3.7% oxygen by mass from oxygenated components, including alcohols and ethers. The Renewable Energy Directive (RED) encourages the use of renewable blending components in petrol. In 2022, a task force (TF) was formed within CEN comprising experts from industry stakeholders to develop a new 'E20' technical specification (TS) and underpinning technical report (TR), building on the prior work within CEN and other bodies. In 2025, drafts were completed, approved and published as CEN TS 18227:2025 [4] and CEN TR 18238:2025 [5]. However, to allow E20 to be sold in the EU would also require changes to the limits on oxygen and bioethanol content currently in the EU Fuel Quality Directive (FQD). The FQD currently limits ethanol and oxygen content to a maximum of 10% (V/V) and 3.7% (m/m), respectively.

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1.2 Rationale for an E20 Grade

The paramount consideration in developing a new E20 fuel grade is the potential for GHG reduction. Substituting petroleum-derived hydrocarbons for oxygenated compounds can deliver reductions in CO2 emissions especially where the oxygenates are produced from renewable sources [6, 7]. Oxygenates commonly used in fuels such as ETBE (Ethyl Tertiary Butyl Ether) and ethanol have high octane quality (ETBE ~118, ethanol ~109, [8]). Substituting higher-octane fossil hydrocarbons for such oxygenates reduces the carbon intensity of the fuel by displacing carbon-intensive molecules leading to lower CO2 at the tailpipe. Where ethanol is 'splash' rather than 'match' blended such that octane quality of the finished fuel increases, further benefits on engine efficiency and therefore further CO2 reduction can be attained [9–11]. Furthermore, ethanol's high enthalpy of evaporation leads to charge cooling effects which can increase the knock-limit in addition to benefits described through conventional octane measurements, particularly for highly boosted, downsized engines with high compression ratios [5, 12, 13]. However, such effects are not always observed in the oxygen range of the E20 TS [14]. Furthermore, the inclusion of more high-octane oxygenates could facilitate the inclusion of lower-octane renewable streams such as bio-naphtha. The size of potential CO2 benefit varies dependent on multiple factors, including assumptions made in WTW calculations, feedstock/crop particulars, oxygenate type, production process as well as the assumed baseline for the displaced fossil hydrocarbon fuel [6]. There is no single definitive CO2 potential benefit for E20 because of the aforementioned variables and because the composition is not fixed – the specification describes limits and ranges rather than a definitive recipe. Figure 1 illustrates example CO2 benefits for a range of fuels meeting the oxygenate and oxygen ranges permitted in the E20 TS, based on a scenario in France [7].

1.3 Viability of E20

Oxygenates such as alcohols and ethers are well established in the European fuel pool. The novelty with the E20 specification is an increase in the allowable ethanol content from 10 to 20% (V/V) and oxygen content from 3.7 to 8.0% (m/m). Fuels containing ethanol above 10% (V/V) are well established in other geographies, including E15 in the US, E27 and E100 in Brazil and E20 in India and Thailand. E85 is also used within and outside Europe. Therefore the prospect of E20 is a matter of adopting practices from elsewhere, rather than tackling an unknown or unproven concept. This applies both to the fuel production, supply and distribution infrastructure and confirming the suitability of a sufficient proportion of vehicles to make the prospect of E20 viable. Details on compatibility specific to the European use case, including elastomer assessments, are discussed in the supporting CEN Technical Report that underpins the rationale for the specific parameter limits in the specification [5]. However, as mentioned in 1.1, to allow E20 to be sold in the EU (comprising the majority of countries participating in CEN) would require changes to the limits on oxygen and bioethanol content currently allowed in the EU FQD.

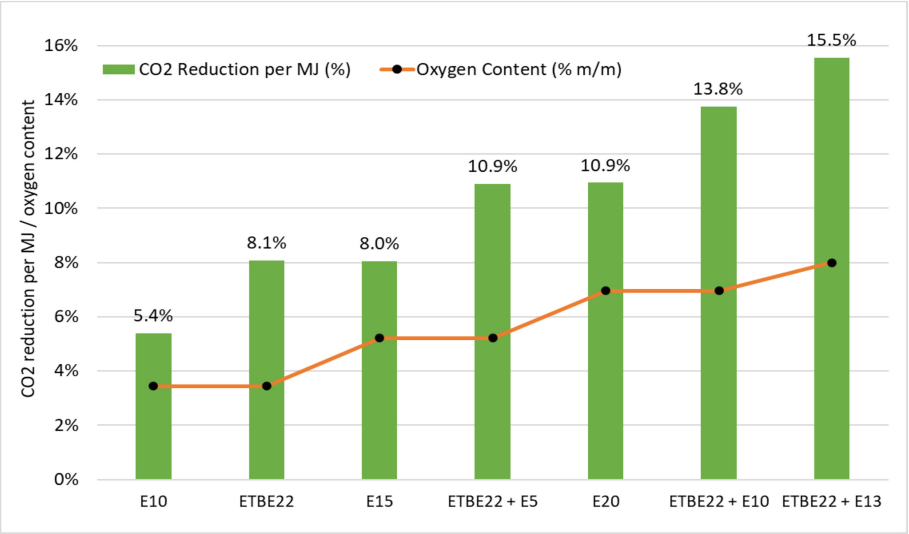


Fig. 1. Example CO2 WTW benefits for a range of fuels meeting the oxygenate and oxygen ranges permitted in the E20 TS [7].

2 E20 Technical Specification Requirements

In the interests of simplicity, the E10+ TF aimed to align the new E20 TS requirements with those of the existing EN 228 standard as far as practical. Deviations were therefore only made in response to the increased ethanol and oxygen content. In the following sections, the rationale for decisions on limit setting is given. The table below summarises the principal differences between EN 228 and the E20 TS (Table 1).

Table 1. Summary of principal differences between EN 228 E10 and E20 TS.

Property	Units	EN 228 E10		E20 TS	
		Min	Max	Min	Max
Ethanol content	% (V/V)	–	10	–	20
Oxygen content	% (m/m)	–	3.7	3.7	8.0
RON	–	95	–	98	–
Water content	% (m/m)	–	–	–	0.20
% evaporated at 70 °C “E70” (Class A-B)	% (V/V)	20	50	20	68
% evaporated at 70 °C “E70” (Class C-F)	% (V/V)	22	52	22	68
% evaporated at 100 °C “E100”	% (V/V)	46	72	46	75
% evaporated at 150 °C “E150”	% (V/V)	75	–	80	–
Final Boiling Point	°C	–	210	–	200

2.1 Oxygen and Oxygenate Content

The primary consideration of the TS definition was to set the oxygen and oxygenate content limits as these would impact some other parameters. It was agreed to increase the maximum permissible level of ethanol from 10 to 20% (V/V) and no higher, to minimise the possibility of vehicle incompatibility [5]. It was also agreed to maintain EN 228 maximum % volume limits for all other oxygenates. Extensive discussions resulted in no minimum ethanol limit being adopted due to concerns that enforcing a minimum ethanol content would disadvantage suppliers of other oxygenates without sufficient technical justification [5]. Maximum oxygen content was set at 8% (m/m) to accommodate 20% (V/V) ethanol which alone provides around 7.4% (m/m) oxygen, depending on the density of the incumbent BOB (Blend stock for Oxygenate Blending). A lower limit of 3.7% (m/m) oxygen was adopted (approximately equivalent to 10% (V/V) ethanol) thus providing surety for vehicle fuel consumption accuracy requirements.

2.2 Research Octane Number (RON) and Motor Octane Number (MON)

Increasing the minimum octane limit in a high-oxygenate petrol can partially offset the volumetric fuel economy penalty that drivers might otherwise experience from fuelling with a higher oxygen-content fuel due to its lower heating value [15]. Splash blending an additional 10% ethanol to E10 would result in a 3 RON increase and in this example the same BOB (Blend stock for Oxygenate Blending) could be used for both E10 and E20 products. This rationale supports setting the RON minimum limit to 98. A proposal was made to increase MON above the EN 228 minimum of 85 to mitigate LSPI risk. However, increasing the MON minimum limit would reduce the fuel sensitivity (RON-MON) and therefore the potential for increasing efficiency associated with higher RON fuel [13]. Accordingly, the minimum octane limits were set as: RON: 98 and MON: 85.

2.3 Water Content and Corrosion Protection

The parameters affecting steel corrosion propensity are controlled in the ethanol specification [16], but there is no mandatory corrosion testing requirement in EN 228 addressing iron corrosivity by water in petrol. It was pointed out that there are no inherent issues with corrosion in European (E10) or US (E15) fuels, but corrosion problems can occur in other (developing) markets. In fuels containing higher levels of ethanol, there is an additional risk of corrosion when water separation occurs. Therefore to limit both risk of corrosion and intentional addition of water, a maximum limit of 0.2% (m/m) was included in the E20 TS.

2.4 Hydrocarbon Content and Final Boiling Point (FBP)

Representatives of the auto-industry proposed some different limits from EN 228 with respect to hydrocarbon content, higher aromatics (C9+ and C10+) and FBP. These measures were proposed to reduce exhaust particulate emissions and limit the low speed pre-ignition (LSPI) risk. In response, works were shared concluding that vehicle technology contributed to broader effects on particulate emissions than fuel composition [17,

18]. A Concawe presentation of SGS Summer 2022 market survey data showed that for 114 fuels sampled, around half would not comply with the proposed C9+ (<10%V/V) and C10+ (<2%V/V) limits, therefore applying such limits could result in substantial changes to fuel production in Europe. Whereas applying an FBP limit of 200 °C would only affect 22 of 114 fuels. Another presentation showed that, according to data from the BEP525 study, [19] adding 20% ethanol to 60 different base petrol fuels reduced FBP on average by 3.5 °C. Furthermore, reducing FBP by lowering the cut temperature between streams, shifts quantities from the petrol to kerosene pool which could be a logical change in the future as petrol demand drops in Europe due to the impact of electrifying light-duty vehicles. A further presentation of SGS fuel survey data showed a strong correlation between C10+ aromatics and FBP and suggested that setting a FBP maximum limit of 200 °C could be used to control fuel properties most affecting particle production and LSPI risk, see Fig. 2.

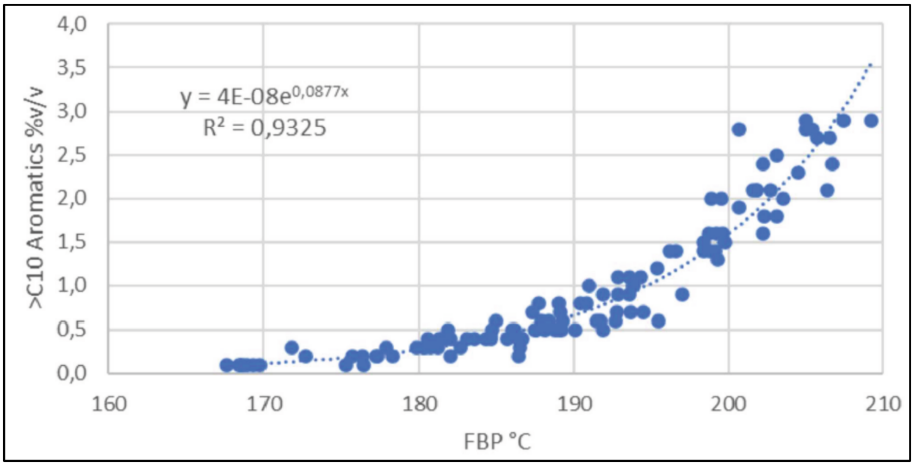


Fig. 2. Correlation between C10+ aromatics and final boiling point (SGS Summer fuel survey 2022)

It was concluded that an FBP maximum limit of 200 °C should be adopted in the E20 TS instead of introducing any revised or new limits for aromatic content or new controls to minimise LSPI given that the lower FBP maximum provides some of the benefits that may be achieved from applying limits to the aforementioned qualities, but without the complexity of adopting additional parameter limits and controls.

2.5 Volatility

Appropriate volatility of petrol is critical to the operation of spark-ignition engines with respect to both performance and emissions, with requirements varying with ambient temperature. Volatility is characterised by two measurements - vapour pressure and distillation. Ethanol increases the vapour pressure of petrol/ethanol mixtures but the effect peaks at very low ethanol concentrations below 5% V/V [19]. Ethanol changes

the distillation characteristics of the petrol/ethanol mixture, increasing the evaporated fraction particularly at lower temperatures, see Fig. 3 [19].

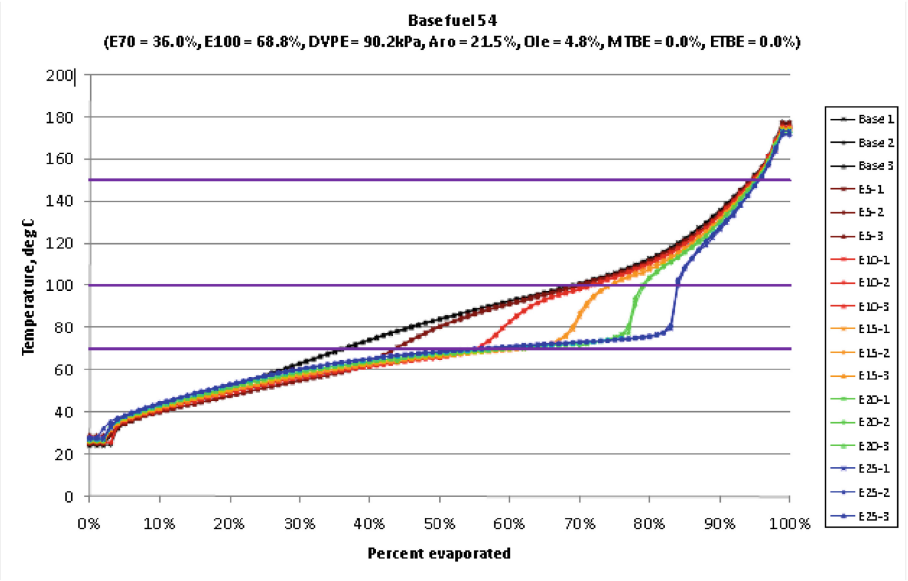


Fig. 3. Impact of ethanol in the range 0–25% (V/V) on distillation profile – representative example from BEP525 study [19].

E70. A proposal was made to impose an E70 minimum of 25% (% (V/V) as per all distillation limits), higher than the one existing in the EN 228 standard (20%), based on the positive impact of ethanol on evaporation in this temperature range. However, some fuels within the E20 specification may not contain 20% (V/V) ethanol or indeed any ethanol. It was agreed to adopt 20% as the E70 minimum limit. It was also agreed to adopt an E70 maximum limit of 68% which is higher than the EN 228 limit and takes account of the impact of adding up to 20% (V/V) ethanol to a range of base fuels as illustrated in [19].

E100. It was proposed that the upper E100 limit should be set at 78% (versus 72% for EN 228) in order to accommodate the effects of up to 20% (V/V) ethanol, as well as the potential impact of adopting an FBP limit of 200 °C as this could force more molecules into the lower boiling range. SGS market survey data examined for 2019–2023 showed that E100 for market fuels up to E10 did not exceed 70% in the vast majority of cases. In conclusion, the E100 maximum limit was set at 75%, with the proviso that if such a limit leads to the requirement for refining changes when the fuel is in the field, this could be reconsidered.

E150. BEP525 study data [19] showed that addition of 20% (V/V) ethanol tends to increase E150, albeit by a limited amount. Proposals were made to adopt the EN 228 E150 minimum limit of 75% and alternative proposals were made to adopt higher limits (80% and 84%) to benefit vehicle emissions. SGS market fuel survey data was

considered, showing that the majority of EN 228 fuels (E10 maximum) had E150 values exceeding 80%. Considering these data and the risk that setting an E150 limit too high might force new refining practices that could impact CO2, it was decided to adopt 80% as the E150 minimum limit.

3 Summary and Outlook

Decarbonisation of road transport is required to help mitigate climate change. In response, a task force representing European industries and NSBs, convened under CEN, has developed a technical specification for a higher-oxygenate-content petrol fuel "E20" for Europe. The designed fuel specification also has potential to reduce vehicle pollutant emissions leading to local air quality benefits and comprises oxygenate fuel technologies already successfully deployed in Europe. The technical specification (CEN TS 18227:2025) and supporting technical report (TR 18238:2025) were published in 2025. However, to allow E20 to be deployed in the EU would also require changes to the limits on oxygen and bioethanol content currently applied in the EU Fuel Quality Directive. As for any new fuel, there are other steps required to bring the product to market such as confirming E20 compatible or tolerant vehicles and preparation of supply and distribution infrastructure, regulations and organization. If E20 passes the remaining hurdles, it has the potential to significantly help the decarbonisation of the current and future legacy passenger car fleet in Europe, in turn making a material contribution to Europe's overall decarbonisation ambition.

References

1. CO2 emissions from cars: facts and figures: European parliament. https://www.europarl.europa.eu/topics/en/article/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics
2. Report – Vehicles on European roads 2025: ACEA. https://www.acea.auto/publication/report-vehicles-on-european-roads-2025/
3. EN 228:2025: Automotive fuels - unleaded petrol - requirements and test methods. https://www.cencenelec.eu/about-cen/
4. CEN TS 18227:2025: Automotive fuels - E20 petrol - requirements and test methods. https://www.cencenelec.eu/about-cen/
5. CEN TR 18238:2025: Automotive fuels - E20 petrol - background on the parameters required, their respective limits and justification. https://www.cencenelec.eu/about-cen/
6. Prussi, M., Yugo, M., De Prada, L., Padella, M. Edwards, R.: JEC well-to-wheels report v5. EUR 30284 EN. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-20109-0 (2020). https://doi.org/10.2760/100379
7. Koupal, J., Cashman, S., Young, B., Henderson, A.D.: Carbon footprint of oxygenated gasolines: case studies in Latin America, Asia, and Europe. Fuels. **5**, 123–136 (2024). https://doi.org/10.3390/fuels5020008
8. Awad, O., et al.: Alcohol and ether as alternative fuels in spark ignition engine: a review. Renew. Sust. Energ. Rev. **82**, 2586–2605 (2018). https://doi.org/10.1016/j.rser.2017.09.074
9. Weichang, Y., et al.: Comparison of real-world vehicle fuels use and tailpipe emissions for gasoline-ethanol fuel blends. Fuel. **249**, 352–364 (2019). https://doi.org/10.1016/j.fuel.2019.03.115

10. Williams, J., Hamje, H.: Testing and modelling the effect of high octane petrols on an adapted vehicle. Concawe report 8/20. https://www.concawe.eu/wp-content/uploads/Rpt_20-8.pdf
11. Amaral, L., et al.: Effects of gasoline composition on engine performance, exhaust gases and operational costs. Renew. Sust. Energ. Rev. **135** (2021). https://doi.org/10.1016/j.rser.2020.110196
12. Wang, C., et al.: Splash blended ethanol in a spark ignition engine – effect of RON, octane sensitivity and charge cooling. Fuel. **196**, 21–31 (2017). https://doi.org/10.1016/j.fuel.2017.01.075
13. Stein, R., et al.: Effect of heat of vaporization, chemical octane, and sensitivity on Knock limit for ethanol-gasoline blends. SAE Int. J. Fuels Lubr. **5**(2), 823–843 (2012)
14. Kalaskar, V., Mitchell, R., Pourreau, D.: Impact of oxygenated fuel components on engine performance and particulate emissions in gasoline blends. SAE Technical Paper 2025-01-8446 (2025). https://doi.org/10.4271/2025-01-8446
15. Horizon 2020 E10+ project: Grant agreement SA/CEN/RESEARCH/ EFTA/000/2014–13
16. EN 15376: Automotive fuels — Ethanol as a blending component for petrol — Requirements and test methods. https://www.cencenelec.eu/about-cen/
17. Chijiiwa, R., Rose, D., Boger, T., Krueger-Venus, J. et al.: Impact from a variety of E10 and E20 gasoline formulations on PN10 and PN23 emissions evaluated in combination with advanced GPF technology generations. SAE Technical Paper 2023-32-0028 (2023). https://doi.org/10.4271/2023-32-0028
18. Pettinen, R., et al.; Gasoline particulate study. Concawe report 2/24. https://www.concawe.eu/wp-content/uploads/Rpt_2_24.pdf
19. Ethanol/Petrol Blends: Volatility characterisation in the range 5–25 vol % (BEP525), Concawe/Shell study funded by EC, TREN/D2/454-2008-SI.2.522.698 (Final Report) 12/31/2009. https://energy.ec.europa.eu/system/files/2015-01/2010_bep525_final_report_0.pdf

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Mandates and Penalties: The Impact of Policy Implementation on Biofuel Markets – A Comparative Study on Road and Aviation Transport Fuel Prices in Different EU Countries

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Abstract. To achieve the EU's 2050 climate neutrality goal, biofuel use in domestic transport is necessary which has mostly been promoted by biofuel blending mandates. By 2022, all EU Member States had implemented such mandates for road transport fuels, while only two had applied them to aviation fuel. The mandates vary in design, criteria and penalties for non-compliance, resulting in varying impacts on the blended fuel market. This study maps penalties for non-compliance with blending mandates in the road and aviation sectors and assesses their impact on fuel prices and mandate fulfilment. Based on penalty levels, it was estimated how much fuel suppliers are willing to pay for biofuels and the calculated maximum prices on blended fuel were compared to actual consumer prices. While no clear correlation between penalty levels and mandate fulfilment could be found, findings highlight the need for a balanced combination of penalty levels, blending mandates, and policy measures to increase the biofuel share in transport fuels without disrupting fuel markets.

Keywords: Biofuels · Blending Mandates · Fuel Prices · Penalties · Policy

1 Introduction

To promote renewable energy consumption in the European Union (EU), the Renewable Energy Directive (RED) was implemented in 2009 [1]. The RED was revised in 2023 to include new targets for the transport sector to be met in 2030: i) a binding share of 29% renewable energy in final energy consumption, or ii) a binding target of 14.5% reduction of greenhouse gas (GHG) emission intensity, as well as sub-targets for advanced biofuels [2]. In addition to RED, the aviation sector is subject to the ReFuelEU Aviation Regulation [3], mandating a minimum share of 6% sustainable aviation fuel (SAF) in aviation fuel supply at EU airports by 2030, rising to 70% by 2050, and stricter limits imposed on feedstocks used for SAF production compared to the road transport sector

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[3]. Biofuel blending mandates have been introduced across all EU Member States for compliance with the RED [4]. These mandates require fuel suppliers to blend a minimum share of biofuels into their supplied fuels, based on either energy content, volume, or GHG emission reduction. However, in the aviation sector, only France and Sweden had implemented blending mandates in 2022.

In recent years, external factors have further affected the dynamics of biofuel blending mandates. The surge in global energy prices began in 2021, following the COVID-19 pandemic and exacerbated by Russia's invasion of Ukraine, causing high inflation and economic pressures across Europe [5]. In response, several Member States adjusted their blending mandates in 2022, where Croatia lowered its penalty for non-compliance, Finland reduced its blending mandate, Czechia and Latvia dismissed theirs completely, and Sweden froze the planned annual mandate increase [6]. In light of these economic strains, the role of penalties for non-compliance with biofuel blending mandates becomes important as they ultimately set the maximum price fuel suppliers are willing to pay for biofuels, thus potentially influencing the final consumer price.

Previous research highlights biofuel policies as a central tool for the defossilisation of the transport sector (see e.g., [7, 8]). However, few studies explore how fuel markets in the EU are influenced by the varying implementations of biofuel blending mandates. This creates a gap in understanding how the design of mandates at the national level affects biofuel markets and fuel prices. Several country-specific studies on biofuel policies exist, such as Germany [6], the Netherlands [7], and Sweden and Finland [8]. Global overviews also occur [9, 10], however these lack quantitative perspectives. An econometric analysis on biofuel policy and biofuel production was performed, although limited to ethanol [11]. The evolution of national blending mandates in the EU road transport sector between 2009–2020 was investigated, exploring the influence of mandates on biofuel production and consumption, fuel prices and emission reduction [4]. Penalties for non-compliance were though only briefly addressed, their potential impact on biofuel blending mandate fulfilment or fuel prices was not further assessed [4].

The aim of this study is to assess the impact of penalties for non-compliance on biofuel markets in the EU, by comparing penalty levels with blending mandate fulfilment, and calculating biofuel mandate threshold prices (i.e., the highest price a fuel supplier would be willing to pay per liter of biofuel to comply with the biofuel blending mandate). That price is then used to identify the highest price of blended fuels that consumers might face, hereby referred to as the calculated maximum blended fuel price. Accordingly, the main questions to be answered are the following: i) How do penalties contribute to calculated maximum blended fuel prices, and how does that compare to actual consumer fuel prices?, and ii) How do specific penalties contribute to biofuel usage and the fulfilment of blending mandates in different Member States and sectors?

In the context of this study, three biofuels for blending in fossil road transport fuels have been considered: fatty acid methyl ester (FAME) and hydrotreated vegetable oil (HVO) in diesel, and ethanol in petrol. For aviation transport, SAF in the form of hydroprocessed esters and fatty acids (HEFA) is considered, as it currently is the mainly utilised route for SAF production in Europe [9].

2 Methodology

The year 2022 was chosen for the analysis since it was marked by elevated fuel prices, which subsequently led to several Member States reducing their blending mandates. Therefore, it is of interest to investigate the impact on EU fuel markets. National penalties for non-compliance with biofuel blending mandates were collected from [6]. As penalties are typically given as energy-based, volume-based, or GHG emission reduction-based, they were transcribed into a common unit, €/MWh, for comparison.

To investigate the connection between penalties and blending mandate fulfilment, the reported share of consumed biofuels in relation to the national mandate was compared to penalty levels. Following the RED methodology, double counting for biofuel use was included for certain mandate types. Double counting promotes biofuels with lower risk of land-use change or food competition, allowing certain advanced biofuels to count twice towards blending mandates, though eligible fuel types may vary across countries [10]. Double counting is included in overall energy- or volume-based mandates, and excluded in specific petrol, diesel and SAF mandates due to reporting practices. Double counting is not permitted for GHG emission mandates. Biofuel blending mandate fulfilment was calculated as shown in Eq. (1), based on biofuel use reported to Eurostat [13–16].

$$Blending\ Mandate\ Fulfillment = \frac{Biofuel\ share\ reported\ to\ Eurostat}{Biofuel\ blending\ mandate} \quad (1)$$

To investigate the effect of penalties on fuel prices, two reference values were calculated: the maximum blended fuel price (i.e., the highest price a fuel blend could get, when the fuel supplier complies with the blending mandate) and the biofuel mandate threshold price (i.e., the highest price per liter of biofuel that a fuel supplier would, theoretically, be willing to pay to comply with a blending mandate). Taxes were excluded to enable cross-country comparisons, so the resulting fuel prices serve as proxies for final consumer prices. Table 1 presents the parameters included in the calculations, along with their denominations and units.

Table 1. Parameters included in the calculations, their denominations and units.

Parameter	Denomination	Unit
Biofuel mandate threshold price	I_M	€/L fuel
Emission intensity of biofuel	E_B	kg CO_2-eq/L fuel
Emission intensity of fossil fuel	E_F	kg CO_2-eq/L fuel
Maximum blended fuel price	$I_{BF,Max}$	€/L fuel
National set penalty for non-compliance	P	€/kg CO_2-eq
Price of biofuel	I_B	€/L fuel
Price of fossil fuel	I_F	€/L fuel
Share of biofuel in blended fuel	X_B	%
Volumetric energy density of fossil fuel	D_F	MJ/L

Following Eq. (2), the maximum blended fuel price per liter, $I_{BF,Max}$, is calculated. Reference prices for fossil-based petrol and diesel, as well as national blended fuel prices, were retrieved from the Weekly Oil Bulletin [17]. Both fossil-based petrol and diesel prices assumed 2022 EU averages, €0.97/L and €1.10/L, respectively.

$$I_{BF,\mathrm{Max}} = (1 - X_B) \bullet I_F + X_B \bullet I_B \tag{2}$$

Under an overall biofuel blending mandate, fuel suppliers can choose how to comply with the mandate by blending in ethanol in petrol or biodiesel in diesel, however it is likely that biofuels are blended into both the petrol and diesel fuels. In Member States with mandates on both overall as well as fuel-specific levels, fuel suppliers have less flexibility as they must comply with all imposed mandates.

The biofuel mandate threshold price, I_M, varies according to the penalty type, and it is calculated according to Eq. (3).

$$I_M = P \bullet (E_F - E_B) + I_F = P \bullet D_F + I_F = P + I_F \tag{3}$$

Equation (3) illustrates the relationship between biofuel price and associated emissions. For Member States with a GHG emission reduction mandate, a lower emission intensity increases the economic incentive for fuel suppliers to purchase biofuel to meet the blending mandate. By inserting the biofuel mandate threshold price calculated in Eq. (3) into Eq. (2) as I_B, it is possible to calculate the maximum price per liter of blended fuel (i.e., the highest potential price of the blend while complying with the mandate).

3 Results and Discussion

3.1 Mandates and Penalties

Figure 1 illustrates penalty levels compared to biofuel blending mandate fulfilment among EU countries. Per-unit based penalties range from below €1/MWh in Croatia to €25/MWh in Hungary, with an average of around €10/MWh (e.g., Czechia, Finland, and Luxembourg). For SAF blending mandates in France and Sweden, the implemented penalties that were slightly higher than their respective road transport penalties.

Figure 1 illustrate how most Member States fall short of meeting their biofuel blending mandates, regardless penalty type. No clear correlation emerges between penalty levels and mandate fulfilment, and while penalties may serve as a compliance mechanism, their effectiveness appears debatable. For example, Italy and Slovakia meet their mandates while imposing penalties of €5/MWh and €16/MWh, respectively, whereas Czechia does not despite a €10/MWh penalty. These cases suggest that while penalties may influence fuel supplier behaviour, they are not the sole determinant of mandate fulfilment. This pattern implies that moderate penalties paired with enabling conditions (e.g., sufficient fuel availability in relation to mandate size and economically viable pricing), may be sufficient to reach the mandates. Figure 1 demonstrate that many countries fulfil around 80–90% of their blending mandates, a few countries met 50% or less, while 11 Member States either meet or exceed their mandates. For countries close to fulfilling their mandates, the remaining gap may be bridged through nationally determined

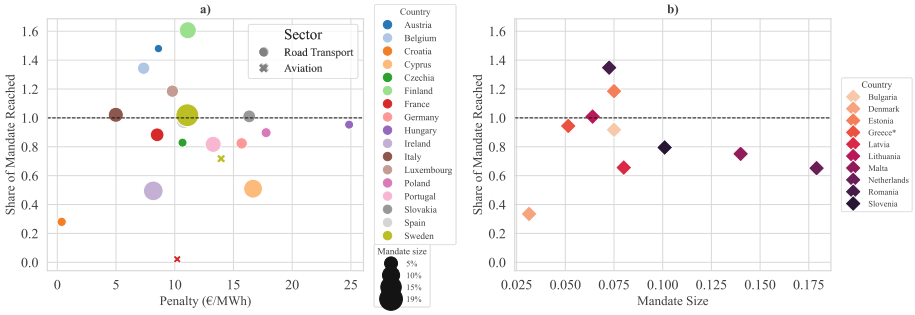


Fig. 1. Fulfilment of national biofuel blending mandates (y-axis) in EU countries in 2022. The horizontal line represents a fulfilled mandate. Fig. a) shows mandate fulfilment for road and aviation sectors in countries with per-unit based penalties, and b) for countries without per-unit based penalties. Greece is shown with 2021 data, since 2022 data was incomplete.

double-counting provisions (e.g., electricity in transport), although such measures were excluded from the study.

In the aviation sector, France and Sweden impose higher penalties compared to road transport, yet both fail to fulfil their SAF blending mandates. This further underscores that the penalty level alone does not guarantee mandate fulfilment. Figure 1a) depict how Sweden reaches 70% of its mandate, while France barely reaches 2%. This likely reflects the early-stage development of the SAF market, where limited supply and higher costs may hinder mandate compliance. In 2020, SAF accounted for less than 0.05% of total EU aviation fuel, with prices 1.5–6 times higher than conventional fossil fuel. Scaling production is therefore critical to reduce costs and meet the anticipated demand of 2.3 million tonnes in 2030 [18]. If SAF remains more expensive than the penalty cost, non-compliance may continue to be the economically rational option for fuel suppliers. Thus, while higher penalties could encourage mandate compliance, they must be accompanied by sufficient market support and fuel availability to be effective.

3.2 Blended Fuel Prices

The relationship between actual fuel prices and calculated maximum prices of blended fuel is visualised in Fig. 2. For road transport, darker bars demonstrate actual consumer prices without taxes, while lighter bars indicate calculated maximum blended fuel prices. Countries without per unit-based penalties were excluded from this analysis. For aviation, the calculated maximum blended fuel price is compared to the EU average aviation fuel price.

To further investigate the impact that biofuel mandates had on diesel fuel prices, a case study of the years 2018–2023 was performed for a few selected countries. Austria, Germany and Sweden were chosen because of the low price differences between calculated maximum prices and actual consumer prices in 2022. Finland was selected because of its large blending mandate, and France because of its low consumer prices. The results are illustrated in Fig. 3 which show the differences between calculated maximum blended fuel prices and actual market prices.

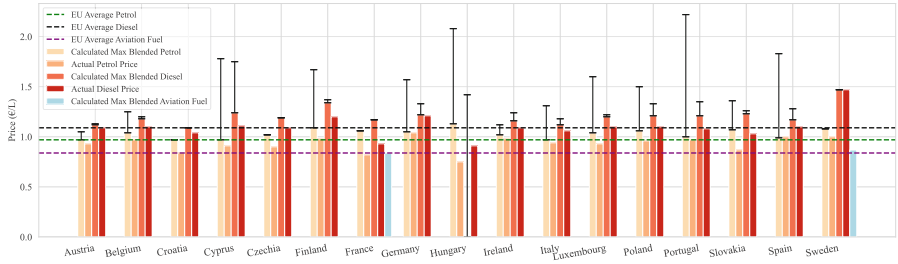


Fig. 2. Calculated maximum blended fuel prices (y-axis) for road transport and aviation fuel, excluding taxes, in EU countries (x-axis) in 2022. Hungary's diesel mandate was excluded due to insufficient data.

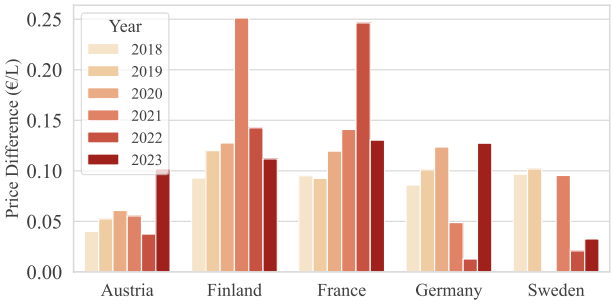


Fig. 3. Case study on price differences between consumer prices and calculated maximum fuel prices (y-axis), for the years 2018–2023 in selected Member States. Data for Sweden in 2020 was incomplete and therefore excluded.

In 2022, Swedish and German consumer diesel fuel prices were near their respective calculated maximum blended fuel prices, as demonstrated in Figs. 2 and 3. This indicates that fuel suppliers paid close to the biofuel mandate threshold price for the biofuel, suggesting that penalty levels might have set the biofuel market prices. Sweden recorded the highest consumer diesel price among all Member States, approximately 35% (€0.5/L) above the EU average diesel price. This implies a connection between penalty levels and consumer price levels. Both German and Swedish markets placed a premium on HVO compared to FAME due to its higher GHG mitigation potential, consistent with their GHG emission reduction mandates, as opposed to biofuel blending mandates based on volume or energy content. Given the limited supply of HVO in 2022, HVO suppliers had the opportunity to let national penalty levels determine fuel prices. In contrast, other markets could more easily adapt by increasing FAME shares or utilizing HVO produced from feedstocks not subject to the same upward price pressures. In such markets, the larger gap between actual fuel prices and the calculated maximum blended fuel prices indicates that penalties were not the binding price-setting mechanism. Instead, biofuel prices were shaped by broader market dynamics, reflecting greater flexibility and a more well-functioning market.

For the aviation sector, the calculated maximum blended aviation fuel price for Sweden and France was very close to the average EU aviation fuel price (see Fig. 2). This largely reflects the low SAF mandates in both countries, which meant that the SAF threshold price had a negligible impact on the blended fuel price. In practice, even if fuel suppliers had sourced SAF at, or just below, the threshold price, the impact on the final fuel price would have been minimal. However, since SAF was more expensive than the penalty cost, the mandates were not fulfilled in either country.

4 Conclusions

Focusing on 2022, a year of high fuel prices that prompted political action to reduce mandates and ease consumer costs, this study examines the biofuel market under stress and interactions between policy and market conditions. While this perspective provides valuable short-term insights, the narrow time frame limits our understanding of long-term policy-market dynamics. Nevertheless, the findings shed light on the role of national penalties in ensuring compliance with biofuel blending mandates across the EU.

The results indicate that while penalty levels can influence mandate compliance, no clear correlation emerges. Instead, mandate compliance might also depend on factors such as mandate size, enforcement of penalties, fuel availability and fuel supplier incentives. As seen in Germany and Sweden in 2022, when penalties are binding in markets with limited biofuel supply, they can become the price-setting mechanism for biofuels. This is an important factor to consider when deciding on penalty levels: in strained markets they can become price setting for biofuels, which in turn might impact final consumer prices. In contrast, the aviation sector highlights how immature markets limit penalty effectiveness: despite France and Sweden having implemented penalty systems, both countries fell short of their mandates. This was likely due to SAF prices being higher than the penalties, and that the SAF market remains underdeveloped.

Looking ahead, blending mandates are set to increase through 2030, alongside the introduction of sub-mandates for advanced biofuels and SAF. These create niche markets risking undersupply if new technologies are slow to commercialize. Against this backdrop, our findings highlight two key considerations for policymakers when setting penalty levels: 1) Penalties set too high risk driving up fuel prices during periods of supply constraints, 2) Penalties set too low risk making it economically rational for market actors to forgo compliance if biofuel production costs exceed the penalty.

To balance these two risks, policymakers should consider the potential cost profiles of the biofuels targeted by new mandates and conduct calculations similar to those in this study to assess the potential impact on consumer prices if the penalty becomes price-setting, and evaluate whether such price levels are acceptable.

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References

1. Council Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, OJ L 140, 5.6.2009 (2009)
2. Council Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018–2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, OJ L, 2023/2413, 31.10.2023 (2023)
3. Council Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation), OJ L 2405 31.10.2023 (2023)
4. Lundberg, L., Cintas Sanchez, O., Zetterholm, J.: The impact of blending mandates on biofuel consumption, production, emission reductions and fuel prices. Energ Policy. **183**, 113835 (2023). https://doi.org/10.1016/j.enpol.2023.113835
5. International Energy Agency: Global energy crisis. Topics - IEA (2025). https://www.iea.org/topics/global-energy-crisis. Accessed 15 Sept 2025
6. Koster, M., De Simone, F., Saint-Supéry, M.V.: Overview of biofuels policies and markets across the EU (2022)
7. European Commission: Directorate-general for climate action: climate action – leading the way – from plans to implementation for a green and competitive europe – progress report 2024, Publications Office of the European Union (2024). https://doi.org/10.2834/8000893
8. Ebadian, M., van Dyk, S., McMillan, J.D., Saddler, J.: Biofuels policies that have encouraged their production and use: an international perspective. Energ Policy. **147**, 111906 (2020). https://doi.org/10.1016/j.enpol.2020.111906
9. Sorda, G., Banse, M., Kemfert, C.: An overview of biofuel policies across the world. Energ Policy. **38**(11), 6977–6988 (2010). https://doi.org/10.1016/j.enpol.2010.06.066
10. Su, Y., Zhang, P., Su, Y., Y.: An overview of biofuels policies and industrialization in the major biofuel producing countries. Renew. Sust. Energ. Rev. **50**, 991–1003 (2015). https://doi.org/10.1016/j.rser.2015.04.032
11. Bryngemark, E., Söderholm, P.: Green industrial policies and domestic production of biofuels: an econometric analysis of OECD countries. Environ. Econ. Policy Stud. **24**(2), 225–261 (2022). https://doi.org/10.1007/s10018-021-00320-y
12. Wang, B., Ting, Z.J., Zhao, M.: Sustainable aviation fuels: key opportunities and challenges in lowering carbon emissions for aviation industry. Carbon Capture Sci. Technol. **13**, 100263 (2024). https://doi.org/10.1016/j.ccst.2024.100263
13. Eurostat: Use of renewables for transport - details [Dataset] (2025). https://ec.europa.eu/eurostat/databrowser/product/page/NRG_IND_URTD. Accessed 15 Sept 2025
14. Eurostat: Final energy consumption in road transport by type of fuel [Dataset] (2025). https://doi.org/10.2908/TEN00127
15. Swedish Energy Agency: Kontrollstation för reduktionsplikten 2022. Delrapport 2 av 2. ER 2022:15 (2022)
16. Eurostat: SHARES detailed results [Dataset]. https://ec.europa.eu/eurostat/web/energy/database/additional-data. Accessed 15 Sept 2025
17. European Commission: Directorate-General for Energy: Weekly Oil Bulletin – Price developments 2025 onwards (xlsx) [Dataset]. https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en. Accessed 15 Sept 2025
18. European Union Aviation Safety Agency and European Environment Agency: European aviation environmental report 2022. Publications office of the European Union (2022). https://doi.org/10.2822/04357

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Predictive Modelling of Battery Degradation in Electric Vehicles Using Digital Twins and Real-World Data

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Abstract. Battery degradation is a critical challenge in the development and deployment of electric vehicles (EVs), directly affecting performance, lifespan, and reliability. The PRIDEBAT project addresses this issue by developing an advanced predictive tool for battery degradation under real-world operating conditions. The approach integrates experimental characterisation of $LiFePO_4$ batteries, digital twin modelling of both the vehicle powertrain and battery systems, and the application of artificial intelligence for predictive analytics. Real-world data acquisition is conducted through instrumented EVs operating in urban environments, enabling the creation of high-fidelity models that reflect actual usage patterns. The project also explores the integration of these models into simulation platforms to validate their accuracy and scalability. By combining experimental data with AI-driven modelling, PRIDEBAT aims to deliver a robust framework for predicting battery life, efficiency, and cycling behaviour, ultimately supporting more reliable and sustainable EV deployment.

Keywords: Battery degradation · Electric vehicles · Digital twins

1 Introduction

The transition to electric mobility aims to reduce transportation emissions and dependence on fossil fuels; however, battery performance remains a critical challenge affecting vehicle range, reliability, and cost. A key issue is understanding battery degradation, which has traditionally been studied through controlled laboratory tests. Although such tests provide reproducible results, they fail to capture real-world operating conditions, leading to limited generalisation of degradation models.

In this context, Digital Twins have emerged as a promising solution for representing battery behaviour and enabling predictive maintenance through continuous data integration. Nevertheless, their practical impact depends on effectively bridging the gap between laboratory-based models and real-world operation, ensuring that they deliver tangible benefits beyond theoretical or controlled environments.

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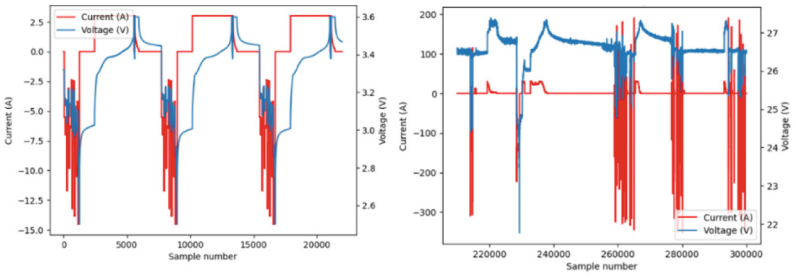
This article presents the methodological approach and conceptual framework of the PRIDEBAT project, conducted in collaboration with the Universidad Pública de Navarra (UPNA), aimed at addressing the prediction of electric vehicle battery degradation and promoting the effective adoption of digital twins in real-world applications.

2 State of the Art

The accurate prediction of State of Health (SOH) and Remaining Useful Life (RUL), as well as the estimation of temporal degradation, are critical research areas for the sustainability of electric vehicles [1, 2]. The literature classifies approaches to these tasks into three main categories: experimental or direct methods (capacity and resistance measurement), physics-based models (electrochemical and equivalent circuit models), and data-driven methods (Machine Learning and Deep Learning) [3, 4]. While physics-based models offer high interpretability of phenomena such as SEI layer growth or loss of lithium inventory, data-driven models have gained significant traction due to their ability to capture highly non-linear relationships without requiring complex governing Equations [5, 6].

However, these methodologies heavily rely on data obtained under controlled laboratory conditions, such as the NASA [7] or CALCE [8] datasets, which limits their generalisation capability [9]. This dependence often leads to overfitting, as laboratory models frequently fail to account for real-world stress factors like extreme temperature fluctuations, partial charging processes, or dynamic driving currents (e.g., WLTC or Artemis cycles) [6]. Recent studies indicate that models trained exclusively on lab data perform suboptimally when confronted with the operational uncertainty and sensor noise typical of real vehicle fleets [10].

As illustrated in Fig. 1, the graphical comparison highlights the clear discrepancies between laboratory-controlled profiles and field data, where the latter exhibit significantly higher variability, noise, and irregular operating patterns, underscoring the challenges in directly transferring laboratory-trained models to real-world applications.



(a) (b)

Fig. 1. Comparison between (a) laboratory data from dataset [11] and (b) vehicle data taken in the field [12]

To bridge this gap, current research emphasizes the identification of robust Health Indicators (HIs) [13]. These are divided into direct HIs (capacity and resistance) and

indirect HIs, which are extracted from measurable variables such as voltage, current, and temperature during short operating periods. Techniques like Incremental Capacity Analysis (ICA) and differential curve analysis have become fundamental non-invasive tools for inferring internal degradation states. Nevertheless, extracting these indicators under dynamic conditions remains a challenge, requiring advanced algorithms such as XGBoost combined with Extended Kalman Filters (EKF) to adaptively correct predictions in real time [14].

In parallel, both industry and academia call for standardized SOH metrics that integrate capacity loss and internal resistance increase to enable comparability across studies [15]. Without clear standards, the practical utility of Digital Twins (DTs) for used vehicle valuation, safety and performance management, or warranty strategies remains limited [2]. Recent advancements propose four-layer DT architectures (Physical, Data & Communication, Virtual Model, and Twin Service) that utilize Cloud-Edge collaboration [16]. In these systems, heavy Deep Learning models (such as LSTM [17] or Transformer networks [18]) run in the cloud, while reduced-order models (ROM) operate on the vehicle to provide immediate diagnostics [16].

In this context, a clear research gap emerges: the effective integration of real-world data, digital twins, and AI models (such as Physics-Informed Neural Networks or PINNs) to predict degradation trajectories at the pack or module level [2]. While most studies focus on controlled validations, there is still a lack of methodological frameworks that robustly connect field experience with scalable predictive models for fleets. Furthermore, data augmentation techniques appear as a promising solution to compensate for the scarcity of labelled real-world data before batteries reach their end-of-life [19]**.** The main contribution of the PRIDEBAT project is to address this gap through a multivariate approach that considers cellular inconsistency, the uncertainty of the vehicle's operating environment, and the uncertainties associated with the virtual model itself, with the ultimate goal of generating a robust Digital Twin.

3 Methodologies and Project Framework

The project is currently in its early stages of development. Therefore, the following section outlines the methodological framework designed to achieve the objectives presented above. This framework combines experimental testing, real-world data acquisition, synthetic data generation, and predictive modelling based on artificial intelligence, with the ultimate goal of developing a digital twin capable of operating under dynamic and heterogeneous real-world conditions.

3.1 Experimental Characterisation

An experimental campaign has been defined to reproduce representative operating conditions of electric vehicle battery systems. The study focuses on $LiFePO_4$ prismatic cells with a nominal capacity of 88 Ah and nominal voltage of 3.2 V.

An initial test campaign will be conducted using eight modules, each consisting of eight cells connected in series. Various charging and discharging protocols will be applied

to these assemblies to evaluate how different factors influence battery degradation. These tests represent a first set of experimental trials that may be expanded in the future.

The experimental campaign is currently being carried out to reproduce representative operating conditions of electric vehicle battery systems. The test matrix considers variations in depth of discharge and actual vehicle loading and unloading patterns, over a predefined number of cycles until reaching a State of Health (SOH) of 80%. Although temperature is a critical factor in battery degradation, it is not explicitly controlled at this preliminary stage, as tests are not conducted in a climatic chamber. Instead, temperature is continuously monitored at cell level and incorporated into the analysis. In future work, the battery stack may be subjected to controlled cycling tests within a climatic chamber to evaluate the influence of environmental conditions, particularly temperature.

Reference load and pulse tests are being performed every 7 days, and rest periods are incorporated to stabilize the battery's internal chemistry. This initial series of tests, conducted on an 8-cell stack connected in series, is generating a first dataset on battery degradation, aimed at identifying and understanding degradation patterns under charging and discharging conditions representative of electric vehicle operation. Data acquisition includes voltage, current, and temperature measurements, recorded at a sampling frequency of 1 Hz.

3.2 Real World Data Acquisition

An electric truck has been fully instrumented to acquire direct data from its battery pack during real-world operation. The collected information includes electrical variables (voltage, current) from the installed sensor, thermal measurements (cell and module temperatures) and operational usage data (driving profiles, charging and braking patterns, acceleration and deceleration cycles) through information from the vehicle's own CAN bus (Fig. 2).



Fig. 2. B008 QEV BUS and the coupled battery sensing system

These data enable an accurate characterisation of the vehicle's physical and dynamic properties, including its electrical and thermal responses under urban traffic conditions. This information will subsequently be used to build a virtual model of the truck within a simulation tool, ensuring that simulated scenarios closely reproduce real operating conditions. In this way, the generated synthetic data can be employed for controlled testing and to train predictive models that behave consistently with the vehicle's performance in dynamic and heterogeneous urban environments.

3.3 Synthetic Data Generation

After collecting real-world vehicle data, synthetic operational data are generated using the DSpace simulation tool, capable of accurately replicating urban environments and predefined routes. DSpace, a hardware-in-the-loop (HIL) and rapid control prototyping platform, allows testing and development of automotive control systems under realistic conditions, simulating complex vehicle dynamics, powertrain behaviour, and battery systems. It is commonly used to validate electric and hybrid vehicle controllers, evaluate energy management strategies, test battery management systems (BMS), and generate synthetic data for model training, reducing the risks and costs of on-road experiments.

The simulation comprehensively models vehicle dynamics, including power demands, acceleration, braking, and charging cycles, in a controlled, configurable, and repeatable way. The generated data feed laboratory tests on battery packs, accurately reproducing the power and charge patterns the vehicle would experience under real operating conditions.

This approach generates a reproducible synthetic power and charge dataset that complements real-world data, preserving vehicle dynamics and enabling systematic analysis of battery degradation. It supports controlled training and validation of predictive SOH and RUL models, providing a foundation for reliable tools transferable to electric vehicle fleets (Fig. 3).

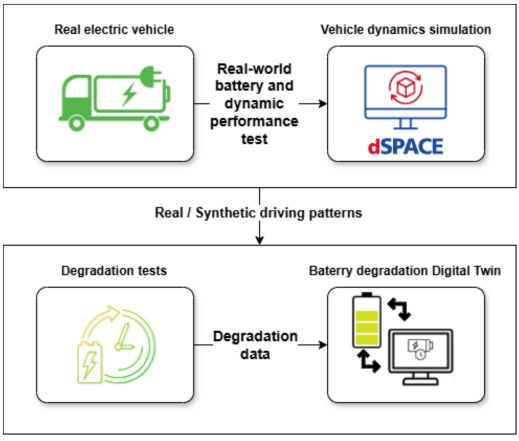


Fig. 3. Workflow for generating and testing with synthetic data

3.4 Digital Twin

Once the dataset is obtained, the next step is to develop a machine learning model capable of processing heterogeneous data sources and providing accurate predictions of battery degradation under real-world operating conditions. The proposed model is designed as a Digital Twin (DT) of the battery, enabling continuous estimation of its State of Health

and Remaining Useful Life. The model's input features include time-series measurements of voltage (V(t)), current (I(t)), and temperature (T(t)), along with derived health indicators (HI) extracted from short operating periods. The model's output consists of the SOH, defined as the ratio of current to nominal capacity, and the RUL, expressed as the number of cycles remaining before reaching the end of its useful life. To capture the temporal dependencies, a recurrent neural network architecture based on layers of Long and Short-Term Memory (LSTM) is considered. The model is trained using supervised learning, where laboratory and synthetic data provide labelled degradation trajectories, while real-world fleet data are incorporated using domain adaptation techniques. The training process includes data normalisation, sequence analysis, and splitting into training, validation, and test sets to ensure generalizability.

Given the inherent uncertainty in battery performance under real-world conditions, the Digital Twin integrates multiple uncertainty management strategies. Model uncertainty, stemming from simplified representations of electrochemical processes, is addressed using Physics-Based Neural Networks (PINNs), which incorporate the physical constraints governing the learning process. Operational uncertainty, caused by stochastic driving patterns and environmental conditions, is modelled using probabilistic approaches that represent degradation trajectories as distributions rather than deterministic outcomes.

Measurement noise, introduced by sensor inaccuracies and communication delays, is mitigated using filtering techniques such as Extended Kalman Filters (EKFs). Inter-cell variability, due to manufacturing inconsistencies, is managed through transfer learning, enabling the adaptation of a global model to individual battery instances. Additionally, synthetic data generated using Generative Adversarial Networks (GANs) are used to supplement the limited degradation data and improve the model's robustness. To address the transition between laboratory and real-world data, online adaptive learning strategies are implemented, allowing the Digital Twin to update its parameters as new field data becomes available. Model performance will be evaluated using standard regression metrics, such as the Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2).

Finally, the proposed framework will be validated by comparing the predictions obtained from laboratory-trained models, models enhanced with synthetic data, and models adapted to real-world conditions. This comparison will allow us to quantify the impact of each data source on the accuracy and robustness of the prediction, providing proof of concept for the integration of heterogeneous data in Digital Twins of batteries.

4 Expected Results and Discussion

Throughout this article, several gaps have been identified in the research on battery pack degradation prediction under real-world operating conditions, which the PRIDEBAT project aims to address. The main expected contributions of the project are:

- Generation of a representative dataset for the development of battery degradation prediction models.
- Development of a synthetic data methodology to reproduce realistic vehicle driving conditions.

- Creation of predictive models combining real and synthetic data for accurate degradation estimation.
- Identification of key Digital Twin applications to enhance battery management and support sustainable electric mobility.

Collectively, these contributions aim to bridge the gap between laboratory models and real-world usage conditions, providing tools to more accurately predict battery degradation and optimize their management in urban environments. Although the PRIDEBAT project is still in its early stages, it is expected that, as development progresses, the generated datasets, methodologies, and models will be made publicly available, thereby contributing to the scientific community and advancing battery degradation prediction tools for real-world applications.

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References

1. Shi, J., Rivera, A., Wu, D.: Battery health management using physics-informed machine learning: online degradation modeling and remaining useful life prediction. Mech. Syst. Signal Process. **179**, 109347 (2022). https://doi.org/10.1016/j.ymssp.2022.109347
2. Wang, Y., Xiao, J., Soo, Y.-Y., Chen, Y., Chen, Z.: Digital twins for battery health prognosis: a comprehensive review of recent advances and challenges. eTransportation. **26**, 100489 (2025). https://doi.org/10.1016/j.etran.2025.100489
3. Li, H. et al.: SOH estimation method for lithium-ion battery packs under real-world operating conditions based on a new attenuated model without additional experiments. Energy. **330**, 136802 (2025). https://doi.org/10.1016/j.energy.2025.136802
4. Li, Q., Xue, W.: A review of feature extraction toward health state estimation of lithium-ion batteries. J. Energy Storage. **112**, 115453 (2025). https://doi.org/10.1016/j.est.2025.115453
5. Qian, C., Xu, B., Xia, Q., Ren, Y., Sun, B., Wang, Z.: SOH prediction for lithium-ion batteries by using historical state and future load information with an AM-seq 2seq model. Appl. Energy. **336**, 120793 (2023). https://doi.org/10.1016/j.apenergy.2023.120793
6. Rufino Júnior, C.A. et al.: Unraveling the degradation mechanisms of lithium-ion batteries. Energies. **17**, 3372 (2024). https://doi.org/10.3390/en17143372
7. Li-ion battery aging datasets - NASA open data portal, https://data.nasa.gov/dataset/li-ion-battery-aging-datasets. Accessed 4 Feb 2026
8. Battery Data: Center for advanced life cycle engineering. https://calce.umd.edu/battery-data. Accessed 25 Mar 2026
9. Li, Y. et al.: A comprehensive review of remaining useful life prediction methods for lithium-ion batteries: models, trends, and engineering applications. J. Energy Chem. **112**, 384–414 (2026). https://doi.org/10.1016/j.jechem.2025.08.056
10. Ji, C., Dai, J., Zhai, C., Wang, J., Tian, Y., Sun, W.: A review on lithium-ion battery Modeling from mechanism-based and data-driven perspectives. PRO. **12**, 1871 (2024). https://doi.org/10.3390/pr12091871
11. Heydarzadeh, M., Toivola, T., Vega-Garita, V., Immonen, E.: Dataset of lithium-ion cell degradation under randomized current profiles for NMC, NCA, and LFP chemistries. Data Brief. **60**, 111531 (2025). https://doi.org/10.1016/j.dib.2025.111531

12. Schaeffer, J., Lenz, E., Gulla, D., Bazant, M., Braatz, R.D., Findeisen, R.: Lithium-ion battery field data: 28 LFP battery systems with 8 cells in series, up to 5 years of operation. https://zenodo.org/records/13715694 (2024). https://doi.org/10.5281/zenodo.13715694
13. Zhou, W., Lu, Q., Zheng, Y.: Review on the selection of health indicator for lithium ion batteries. Machines. **10**, 512 (2022). https://doi.org/10.3390/machines10070512
14. Jafari, S., Byun, Y.-C.: Prediction of the battery state using the digital twin framework based on the battery management system. IEEE Access. **10**, 124685–124696 (2022). https://doi.org/10.1109/ACCESS.2022.3225093
15. Soo, Y.-Y., Wang, Y., Xiang, H., Chen, Z.: Machine learning based battery pack health prediction using real-world data. Energy. **308**, 132856 (2024). https://doi.org/10.1016/j.energy.2024.132856
16. Xie, J., Yang, R., Hui, S.-Y.R., Nguyen, H.D.: Dual digital twin: cloud–edge collaboration with Lyapunov-based incremental learning in EV batteries. Appl. Energy. **355**, 122237 (2024). https://doi.org/10.1016/j.apenergy.2023.122237
17. Li, W., Li, Y., Garg, A., Gao, L.: Enhancing real-time degradation prediction of lithium-ion battery: a digital twin framework with CNN-LSTM-attention model. Energy. **286**, 129681 (2024). https://doi.org/10.1016/j.energy.2023.129681
18. Apribowo, C.H.B., Ashidqi, M.D., Nizam, M., Purwanto, A.: Data-driven modeling of lithium-ion battery degradation using XGBoost with extended Kalman filter-based internal resistance correction. Results Eng. **28**, 108100 (2025). https://doi.org/10.1016/j.rineng.2025.108100
19. Pooyandeh, M., Sohn, I.: Smart lithium-ion battery monitoring in electric vehicles: an AI-empowered digital twin approach. Mathematics. **11**, 4865 (2023). https://doi.org/10.3390/math11234865

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Urban EV Adoption Charging Infrastructure Readiness Level (ECIRL) Index: A Strategic Tool for Policymakers to Assess Public Charging Infrastructure

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Abstract. The electrification and decarbonisation of the transport sector are key responses to escalating environmental and energy challenges, placing increasing emphasis on the development of adequate public charging infrastructure for electric vehicles (EVs). This study presents a methodology to assess the readiness of urban AC Level 2 charging infrastructure based on three core dimensions: density, spatial distribution, and accessibility. A composite indicator, the Urban EV Adoption Charging Infrastructure Readiness Level (ECIRL), is developed using a weighted factor approach to quantify overall performance. The methodology is applied to six European cities, Thessaloniki, Leeds, Oslo, Timişoara, Ljubljana, and Split, revealing significant disparities among them. Oslo ranks highest across all components, while Split and Timişoara show the lowest readiness levels. By evaluating each dimension separately, the framework enables the identification of specific infrastructure gaps and supports the design of targeted, context-sensitive policies to accelerate EV adoption and improve charging network planning.

Keywords: Electromobility · Charging Infrastructure · Urban Planning

1 Introduction

The electrification of transport has accelerated in response to the environmental crisis, driving global efforts toward renewable energy–based mobility. Innovation now spans multiple modes, from electric bicycles to fully electric aircraft, while reshaping the wider mobility ecosystem. New stakeholders—such as power grid operators and charging infrastructure providers—have become integral to urban mobility and closely connected to EV users. By 2023, global EV sales reached 14 million units, representing 18% of total car sales, led by China, the United States, and Europe. Despite this growth, charging infrastructure expansion remains challenging, especially in dense urban areas

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where space constraints, regulatory complexity, and high capital costs hinder deployment. Grid capacity limits and peak demand pressures add further planning challenges. These barriers underscore the need for robust assessment tools to help policymakers evaluate infrastructure readiness and support sustainable expansion strategies.

2 Literature Review

Effective planning and assessment of charging infrastructure are essential for policymakers and urban planners, as well-designed networks enhance EV acceptance. This requires comprehensive yet standardized evaluation methods for urban environments.

Although several assessment tools exist [1–3], they often rely on complex and data-intensive approaches that are difficult for public authorities to implement. The literature consistently highlights two key dimensions: availability and accessibility [4, 5]. Availability is typically measured through the presence and spatial distribution of charging stations, providing a clear quantitative indicator [6, 7]. Accessibility, closely linked to availability, varies conceptually but in transport studies is commonly framed through origin–destination relationships and social inclusion perspectives [8–10]. In this context, accessibility reflects the ease of reaching charging infrastructure from key activity centres and vice versa.

3 Methodology

The proposed Urban EV Adoption Charging Infrastructure Readiness Level (ECIRL) index provides a standardized indicator for the EV charging infrastructure within urban areas, by dividing them into small hexagonal regions for better assessment. The ECIRL index breaks down the analysis into three metrics: density, distribution, and accessibility, allowing stakeholders to assess both the overall readiness of the infrastructure and identify specific areas for improvement.

Density analysis provides a systematic approach to assess the availability of charging stations within a given geographic area. To evaluate density, a straightforward method is applied: the total number of charging stations in the metropolitan area is divided by its total inhabited geographic area. Then, a scoring system categorizes charging station density into distinct levels, assigning scores based on the ideal number of charging stations per square kilometer.

Urban areas are classified according to OECD [11] into large metropolitan, metropolitan, medium-sized, and small-sized cities. Certain thresholds were defined using quantitative analysis of the minimum and maximum number of charging stations per square meter, varying according to the city's size. Then a score is assigned as represented in the following Table 1:

The threshold ranges were defined based on the empirical distribution of charging station densities, grouping values into low, medium, and high categories for each city-size class. The scores for the urban areas are divided by the maximum possible score (10) to obtain a normalized density score between 0 and 1.

Table 1. Number of charging stations per km2 and corresponding scores for different city sizes

	Large Metropolitan City	Metropolitan City	Small Medium Size City	Score
Range				
A	≥ 7	≥ 6	≥ 4	10
B	$5 \leq x < 7$	$4.5 \leq x < 6$	$3 \leq x < 4$	9
C	$3 \leq x < 5$	$3 \leq x < 4.5$	$2 \leq x < 3$	8
D	$2 \leq x < 3$	$1.5 \leq x < 3$	$1 \leq x < 2$	7
E	$1 \leq x < 2$	$0.5 \leq x < 1.5$	$0.25 \leq x < 1$	5
F	< 1	< 0.5	< 0.25	2

3.1 Distribution Analysis

The distribution analysis is related to the concept of availability, as it assesses the allocation of charging stations among urban areas relative to population density. This is achieved by creating small hexagonal grids with a radius of 400 m using GIS soft-ware. The Population Ratio (PRi) is introduced and serves as a foundational metric for normalizing the distribution of charging stations in relation to population density and is calculated by dividing each hexagon area (HAi) over the population of the Examined Area (EA) (1).

$$PRi = (Population\ of\ HAi)/(Total\ Population\ of\ EA) \tag{1}$$

Later, another metric is used, the Quantity Ratio (QRi) (2), which focuses on the charging stations.

$$QRi = (Stations\ within\ the\ HAi)/(Total\ stations\ within\ the\ EA) \tag{2}$$

Another metric used is the Adjusted Quantity Ratio (AQRi) (3) which establishes a relation between the previous metrics, offering an analysis of how charging infrastructures are distributed relative to the population.

$$AQRi = (QRi)/(PRi) \tag{3}$$

The last metric of this part of the methodology is the Adjusted Probability APi (4), which indicates the probability of encountering a charging station within an HA:

$$APi = (AQRi)/\left(\sum(i = 1)AQRi\right) \tag{4}$$

To capture the level of distribution, the Shannon entropy is introduced as an efficient indicator of the uncertainty in finding a charging station [12], especially since it has been widely utilized in urban transport studies to assess data distribution [13, 14]. In this context, the metric is defined as Charging Infrastructure Entropy (CE) (5).

$$CE = _\sum(i = 1)APi \ln APi \tag{5}$$

To ensure that CE remains a finite and bounded number between 0 and 1, the maximum CEmax is defined based on the scenario of equal distribution within administrative regions. In other words, an HA has an equal probability of finding a charging station within its boundaries taking into consideration the population density.

$$UniAPi = (1)/(Total\ number\ of\ AR) \tag{6}$$

CE values close to 0 indicate low entropy and high predictability in the spatial distribution of charging stations, meaning they are mainly concentrated in dense areas. Conversely, values approaching 1 reflect greater randomness and uncertainty in infrastructure availability (7). For Areas of Reference (ARs) without stations, a near-zero probability is assigned for CE calculation (8). The resulting distribution index, DisS (Distribution Score), is computed using Eq. (9).

$$CE\max = _\sum(i = 1)UniAPi \ln UniAPi \tag{7}$$

$$CEnorm = (CE)/(CEmax) \tag{8}$$

$$DisS = (1) - CEnorm \tag{9}$$

3.2 Accessibility Analysis

The accessibility across the EA is assessed by using a scoring system based on walking distances considered under normal traffic conditions, ensuring that the score reflects typical commuting scenarios and provides a baseline for quantifying accessibility levels. Key points and population data for each Hexagon Area (HA) were derived from Overpass Turbo linked to the OpenStreetMap database. Central urban functions, including commercial areas, transport hubs, schools, healthcare facilities, recreational spaces, and government institutions, were mapped to assess proximity to essential ser-vices and evaluate spatial and social equity in urban environments [15]. Heat maps were produced in QGIS and HAs were classified using the natural breaks method (six classes). Each area received 0–5 points per category, and total significance scores were calculated by summing across categories. HAs scoring below 5 were excluded from further accessibility analysis.

Walking distance was incorporated as a key accessibility parameter, as willingness to walk decreases with increasing perceived distance, while overall travel time significantly shapes this perception [16]. Empirical evidence from Munich indicates that distances up to 800 m are generally acceptable, particularly in well-designed urban settings [17]. Based on these findings, a five-level scoring system was developed to represent varying accessibility ranges according to city size. The scores are presented in Table 2.

Accessibility scores are adjusted to reflect the availability of AC Type 2 chargers, given that most EVs are compatible with these outlets. A score reduction is applied to each HA based on the share of Type 2 chargers relative to the total number of chargers. Four percentage ranges (0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8) correspond to score reductions of 10, 8, 6, and 4 points, respectively.

Table 2. Walking distance ranges from a key central point to nearby charging stations and corresponding points for different city sizes

Range	Large Metropolitan City	Metropolitan City	Small Medium Size City	Score
A	< 150	< 150	< 150	10
B	$150 \leq x < 300$	$150 \leq x < 300$	$150 \leq x < 300$	7
C	$300 \leq x < 500$	$300 \leq x < 500$	$300 \leq x < 500$	5
D	$500 \leq x < 800$	$500 \leq x < 700$	$500 \leq x < 650$	3
E	< 800	< 700	< 650	2

Total points for each HA are calculated by aggregating the scores of all charging stations within the defined maximum radius. Based on accumulated points, HAs are classified into five categories—Very Low to Very High—corresponding to scores of 2, 4, 6, 8, and 10. The thresholds are determined using the minimum and maximum observed values across all HAs.

Overall accessibility at the EA level is derived by averaging HA scores and normalizing the result by the maximum possible score (10), yielding a value between 0 and 1.

3.3 Charging Infrastructure Readiness Level (ECIRL)

To obtain the overall charging infrastructure index for the selected area, a weighted aggregation method that integrates density, distribution and accessibility scores are used. The weights Wden, Wdis, and Wa represent the relative importance assigned to the Density Score (DenS), Distribution Score (DisS), and Accessibility Score (AS), respectively, in determining the overall combined index (10). This makes DisS a practical proxy for spatial equity in infrastructure provision, complementing the purely quantitative density measure.

$$ECIRL = WdenDenS + WdisDisS + WaAS \tag{10}$$

4 Application

In this section, the applicability of the charging infrastructure index methodology is examined through three metropolitan cities (Thessaloniki in Greece, Leeds in the UK and Oslo in Norway), two medium-sized urban cities (Timişoara in Romania and Ljubljana in Slovenia), and one small urban city (Split in Croatia), each representing distinct contexts and stages of EV adoption. Figure 1 illustrates the population heat map and locations of charging stations.

The analysis of the provided data reveals differences in the charging infrastructure metrics for six use cases, Oslo scored highest across all dimensions, while Thessaloniki excelled only in distribution. Leeds showed moderate density but weak accessibility.

Among smaller cities, Ljubljana had strong distribution but poor density, whereas Split and Timişoara performed worst overall. Table 3 provides the analytical and total scores for each use case.

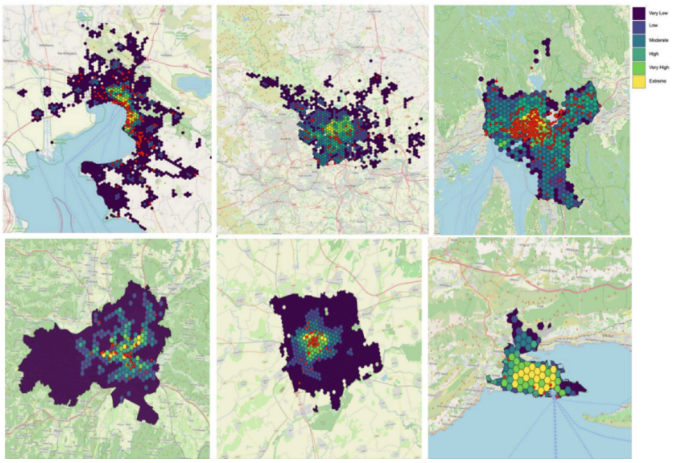


Fig. 1. First row: heat map population and charging stations in (from left to right) Thessaloniki, Leeds and Oslo. Second row: heat map population and charging stations in (from left to right) Ljubljana, Timisoara, and Split.

Table 3. Walking distance ranges from a key central point to nearby charging stations and corresponding points for different city sizes

Use Case	Density Score (DenS)	Distribution Score (DisS)	Accessibility Score (AS)	ECIRL
Thessaloniki, Greece	0.2	0.86	0.45	0.56
Leeds, UK	0.5	0.65	0.31	0.48
Oslo, Norway	1.0	0.74	0.79	0.83
Ljubljana, Slovenia	0.2	1.00	0.42	0.53
Timisoara, Romania	0.2	0.63	0.22	0.35
Split, Croatia	0.2	0.66	0.30	0.38

5 Conclusions and Future Research

This study introduces the ECIRL Index as a strategic tool for evaluating EV charging infrastructure readiness in urban areas. By integrating density, distribution, and accessibility metrics, the index provides a comprehensive and comparable assessment framework. Application across case studies reveals significant disparities, identifying specific gaps and priorities for improvement. The weights Wden, Wdis, and Wa were as-signed based on the author's expert judgement, drawing on practical experience in urban planning, transport modelling, and electromobility. The ECIRL supports policy-makers and urban planners with a clear, data-driven basis for targeted infrastructure development, facilitating a more efficient transition to electric mobility. Future research could expand the framework to additional cities, will incorporate further factors, such as infrastructure quality and traffic impacts on accessibility and will strengthen the ECIRL index through systematic sensitivity analysis and a more stakeholder-informed weighting process.

References

1. Zhang, L., Zhao, Z., Yang, M., Li, S.: A multi-criteria decision method for performance evaluation of public charging service quality. Energy. **196**, 117130 (2020)
2. Berger, R.: EV charging index 2024: EV growth slows as attention turns to infrastructure. https://www.rolandberger.com/en/Insights/Publications/EV-Charging-Index-2024-EV-growth-slows-as-attention-turns-to-infrastructure.html (2024). Accessed 20 Mar 2026
3. P3 Group: P3 charging index. https://www.p3-group.com/en/p3-charging-index/ (2024). Accessed 20 Mar 2026
4. Alanazi, F., Talal, O.A., Abdelhalim, A.: Optimal charging station placement and scheduling for electric vehicles in smart cities. Sustainability. **15**(22), 15831 (2023)
5. Singh, P., et al.: Electric vehicles charging infrastructure demand and deployment: challenges and solutions. Energies. **16**(7), 3232 (2022)
6. Hecht, C., Figgener, J., Sauer, D.U.: Predicting electric vehicle charging station availability using ensemble machine learning. Energies. (2021)
7. Bikcora, C., Refa, N., Verheijen, L., Weiland, S.: Prediction of availability and charging rate at charging stations for electric vehicles. In: Proceedings, Beijing, China (2016)
8. Carlton, G., Sultana, S.: Transport equity considerations in electric vehicle charging re-search: a scoping review. Transp. Rev. **43**, 330–355 (2022)
9. Gazmeh, H., Guo, Y., Qian, X.: Understanding the opportunity-centric accessibility for public charging infrastructure. Transp. Res. D: Transp. Environ. **131**, 104222 (2024)
10. Persson, H., Åhman, H., Yngling, A., Gulliksen, J.: Universal design, inclusive design, accessible design, design for all: different concepts—one goal? Univ. Access Inf. Soc., 505–526 (2015)
11. OECD: Cities in the world: a new perspective on urbanisation. OECD Publishing (2020)
12. Cincotta, P.M., Giordano, C.M., Silva, R.A., Beaugé, C.: The Shannon entropy: an efficient indicator of dynamical stability. Phys. D: Nonlinear Phenom. (2020)
13. Poliziani, C., et al.: Modeling cyclist behavior using entropy and GPS data. Int. J. Sustain. Transp. **17**(6), 639–648 (2022)
14. Arellano-Valle, R., Contreras-Reyes, J., Genton, M.: Shannon entropy and mutual information for multivariate skew-elliptical distributions. Scand. J. Stat. **40**(1), 42–62 (2023)
15. Fotini, M.: A new anthropocentric approach in accessibility analysis: the activity space and the accessibility measures. Transport. Res. Procedia. **24**, 491–498 (2017)

16. Hatamzadeh, Y.: Do people desire to walk more in commuting to work? Transport. Res. Rec. **2673**(7), 351–361 (2019)
17. Sarker, R.I., Mailer, M., Sikder, S.K.: Walking to a public transport station: Empirical evidence on willingness and acceptance in Munich, Germany (2020)

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Interactive Comparators – Life-Cycle Assessment of Greenhouse Gas Emissions from Passenger Cars and Heavy-Duty Vehicles

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Abstract. This paper summarises detailed studies across various powertrain technology and energy options to create two interactive life-cycle assessment comparator tools for passenger cars and heavy-duty vehicles. This enables a comparison of the CO_2 emission intensity of various transport technology pathways to determine the best decarbonisation options for a range of vehicle categories and use cases. Understanding the merits of each solution from a life-cycle perspective for a given use case is difficult, hence these comparators aim to improve this understanding and assist in decision-making. The tools combine a wide range of parameters to compare specific options of transportation pathways:

- Powertrains and their efficiencies: ICEV; HEV; PHEV; FCEV; BEV and CEV.
- Energy carriers: Diesel or diesel-like renewable fuels, Gasoline or gasoline-like renewable fuels, gaseous fuels, hydrogen, and electricity (with variations in carbon intensity).
- Vehicle categories: D-segment passenger car, long-haul truck (Class 5), delivery truck (Class 2), city bus, coach, and refuse truck.
- Sensitivities around battery, fuel cell capacity and hydrogen tank production emissions.
- Number of battery packs used.
- Use cases (payload, trip profile, charging frequency).

All of this provides the user with a comprehensive yet simple tool, based on sound scientific studies, to make direct comparisons on a free-to-use platform via the Concawe website.

Keywords: Life-Cycle Assessment · Renewable Fuels · Passenger Cars · Heavy-Duty Vehicles · CO_2 emissions

1 Introduction

From a climate perspective, the impact depends on total greenhouse gas emissions, not the phase at which they occur. A life cycle assessment considers GHG emissions during the production of the vehicle, the infrastructure, the energy carrier, and emissions at the tailpipe. This approach considers GHG emissions for each kilometre travelled, providing the real climate impact of each technology and fuel combination. A Tank-to-Wheel

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(TTW) approach is much easier to measure and regulate as it only measures the physical emissions at the tailpipe, but in many cases, this is not the whole picture. Expanding this to cover the full life-cycle requires consideration of the electricity production/energy carrier production (Well-to-Tank), manufacture of the vehicle, infrastructure and recycling. The challenge with this evaluation is that it involves some assumptions, different scenarios and various use cases. Concawe commissioned IFPEN to develop two interactive comparator tools that allow users to visualise carbon intensity of different pathways for passenger cars and heavy-duty transport. The underlying LCA methodology and datasets used in these tools are documented in the following studies: The passenger car comparator is based on a study undertaken by Concawe on the evaluation of Plug-in Hybrid Vehicles (PHEVs) in real-world conditions [1]. A combination of vehicle testing and vehicle simulation modelling provided the basis for the vehicle use-phase emissions. A detailed Well-to-Wheels study on future automotive fuels and powertrains provided much of the data for the fuels available in the comparators [2], together with a further study on e-fuels [3]. Finally, a life-cycle assessment study on heavy-duty vehicles [4] was commissioned. The interactive comparators bring the results of these scientific studies together to provide a platform where LCA results from a wide variety of powertrain and energy carrier combinations can be visualised.

2 Overview of the Comparator Functionality and Methodology

For the passenger car CO_2 comparator, the user is presented with a dashboard divided into a results panel on the left-hand side and a configuration panel on the right-hand side. When the various configurations are selected, the results panel is updated immediately to display the CO_2 emissions of the selected vehicle and fuel combinations (Fig. 1).

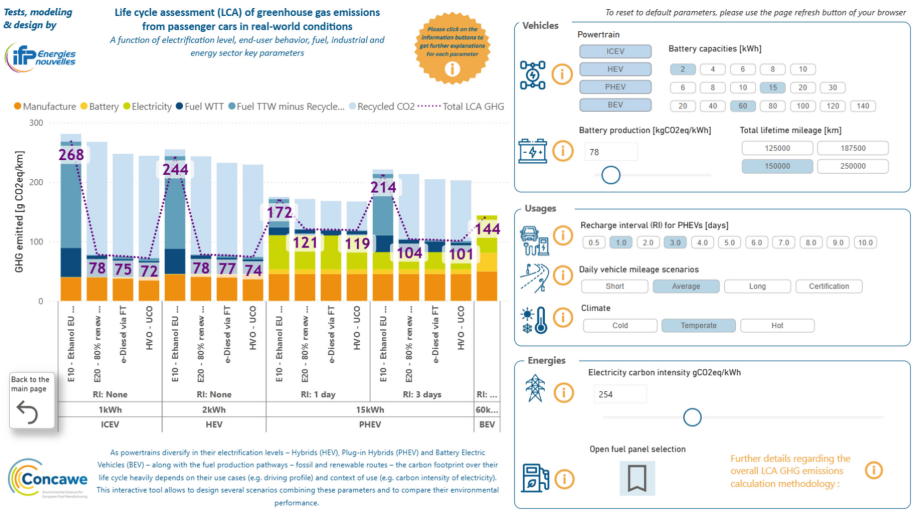


Fig. 1. Dashboard view the Concawe passenger car CO_2 comparator

Results are presented as a bar chart which sum the CO_2 emissions from vehicle manufacture, battery manufacture, electricity used in charging, fuel Well-to-Tank (WTT), fuel Tank-to-Wheel (TTW) and the credit from any recycled CO_2 in the fuel production. All results are based on a D-segment passenger car. (e.g.: Mercedes-Benz C-class)

The basis of the passenger car comparator focussed on the complex task of assessing the real-world energetic performance and emissions of PHEVs. This technology pairs thermal and electric propulsion, making results sensitive to their usage while driving (e.g. trip distance) and before driving (e.g. recharging behaviour). Two Euro 6d PHEVs were selected to allow a back-to-back comparison between petrol and diesel internal combustion engines with real vehicle tests. These experimental measurements allowed the calibration of energy simulation models for both vehicles, using Simcenter Amesim™ software and its IFP-Drive library to determine the results, and to expand the comparator to include the other powertrains for similar size vehicles. The ICEV baseline was more recently added in an update based on the same simulation.

In the vehicle configuration panel, four powertrain options can be selected, with a range of battery capacities for the electrified powertrains:

- ICEV = internal combustion-engine vehicle
- HEV = hybrid electric vehicle
- PHEV = plug-in hybrid electric vehicle
- BEV = battery electric vehicle

An information icon next to each configuration provides an explanation of the options as well as the scientific source of any data used. Sensitivities are offered to the user to input based on the use case the user wishes to compare. The CO_2 emissions from battery production uses a default value of 78 $kgCO_2eq/kWh$ based on a LCA model for battery cell production for various chemistries, production regions and time frames [5]. The user can however change this based on the specific battery desired. The total lifetime mileage can also be selected as a key vehicle parameter.

The usage configuration panel provides selection of the recharge interval for PHEV vehicles. This is a critical user behaviour sensitivity and it is useful to be able to select more than 1 case for direct comparison of this effect. No utility factor is assumed, but rather the user behaviour can be simulated by inputting the distance travelled and recharge intervals, showing the effectiveness of the technology if used correctly. This, in combination with the battery capacity will determine the utility factor. For example, a gasoline PHEV with a 15kWh battery capacity recharged every day has an average utility factor of 77%. A gasoline PHEV with a 5kWh battery capacity recharged every 5 days has an average utility factor of 28% [6].

For a given charging period, the daily distance travelled by a PHEV affects its behaviour, particular to what extent it operates using electrical or fuel energy. The user can select four daily vehicle mileage scenarios where short is under 5 km daily and long is over 100 km daily. The scenario labelled ‘certification’ uses the WLTP drive cycle.

Climatic conditions affect battery performance and energy required for cabin conditioning; hence three climate options are provided in the model.

The energies configuration completes the comparison. Electricity carbon intensity varies significantly depending on how the electricity used to charge the vehicle is produced. In Europe, each country has a difference electricity mix and these values may

change over time, making it necessary to allow the user to input a specific value here. A European 2024 average default value of 254kgCO_2eq/kWh is sourced from the ElectricityMaps service which was adopted as a new reference source for both comparators. This platform provides carbon intensity data for European countries from grid operators, adhering to robust LCA methodology. Specific values for each country in Europe are provided on the information icon to guide the user [7].

The fuel selection panel offers many diesel-like and gasoline-like fuel options ranging from currently available fuels to various renewable fuels [2]. This makes for a very interesting comparison, as depending on the production process the total GHG emissions can vary significantly. E-fuels are also included in the comparator [3]. The renewable fuel options are an integral part of the studies and will be discussed further.

Due to the success of the cars CO_2 comparator, a similar approach was used to build a comparator for heavy-duty vehicles [4]. In this case, vehicle energy consumption and emissions were based on vehicle simulations. These were developed using Simcenter Amesim™ sketches. First, the simulations were calibrated using the VECTO tool [8] on the 'mainstream' ICEV configurations. This tool, mandated by the European Commission, is designed to simulate and calculate CO_2 emissions and fuel consumption of HDVs. This showed a good fit, with a less than 2% difference in fuel consumption on typical driving cycles. The simulations were then expanded to alternative powertrains (HEV, PHEV, FCEV, BEV). The vehicle configurations (powertrain characteristics, weight, efficiencies, battery capacity, etc.) and their conditions of use (driving cycles, payload) were selected based on a literature review of existing vehicles. The simulation results (energy consumption) were cross-checked with data found in the literature and showed a fairly good consistency considering that the driving cycles used in the literature may vary and are not always described.

The HDV CO_2 comparator dashboard is designed in the same way the cars version. The user is however first offered a choice of 5 vehicle types:

- Long haul truck – Class 5
- Delivery truck – Class 2
- City bus
- Inter-regional coach
- Refuse truck

Once selected, the dashboard appears based on the vehicle type and the configuration is tailored to the heavy-duty vehicle type considered. Each vehicle type is modelled in six powertrain options which can be selected.

- ICEV = internal combustion-engine vehicle
- HEV = hybrid electric vehicle
- PHEV = plug-in hybrid electric vehicle
- FCEV = fuel cell electric vehicle
- BEV = battery electric vehicle
- CEV = catenary electric vehicle

The technical details of the powertrains modelled are given in the corresponding information icon. Once selected the GHG results appear as a bar chart in the results panel, as shown in Fig. 2 for the case of the long-haul truck:

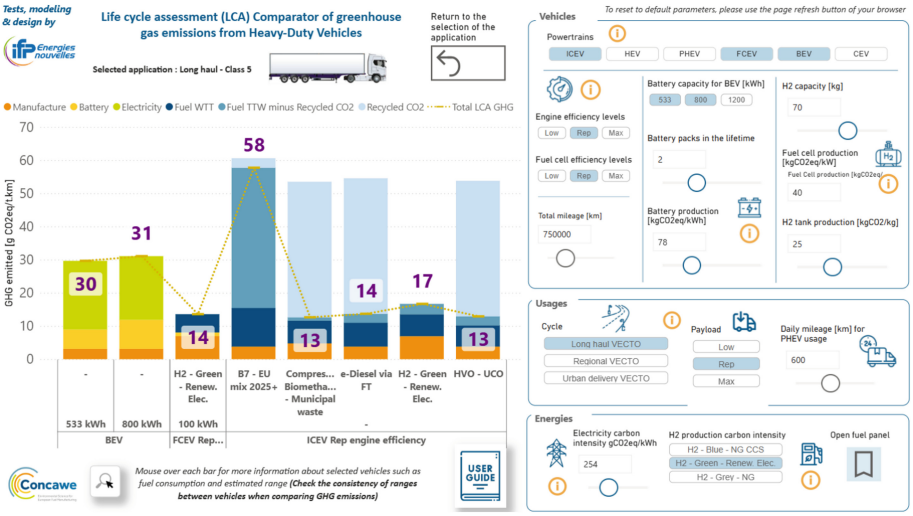


Fig. 2. Dashboard view the Concawe HDV CO_2 comparator

Engine and fuel cell efficiency levels can be selected, with data sourced either from the IFPEN engine database or the generic engine database within the EU VECTO tool [8] The default setting is 'Representative' which corresponds to the efficiencies in the powertrain technical details. For diesel, gas and H_2 engines, 'Low' and 'Max' correspond to peak efficiencies of 40% and 50%, respectively. For the fuel cell, 'Low' and 'Max' correspond to peak efficiencies of 55% and 70%, respectively.

The user can select the total mileage in the lifetime of the vehicle, and for the case of BEV powertrains, three battery capacity options are offered. The effect of replacing battery packs is taken account by entering the number of packs. Battery production emissions can be selected by the user, with the default value and source data as per the cars comparator.

For the fuel cell and H_2 tank production, a power of 225 W/cell was considered. The fuel cell modelling is based on a number of studies as detailed under the information icon, which lead to an estimated emission factor of 40kgCO_2eq/kW_fuel_cell for the fuel cell as a whole, which is set as a default value for the corresponding input field.

The H_2 capacity can be inserted by the user. This parameter has an impact on the vehicle's estimated range (visible by hovering the mouse over the results bar chart). It also has an impact on the emissions associated with the carbon fibre tank, whose emission factor can also be modified using a slider.

Under the Usage configuration a drive cycle can be selected, tailored as appropriate to each vehicle category with cycles coming from the VECTO tool database. For example, for the refuse truck, a specific cycle including driving displacement and power take-off (PTO) work called 'Municipal Utility PTO' is considered. This cycle is an urban driving cycle with several standstill phases using a PTO cycle consistent with a refuse collecting phase. Variations in payload are considered for the vehicle from low to maximum payload. Payload is the weight of goods transported for the trucks. For the busses,

it corresponds to the number of passengers. Maximum payload is adjusted to stay within the maximum vehicle weight according to the vehicle type. 'Low' and 'representative' payloads are taken from the VECTO definitions.

For PHEV consumption, the 'utility factor' is defined as the ratio between the all-electric range and the vehicle's daily distance (which can be directly selected by the user), assuming that drivers will recharge their PHEV every night between two driving days.

In the Energies configuration, the electricity carbon intensity is as per the cars comparator [7]. The fuels panel offers many diesel-like and CNG-like fuels that can be selected. Where hydrogen is considered, the user can choose between three different hydrogen production sources:

- H_2-blue (natural gas reforming coupled with carbon capture and storage (CCS))
- H_2-green (electrolysis using renewable electricity)
- H_2-grey (natural gas/methane reforming with no CCS)

3 Life-Cycle Assessment

The GHG emission factors used in the simulators are determined from three categories: fuel emission factors; carbon intensity of the electricity mix; and emission factors associated with vehicle production and recycling (for chassis, tyres and battery). These emission factors were obtained using LCA methodology performed in accordance with ISO14040 and ISO14044 standards. The functional unit for cars is gCO_2eq/km, and for HDV is $gCO_2eq/t.km$, where 't' refers to the payload.

The combustion of fuel generates GHG emissions. However, to assess the life-cycle impact of fuel use, it is also necessary to consider the production and supply phases of the fuel. Therefore, fuel emission factors are generally subdivided in two categories: Well-to-Tank (WTT) for the production and supply phases, and Tank-to-Wheel (TTW) for the use phase. The sum of these contributions is the emission factor of the fuel over its entire life cycle, and is usually denoted as Well-to-Wheel (WTW).

For some fuels, such as biofuels or e-fuels, CO_2 is captured from the atmosphere to produce the fuel. This CO_2 consumption is either absorbed by the plants grown for the biomass used to produce the fuel, or captured directedly from the air (direct air capture, or DAC) or taken from industrial flue gas stacks which would otherwise emit the CO_2 to the atmosphere. This means that some credit (called recycled CO_2) can be applied to the emission factors of these fuels. For example, for biofuels this would be the CO_2 captured by biomass from the air when it grows, or for e-fuels the CO_2 captured from the air via DAC.

Fuel blends are also considered, for example petroleum diesel blended with biodiesel in B7 or B30. Emission factors of such blends can be calculated from the known composition. The results of the fuel emission factors for the diesel-like and gasoline-like fuels are shown in Fig. 3:

The WTT scope considered for petroleum-based fuels and biofuels [2] refers to the production, transport, manufacture and distribution of the fuels. For e-fuels (green H_2, e-diesel, e-methane), the emission scope is extended with upstream emissions from infrastructure needed to produce them (mainly solar panels and wind turbines) [3]. It was

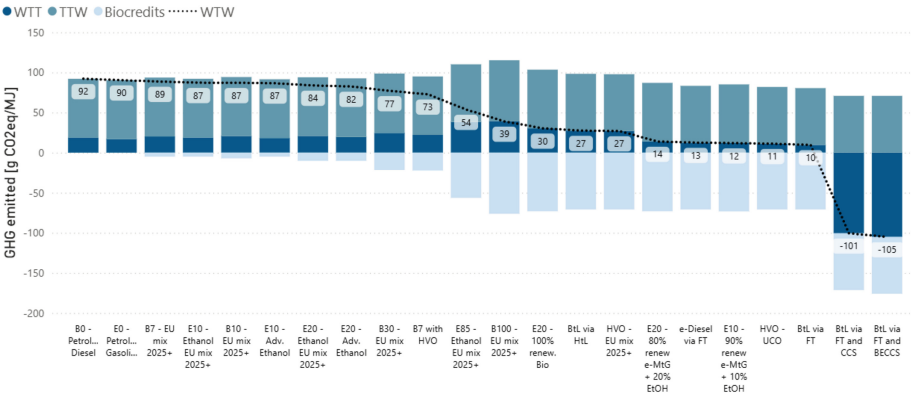


Fig. 3. Fuel emission factors for the diesel-like and gasoline-like fuels

observed that infrastructure requirements (per unit of energy produced) are significantly higher for e-fuels than for petroleum fuels and biofuels, and could not reasonably be neglected for e-fuels.

The TTW scope covers the combustion process within the engine that converts fuel energy into CO_2 emissions. N_2O and CH_4 were added to the total TTW part of the GHG results. For example, the contribution of N_2O and CH_4 in terms of CO_2-equivalent emissions represents around 6.6% of CO_2 exhaust emissions for diesel fuelled-trucks [9] and 2.5% of CO_2 exhaust emissions for CNG fuelled-trucks [10]. For ICE-H_2 fuelled-trucks, it is assumed that the after-treatment system and the N_2O emissions are the same as for diesel-fuelled trucks.

The GHG emission factors of the various vehicle components: chassis, tyres, battery, fuel cell, electric motor, ICE and tanks are also considered and are built into the comparators. These emission factors were recently updated using the PREMISE framework [11], which draws on Ecoinvent v3.9.0 data. PREMISE integrates detailed life cycle inventories for European material production, energy use, and electricity mix. It models the production of vehicle components assuming European manufacturing conditions, also including end-of-life (EOL) phases.

The exact values used for the calculation parameters in an LCA can be contentious, but in these comparators, this is dealt with by allowing user inputs for all critical parameters, which makes them unbiased and a very useful tool for sensitivity analysis.

4 Conclusion

The interactive CO_2 comparators developed from these studies are powerful tools providing valuable insights into life-cycle emissions of different vehicle technology choices. A life-cycle assessment is the most scientifically sound way to assess the real climate impact of various transport technologies. In many cases, low carbon fuels can emit lower life-cycle GHG emissions than battery electric counterparts, depending on the use case and electricity source.

The detailed study on PHEV performance highlights the optimisation characteristics of this technology. It also shows that in a battery constrained market, the use of PHEV vehicles would better deploy battery resources to achieve climate goals faster.

The use of these LCA comparators show that the optimal options for decarbonisation are highly dependent on the use case considered. The best technology and energy options may differ according to the use case, highlighting the importance of technology neutrality when selecting the best options for decarbonisation.

References

1. Concawe: Evaluation of plug-in hybrid vehicles in real-world conditions. Concawe Report 10/22 (2022)
2. Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R.: JEC Well-to-Wheels Report v5, EUR 30284 EN. publications office of the european union, luxembourg., ISBN 978-92-76-20109-0, JRC121213 (2020). https://doi.org/10.2760/100379
3. Concawe: E-Fuels: a techno-economic assessment of European domestic production and imports towards 2050. Concawe Report 17/22 (2022)
4. Concawe: A life-cycle assessment tool for heavy-duty vehicles. Concawe Report 3/24 (2024)
5. Xu, C., Steubing, B., Hu, M., Harpprecht, C., van der Meide, M., Tukker, A.: Future greenhouse gas emissions of automotive lithium-ion battery cell production. Resour. Conserv. Recycl. **187**, 106606. ISSN 0921-3449 (2022). https://doi.org/10.1016/j.resconrec.2022.106606
6. Shafiei, E., Dauphin, R., Yugo, M.: Optimal electrification level of passenger cars in Europe in a battery-constrained future. Transp. Res. D: Transp. Environ. **102**, 103132., ISSN 1361-9209 (2022). https://doi.org/10.1016/j.trd.2021.103132
7. ElectricityMaps: Electricity carbon intensity data for European countries. https://electricitymaps.com. Accessed 16 Dec 2024
8. European Commission: Vehicle energy consumption calculation tool - VECTO (2019). https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissionsvehicles/vehicle-energy-consumption-calculation-tool-vecto_en
9. ICCT: A comparison of the life-cycle greenhouse gas emissions of European heavy-duty vehicles and fuels. international council on clean transportation, white paper (2023). https://theicct.org/wp-content/uploads/2023/02/Lifecycle-assessment-EU HDVs_final2.pdf
10. Concawe: Three-way catalyst performance using natural gas with two different sulphur levels. Concawe report 6/20 (2020)
11. Sacchi, R., et al.: PRospective EnvironMental impact asSEment (PREMISE): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew. Sust. Energ. Rev. **160**, 112311 (2022)

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The Role of EU Funding Instruments and IPCEIs in Enabling Maritime Decarbonisation

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Abstract. For the EU, decarbonising the maritime industry represents a fundamental test of its capacity to enhance industrial competitiveness in a contested global market. This paper examines the relationship between EU funding mechanisms, industrial policy, and the drive for breakthrough innovation, focusing specifically on the adoption of hydrogen technologies. The analysis charts the EU's current funding architecture, assessing how instruments like Horizon Europe, the Innovation Fund, and the Connecting Europe Facility support different stages of the innovation lifecycle. This paper argues that the Important Projects of Common European Interest function as unique, ecosystem-building tools, capable of tackling the systemic market failures in "hard-to-abate" sectors. The strategic construction of the hydrogen value chain through four IPCEI "waves" is examined, with Fincantieri's "Wave 2 the Future" project as an example of this integrated policy's real-world impact on maritime innovation. The paper situates the debate within the EU's strategic evolution from a "Green Deal" to a "Clean Deal" where competitiveness is the central pillar. The vision for a consolidated post-2027 framework, exemplified by the proposed European Competitiveness Fund, aims to rectify current systemic fragmentation. A strategic, streamlined, and market-focused funding ecosystem positions Europe's maritime industry as a leader in the global green transition.

Keywords: Maritime · Hydrogen · Transport · Decarbonization · Alliances

1 Introduction

1.1 The Systemic Challenge of Decarbonisation

The maritime sector facilitates more than 80% of global trade, serving as a fundamental pillar of the world economy and underpinning the prosperity and strategic independence of the European Union [1]. Yet this role comes with a significant environmental cost. Shipping contributes substantially to greenhouse gas (GHG) emissions and, without decisive action, risks undermining the climate neutrality targets set by the Paris Agreement and EU legislation. In response, a broad policy framework has emerged, from the IMO's global net-zero strategy to the EU's European Green Deal and the "Fit for 55" package, including the extension of the EU Emissions Trading System (ETS) to maritime transport [2–4].

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At the same time, recent geopolitical shocks, including the pandemic and the war in Ukraine, have exposed Europe's strategic vulnerabilities and intensified global industrial competition. As a result, EU policy has increasingly linked decarbonisation with industrial competitiveness, technological sovereignty and resilient supply chains. In this context, the decarbonisation of maritime transport has become a key test of Europe's industrial and climate strategy.

1.2 R&D Objectives and Forward-Looking Approach

In the capital-intensive maritime sector, deep decarbonisation relies on breakthrough innovation, which entails significant technological and financial risks. Public policy therefore plays a crucial role in accelerating this transition by combining regulatory signals with funding instruments that de-risk innovation. In this context, ecosystem-building tools such as Important Projects of Common European Interest (IPCEIs) have become central to the EU strategy.

This paper examines how EU funding instruments support maritime decarbonisation and provides recommendations for the post-2027 framework. It first introduces the "Innovation Value Chain" as a conceptual model to map the EU policy toolkit. It then analyses IPCEIs as a key instrument for ecosystem development, focusing on the four hydrogen "waves" and presenting Fincantieri's Wave 2 the Future project as a case study. Finally, the paper outlines policy recommendations for a more integrated funding architecture supporting both decarbonisation and industrial competitiveness in Europe's maritime sector.

2 A Strategic Framework for Innovation Policy

2.1 The Innovation Value Chain Model

To make sense of European innovation policy for a "hard-to-abate" sector like maritime, a robust conceptual framework is needed. Decarbonisation here is a systemic challenge, requiring an orchestrated transition across a network of stakeholders involving new vessel propulsion, port infrastructure, and green fuel supply chains. Clayton Christensen's "S-curve" model helps frame this transition as a shift from a long period of **incremental innovation** to a new, turbulent era of **breakthrough innovation** [5].

This journey from concept to market can be visualized along an "Innovation Value Chain" with distinct, high-risk stages: R&D (TRL 1-4), Demonstration & Piloting (TRL 5-7), and First Commercial Deployment & Scale-up (TRL 8-9). This path contains two major **"*valleys of death*"**, where high technical and commercial risks deter private capital [6]. The systemic nature of maritime decarbonisation amplifies this by creating a powerful coordination failure: shipowners will not invest in new vessels without fuel access, while energy firms will not produce new fuels without guaranteed demand. This deadlock, a classic market failure, can only be broken by a coordinated policy intervention that catalyses investment across the entire value chain at once.

2.2 The EU's Current Toolkit (MFF 2021-2027)

The EU's 2021-2027 Multiannual Financial Framework (MFF) intends to support innovation across this value chain. **Horizon Europe** functions as the primary engine for R&D, shepherding ideas from frontier science to industry-led collaborative research [7, 8]. Further down the chain, the **Connecting Europe Facility (CEF)** targets the deployment of mature, market-ready infrastructure like port upgrades.

However, these instruments are insufficient for large-scale, systemic innovation. This gap is meant to be filled by the **Innovation Fund (IF)** and **Important Projects of Common European Interest (IPCEIs).**

The Innovation Fund, fuelled by EU ETS revenues, is a massive programme aimed at de-risking first-of-a-kind commercial projects by covering their "*green premium*". The maritime sector, included in the ETS only since January 2024, is a newcomer to this funding stream.

While the Innovation Fund supports standalone projects, IPCEIs have a more profound, systemic ambition: to construct entire, cross-border European value chains. They are a unique state aid tool designed to rectify significant market failures by allowing coordinated public support from R&D to first industrial deployment. The maritime sector's engagement is currently limited to a single project, Fincantieri's *Wave 2 the Future*, highlighting the nascent state of this approach in the industry.

2.3 The Evolving Policy Landscape

While comprehensive, the 2021–2027 EU funding toolkit remains fragmented. Multiple programmes and rulebooks create administrative complexity and dilute strategic focus, a weakness in the face of intensifying global competition. This challenge was highlighted by Mario Draghi report on competitiveness in 2024, noting that Europe often disperses public funding across small, uncoordinated initiatives rather than concentrating resources to build European industrial champions.

To address this issue, the European Commission has proposed the **European Competitiveness Fund (ECF)** for the post-2027 framework. The ECF aims to consolidate multiple programmes into a single instrument, simplify procedures through a common rulebook, and strengthen strategic coordination. It would also integrate targeted tools, including top-up support for IPCEI projects. Overall, this reform reflects a shift toward a more assertive industrial policy focused on building competitive European clean-technology value chains.

3 EU Funding in Practice: Maritime Decarbonisation Examples

The instruments outlined in the previous section operate at different stages of the innovation value chain and support correspondingly different types of projects. To illustrate how this architecture translates into practice for maritime decarbonisation, this section examines selected initiatives funded under those instruments before turning into IPCEIs as the most systemic instrument available within the EU industrial policy framework.

Within **Horizon Europe**, projects address pre-commercial research challenges where technical uncertainty remains high. **POSEIDON** investigates the use of synthetic methanol (e-methanol) as a marine fuel, developing a prototype production plant, testing the fuel onboard, and preparing deployment roadmaps for ports [9]. **NAVHYS** tackles the integration of liquid hydrogen storage and fuel distribution systems onboard, transferring cryogenic technologies from the space sector to maritime applications [10]. Both projects exemplify Horizon Europe's role in advancing technologies that are not yet bankable but require cross-border collaboration to reach demonstration stage.

The **Connecting Europe Facility** operates at a fundamentally different level, financing the deployment of mature infrastructure that enables the uptake of low-carbon fuels. Under the **CEF Energy** window, **H2Med** is developing Europe's first large-scale green hydrogen corridor, comprising a pipeline between Portugal and Spain and an undersea pipeline between Barcelona and Marseille. Although not a maritime project per se, the availability of competitively priced green hydrogen at major Mediterranean port hubs is a critical precondition for hydrogen-based marine fuels. Through the **Alternative Fuels Infrastructure Facility** (AFIF), CEF also co-finances port electrification for shore-side power supply, enabling docked vessels to shut down auxiliary engines and draw electricity from the onshore grid, thereby eliminating in-port emissions of SOx, NOx, particulate matter and CO_2 [11].

At the final stage of the value chain, the **Innovation Fund** de-risks first-of-a-kind commercial deployments by covering their green premium. Since the maritime sector's inclusion in the EU ETS in January 2024, the Fund has explicitly targeted shipping decarbonisation. Representative projects include **FirstBio2Shipping**, which demonstrates commercial-scale production of bio-LNG from waste feedstock for marine bunkering [12], and **SustainSea**, which validates wind-assisted propulsion technologies on operating vessels [13]. These initiatives close the gap between demonstration and market viability, proving bankability to attract private investment.

This survey reveals a deliberate division of labour: Horizon Europe matures technologies, CEF builds enabling infrastructure, and the Innovation Fund de-risks early deployment.

4 The IPCEI as a Catalyst for Systemic Change

4.1 IPCEI as a Strategic Industrial Policy Tool

At the heart of Europe's industrial strategy lies IPCEI. Rooted in the TFEU, an IPCEI is a strategic framework allowing Member States to collectively support transnational projects of European importance under more flexible state aid rules. Its purpose is to overcome market failures where technological or financial risks discourage private investment. To qualify, a project must contribute to EU strategic objectives, involve deep R&D, and generate positive *spillover* effects across the Union. The framework is explicitly designed to fund projects that would not otherwise materialize, enabling public support from R&D to first industrial deployment. It is, in essence, a surgical tool for building new, competitive European industrial value chains [14].

4.2 The Four Hydrogen IPCEI "Waves"

The EU's ambition to lead in the hydrogen economy provided the first large-scale testbed for the IPCEI's ecosystem-building power. To address the systemic market failures plaguing the sector, the Commission and Member States orchestrated a strategic intervention through four interconnected "waves", a deliberate effort to construct an integrated European hydrogen value chain [15].

1. **Hy2Tech** (July 2022, €5.4bn): focused on developing core technologies like electrolysers and fuel cells [16].
2. **Hy2Use** (Sept 2022, €5.2bn): targeted the industrial application of hydrogen in hard-to-abate sectors, creating initial demand [17].
3. **Hy2Infra** (Feb 2024, €6.9bn): aimed at building the logistical backbone, including pipelines, storage, and port terminals [18].
4. **Hy2Move** (May 2024, €1.4bn): will support end-use in the mobility sector, including refuelling infrastructure [19].

4.3 The Enabling Impact

The true impact of the hydrogen IPCEIs transcends their funded projects. Their primary function is that of an "ecosystem catalyst". By de-risking investment across the entire value chain simultaneously, they solve the "chicken-and-egg" dilemma and unlock massive private investment. Furthermore, the IPCEI mechanism fosters deep cross-border collaboration, breaking down national silos and encouraging pan-European partnerships. The stringent selection process ensures projects contribute to a coherent European strategy, making the IPCEI a powerful tool for industrial policy, allowing the EU to build sovereign capabilities in critical sectors.

5 IPCEI Case Study: Fincantieri's Wave 2 the Future

5.1 Project Overview and Strategic Context

Fincantieri's *Wave 2 the Future* (W2F) project is a microcosm of the IPCEI logic, representing the sole maritime-focused initiative within the foundational **Hy2Tech** wave [20]. Its inclusion here is significant, framing shipping decarbonisation as a core technological challenge. W2F is an ambitious R&D and industrialisation project aimed at developing the foundational building blocks for zero-emission vessels. Its core objective is to design and validate a multi-megawatt-scale, fuel-flexible power generation platform. The project explores a portfolio of technologies, including Proton Exchange Membrane (PEM) and Solid Oxide (SOFC) fuel cells, and aims to deliver MW-scale fuel cell power platform, able to power a cruise ship's auxiliary services or even propulsion in special and limited conditions, a critical step towards full vessel decarbonisation.

5.2 Practical Outcomes of an Integrated Ecosystem

The significance of the W2F project extends far beyond its direct technological outputs. Being embedded within the Hy2Tech ecosystem, it achieves outcomes unattainable for a

standalone project. First, it **de-risks radical innovation**, providing the financial stability to pursue high-risk research. Second, it **builds a nascent supply chain** by fostering collaboration with a network of European component suppliers, many also part of the hydrogen IPCEI. Third, it **creates positive spillovers**, as the knowledge generated on system integration and safety is mandated to be disseminated throughout the European industry. In essence, W2F acts as a trailblazer, ensuring the path it clears benefits the wider European maritime cluster.

6 The Path Forward

6.1 Lessons Learned from the Past

Our analysis of the EU's current funding landscape yields several critical insights for future policy design. The central message is that while the EU has a powerful suite of tools, their effectiveness can be further enhanced.

First, **fragmentation is an aspect to overcome at times of radical transformation**. Siloed approach forces innovators to navigate a complex bureaucratic maze, diverting resources from innovation to administration.

Second, **scale and speed matter**. Resources need to be focused on high impact initiatives bridging the gap between innovative research and competitive innovation, especially in the global race for clean-tech or digital leadership.

Third, **ecosystem-building is key**. The IPCEI model's success demonstrates that the most effective interventions are those that orchestrate investment across an entire value chain, overcoming the coordination failures that lock in fossil-fuel-based systems. This logic must become a core principle of EU industrial policy.

6.2 A Way Forward

To forge a funding framework fit for the "Clean Deal" era, three principles may drive the long term vision.

1. **Coherence, consolidation and simplification** must drive the research opportunities in the near future. Coherence between instruments, consolidation of results and simplification of procedures to lower barriers for innovators and allow for greater strategic focus.
2. **Strategic, market-creating instruments**. The leadership on R&D must accelerate market gains to boost competitiveness and support the demand for European qualified jobs.
3. **Flexible, portfolio-based approach**. The development of ecosystems is necessary to support a fast transformation. Funding instruments must be flexible, allowing support to be scaled up for technologies that demonstrate commercial promise, ensuring that public money is channelled to the most effective solutions for the maritime sector.

7 Conclusion

The decarbonisation of the maritime sector is a generational challenge for the European Union, but it is equally a profound industrial opportunity. Navigating this transition requires a sophisticated, powerful, and strategically coherent industrial policy. This paper has argued that while the EU possesses a formidable array of funding instruments, our analysis shows that ecosystem-building instruments may address the challenges of hard-to-abate sectors.

The future of European industrial policy, as envisioned in the proposed European Competitiveness Fund, lies in radical simplification, strategic consolidation, and a clear focus on building resilient and globally competitive clean-tech value chains. By strengthening its most effective ecosystem-building tools and creating a simpler, more powerful funding architecture, the EU can effectively bridge the gap between policy, innovation, and infrastructure, securing a future where its maritime industry leads not just in sustainability, but in the global market.

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References

1. Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D.: Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy. **1**, 100008 (2021)
2. International Maritime Organization: 2023 IMO strategy on reduction of GHG emissions from ships. IMO, London (2023)
3. Wang, S., Zhen, L., Psaraftis, H.N., Yan, R.: Implications of the EU's Inclusion of Maritime Transport in the Emissions Trading System for Shipping Companies. Engineering. **7**(5), 554–557 (2021)
4. Kountouris, I., Bramstoft, R., Madsen, T., et al.: A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. Nat. Commun. **5517** (2024)
5. Christensen, C.M.: The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press, Boston (1997)
6. Ellwood, P., Williams, C., Egan, J.: Crossing the valley of death: Five underlying innovation processes. Technovation. **109**, 102162 (2022)
7. González Fernández, S., Kubus, R., Mascareñas Pérez-Iñigo, J.: Innovation Ecosystems in the EU: Policy Evolution and Horizon Europe Proposal Case Study (the Actors' Perspective). Sustainability. **11**(17), 4735 (2019)
8. Larosa, F., et al.: Closing the gap between research and projects in climate change innovation in Europe (2023)
9. CORDIS: POSEIDON — Propulsion of ships with e-methanol in favour of the decarbonisation of naval transport. https://cordis.europa.eu/project/id/101117616 (2026). Accessed 20 Mar 2026
10. CORDIS: NAVHYS — LH2 storage and fuel-system below deck, integrated in a service operating vessel. https://cordis.europa.eu/project/id/101192425 (2026). Accessed 20 Mar 2026

11. European Commission: Alternative fuels infrastructure facility (AFIF) under the connecting Europe Facility. Directorate-General for Mobility and Transport, Brussels (2023)
12. European Commission: Innovation fund project factsheet: FirstBio2Shipping – First Bio-LNG to marine shipping. Brussels (2021)
13. European Commission: Innovation Fund Project Factsheet: SustainSea – Reducing maritime transport CO_2 emissions using wind. Brussels (2023)
14. Lopes-Valença, H.: EU Industrial Policy and Convergent Development in EU Peripheries: An Assessment of the 'Important Project of Common European Interest' (IPCEI) Template. J. Common Mark. Stud. **63**(3), 880–896 (2025)
15. Brusiło, P.: The EU Green Industrial Policy for Hydrogen Economy Development. Econ. 21st Century. **26**, 17–26 (2023)
16. European Commission: Press release: state aid: commission approves up to €5.4 billion of public support by fifteen Member States for an IPCEI in the hydrogen value chain (2022)
17. European Commission: Press release: state aid: commission approves up to €5.2 billion of public support by thirteen Member States for a second IPCEI in the hydrogen value chain (2022)
18. European Commission: Press release: state aid: commission approves up to €6.9 billion of public support by seven Member States for a third IPCEI in the hydrogen value chain (2024)
19. European Commission: Press release: state aid: commission approves up to €1.4 billion of public support by seven Member States for the fourth IPCEI in the hydrogen value chain (2024)
20. Gandiglio, M., Marocco, P.: Mapping hydrogen initiatives in Italy: an overview of funding and projects. Energies. **17**(11), 2614 (2024)

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Benefits Analysis of Battery-Equipped EMU under Catenary Operation

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Abstract. Energy Storage System (ESS) equipped suburban trains are pioneering a new era in sustainable mass transit, offering enhanced energy efficiency and operational robustness. These trains utilize advanced ESS technologies and control to optimize energy consumption. They are also game-changers in mitigating operational disruptions, ensuring reliable service in urban environments where robustness is the key-factor.

Under the Europe's Rail Joint Undertaking (ERJU) framework, in the Rail4Earth project, a comparative study between conventional Electric Multiple Units (EMU) and battery-equipped EMUs is underway. This study is crucial in highlighting the energy savings realized through reduced reliance on mechanical braking and the implementation of "peak shaving" techniques, which reduce the power demand on the catenary by utilizing stored energy at the ESS.

The findings of this comparative study will illustrate the tangible benefits of incorporating energy storage systems in suburban rail transport, showcasing reductions in energy usage and mechanical wear and tear. These innovations are set to transform urban mobility, aligning with broader sustainability goals and contributing to the development of resilient transport networks across Europe.

Keywords: Mass Transit · Energy Storage System · Energy Efficiency · Operational robustness

1 Introduction

The railway sector has been under pressure from the energy crisis and rising prices for the past few years. This context is pushing the railway industry to become more energy efficient and to meet the growing demands for passenger and freight transportation. Additionally, several threats, such as climate change and air quality issues, are urging the railway community to move forward and find new solutions.

In terms of operations, the main challenge is to maintain and improve everyday service robustness. This is particularly difficult in a complex context with high infrastructure

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maintenance costs, the inability to consolidate infrastructure in densely populated urban areas, difficulties in matching investments and costs, delays, and workforce availability.

Recently, major advancements in energy storage technologies, particularly in lithium-ion batteries and hybrid supercapacitors, are supporting the global mobility sector in shifting from fossil fuels to more energy-efficient solutions. This creates an opportunity by integrating a new solution for railway rolling stock with an on-board energy storage system (hybrid system) operating under electrified lines.

Therefore, the European research and development program "Europe's Rail" and one of its flagship projects, "RAIL4EARTH," are studying the potential of this new concept for suburban trains. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No: 101101917.

2 Electrical Multiple Units with on-Board Energy Storage System Description

Electrical multiple units (EMUs) are a well-known type of train rolling stock, widely deployed and used in railway systems. This type of vehicle can operate with different power supply variants, using single or multiple high voltages, compliant with conventional standardized voltages in DC (e.g., 1.5 kV DC, 3 kV DC) or AC (e.g., 15 kV 16.7 Hz, 25 kV 50 Hz).

Recently, technological progress in energy storage systems (such as lithium-ion batteries and supercapacitors) and in power electronics (Silicon Carbide semiconductors) has enabled new train architecture designs and improvements. These developments have led to the creation of more energy-efficient and decarbonized trains for non-electrified routes.

The new approach proposes a hybrid traction system on railway rolling stock operating on electrified lines. The main principle is to combine the power supply from the conventional traction substation/current collector system with an on-board energy storage system. The objective is to downsize the high-voltage conversion system (e.g., traction transformer, line inductor, main rectifier, etc.) using the power provided by the on-board energy storage system. This structure is similar to other hybrid traction systems, typically used with combustion engines in railways and other mobility applications, especially in road and heavy-duty vehicles. Figure 1 below illustrates the difference between DC contact line powered vehicles without ESS and those with an on-board ESS in parallel connection [1].

The hybrid traction system is particularly advantageous for operations with regular traction/braking cycles. The benefit of an on-board ESS is to capture and store the energy recovered during regenerative braking, while providing assistance during the traction phase. This is especially valuable for DC power supply systems, due to their non-bidirectional traction substations. In such cases, regenerative braking might be ineffective if there is no synchronization between regenerative power production and power absorption elsewhere on the network.

This issue impacts both energy efficiency and air quality. Regarding energy efficiency, reduced regenerative braking effectiveness increases the overall energy consumption of

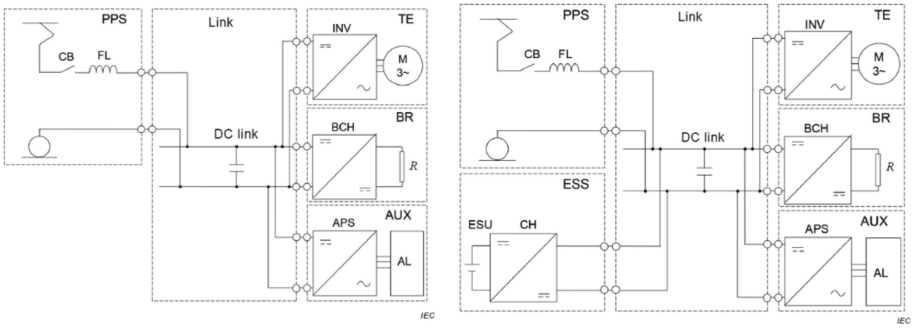


Fig. 1. DC contact line power architecture without ESS (left side) and with on-board ESS in parallel connection (right side) based on IEC 62864–1:2016 standard for a DC operated train

vehicles. Regenerative braking can represent from a few to several dozen percent of energy savings, depending on the rail service [2–4]. Regarding air quality, limitations on regenerative braking necessitate the use of mechanical braking, which creates airborne particles through the friction of braking shoes on wheels. When combined with highly efficient conversion systems, significant energy savings can be achieved, as demonstrated by the train operator "Tokyo Metro" in Japan with their S2000 train series. This 2000 series employs a hybrid traction architecture based on lithium-ion batteries, full SiC power electronics converters, and permanent magnet synchronous motors (PMSM). Compared to previous generations of rolling stock, energy savings of 27% have been achieved.

The power and energy support from the on-board ESS can also compensate for voltage drops. Particularly under DC voltage systems, voltage drops occur due to resistance variations between traction substations. These voltage fluctuations can result in degraded tractive performance of the vehicle. Consequently, this issue affects not only the operation of the vehicle itself but also potentially other trains in high-traffic density areas. The on-board ESS can be activated to reduce power drawn from the electrical infrastructure and consequently stabilize the voltage supply of the line. This provides additional benefits for infrastructure management by potentially avoiding the installation of additional traction substations when higher traffic demand occurs on the line.

Another advantage of the on-board ESS is the ability to operate without external power supply. In case of a traction substation failure or other issues affecting power voltage (e.g., failures related to extreme temperature conditions due to climate change), a conventional EMU cannot run and must switch to safety mode with low-voltage battery supply. However, with an on-board ESS, the system can supply energy to the traction system and/or to auxiliary loads. This enables the train to reach the next station and safely evacuate passengers, or maintain auxiliary loads for passenger comfort (in cases where the train cannot move). This application is currently used in various rail vehicles, such as the next generation of TGV in France, "TGV M" [5], or on the commuter/suburban series 235–1000 of JR EAST, which has a range of approximately 10 km in battery mode [6].

3 Use Case on Mass-Transit Line and Comparison with Traditional Electrical Multiple Units

In this chapter, a comparison between the operation of a traditional EMU train and an ESS-equipped EMU train on different suburban lines will be presented. The benefits obtained in various areas will be analyzed.

3.1 Train and Line Characteristics

There is no universal definition of what constitutes a suburban train. The following parameters define a suburban train according to SNCF Voyageurs (Table 1):

Table 1. France - SNCF Voyageurs' suburban train characteristics

Characteristics	Traditional EMU	ESS equipped EMU
Empty mass	250 t	250 t
Total passenger capacity	1000	1000
Maximum speed	140 km/h	140 km/h
Tractive power	3 200 kW	3 200 kW
HV system power	3 200 kW	1 000 kW
Total ESS Capacity	–	150 kWh
High power ESS	–	50 kWh
High energy ESS	–	100 kWh

Another special characteristic of French EMUs for suburban services is that they are not equipped with a brake resistor. Therefore, when the catenary cannot accept more energy injections, the train initiates mechanical braking.

Various suburban lines have been simulated in this study. All the lines have a total travel time of approximately 2 h, with an average distance of around 80 km and 30 intermediate stops. All lines are equipped with a 1.5 kV DC catenary. The substations are not reversible in terms of energy; therefore, the receptivity of the catenary depends on the energy consumption of the other trains in the sector.

3.2 Simulation Results on Infrastructure Impact

The following figures show the results of the simulation of the entire suburban traffic of a given line during a peak period. Previous studies on voltage levels and the impacts of different infrastructure parameters have been conducted for suburban lines and traditional EMUs [7, 8]. In Fig. 2, the instantaneous observed line voltage (at the pantograph level) of the different trains at various points on the lines can be observed. The left side represents the voltage drop obtained by traditional EMUs, and the right side represents

the voltage drop obtained by ESS-equipped EMUs. The operation of the ESS-equipped EMU fleet significantly limits voltage drops and eliminates all overvoltages above the substation's setting voltage, as a result of regenerative braking not being used on the catenary. Furthermore, ESS-equipped EMUs can impact on the overall energy consumption of a service even with partial deployment. ESS-equipped EMUs increase the line's receptivity to energy recovery for traditional EMUs with regenerative braking to the line.

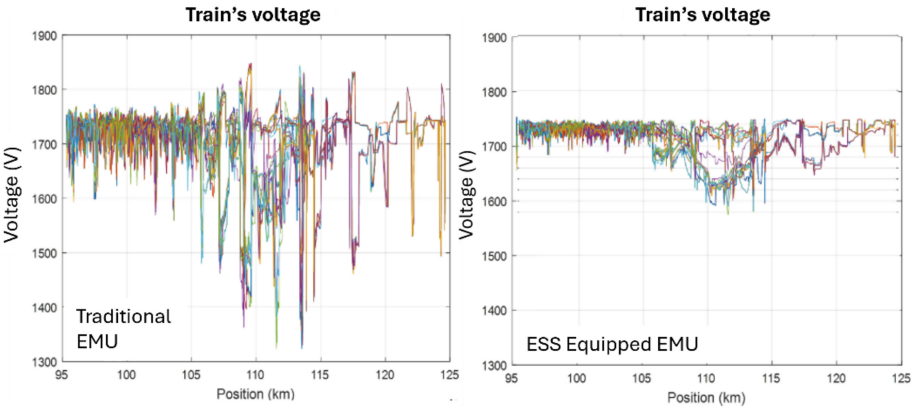


Fig. 2. Train's voltage at pantograph on different points of the line on a traditional EMU on the left and an ESS equipped EMU on the right.

Figure 3 shows the total current drawn from the catenary by a traditional EMU with regenerative braking and by an ESS-equipped EMU operating on the same service.

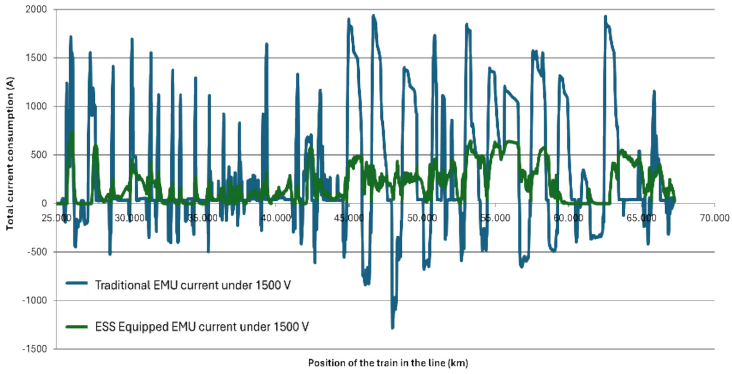


Fig. 3. Total electrical current consumption of a traditional EMU in blue and of an ESS equipped EMU in green.

This graph shows the main impact on the traction current. The current of the ESS-equipped EMU (in green) is always positive, because the traction system is intentionally

unidirectional. This feature prioritizing on-board energy recovery instead of reinjecting energy into the line during electric braking provides several advantages:

- It prevents increases in catenary voltage during braking, which enables higher voltage adjustment and can result in additional power capacity gains at electrical substations, while also limiting losses on the catenary.
- It allows for a less expensive, simpler, and more reliable unidirectional high-voltage conversion system (such as the traction transformer, line inductor, main rectifier, etc.), since the maximum current observed is less than half that of a traditional EMU. The current of an ESS-equipped EMU is limited to 1 MW divided by the catenary voltage (approximately 600 A, compared to nearly 1900 A for a traditional EMU).

During certain operating phases, the current consumption of ESS-equipped EMUs is nearly zero. These phases correspond to gradients, even slight ones, where the energy recovered by the descending train is sufficient to power the train and its auxiliaries. The dynamic aspect of station stops is managed in parallel by the internal storage device and is therefore invisible on the catenary current measured.

Finally, although it may not be visible on the graph, the state of charge of the energy storage devices is identical at the beginning and end of the journey, as their respective levels are linked solely to train dynamics and specific needs that are quickly compensated. Except for special situations (such as ESS-only mode due to an incident or maintenance works on the infrastructure, resulting in no available catenary power), there is no dedicated charging phase. ESS-equipped EMUs do not encounter the drawbacks associated with high current consumption at standstill that BEMU trains face during charging (such as overheating of the overhead line, need for dedicated charging infrastructure, and train unavailability during charging phases, etc.).

3.3 Energy Savings

Table 2. Energy consumption comparison between a traditional EMU and ESS equipped EMU in two different lines

Simulated case	Consumed Energy 1500 V Trad EMU	Consumed Energy 1500 V ESS equipped EMU	Energy saving	Mech Brake reduction
Case 1 outward	349,3 kWh	219,9 kWh	−37,0%	−90,4%
Case 1 return	343,8 kWh	234,8 kWh	−31,7%	−96,5%
Case 2 outward	696,1 kWh	513,4 kWh	−26,2%	−88,6%
Case 2 return	664,2 kWh	487,5 kWh	−26,6%	−91,3%

In Table 2, the estimated energy results can be observed. The results take into account the efficiency of the different components of the traction chain and are based on a simple control law. The ESS-equipped EMU achieves energy savings of 25% to 30% on average

at the pantograph level compared to a traditional EMU. The savings are even greater (30% to 40%) if gains on the power supply network (catenary and substations) are considered. Thanks to the ESS, most of the braking energy is recovered, the load on the mechanical brakes is reduced by 85% to 95%, and consequently, brake dust emissions are also reduced. The systematic regenerative braking of ESS-equipped EMUs enables frictionless braking, all the way to a stop, in most real-world use cases. This is an important advantage, as the majority of stops in urban areas are in underground stations, where brake dust emissions can raise air quality concerns. This provides a clear benefit by reducing fine particle generation and lowering tunnel heating, which is problematic for air conditioning systems, for example. However, for hard braking at high speeds or in an emergency, mechanical braking is still needed to avoid oversizing the powertrain components.

The energy source management algorithm applied in this case study is a simple one with fixed conditions. Other, more complex algorithms have also been studied, such as the trading algorithm, in which a seller/buyer relationship is established between energy producers and energy consumers. This trading algorithm reduces constraints on the ESS and optimizes energy flow between the components, boosting the overall system efficiency. An algorithm based on frequency distribution [9, 10] was also tested; this approach optimally separates the roles of energy and power between different ESS subsystems. However, unlike the previous strategies, this method is not adaptive to partial failures of ESS subsystems.

4 Conclusion and Future Work

In this paper, the benefits of the ESS-equipped EMU compared to a traditional EMU have been demonstrated. On the rolling stock side, the introduction of an ESS in an EMU enables high-voltage conversion system reduction, enhances energy savings, and achieves a significant reduction in mechanical braking. On the infrastructure side, the current consumption of the ESS-equipped EMU becomes unidirectional and more uniform compared to that of traditional EMUs. This also results in a more stable voltage on the catenary, which no longer limits the performance of other trains during traction phases. Additionally, ESS-equipped EMUs boost the receptivity of the catenary to the regenerative current of traditional EMUs.

Other benefits of ESS-equipped EMUs have not been explored in this paper. One example is their ability to mitigate LFO (low-frequency oscillations) generated by new-generation trains equipped with power electronics operating under alternating current catenary systems [11]. Another example is the possibility to implement peak shaving and/or load shedding. In these scenarios, when requested by the grid manager, the energy consumption of ESS-equipped EMUs can be temporarily reduced or eliminated [12, 13].

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References

1. IEC: IEC 62864–1:2016, ISBN 9782832234532
2. CTNC: Regenerative braking in trains (2026). https://www.ctc-n.org/technologies/regenerative-braking-trains#:~:text=When%20regenerative%20braking%20is%20employed,to%20the%20power%20distribution%20system. Accessed 2 Mar 2026
3. Sang Hoo, D., Huat Chua, K., Seng Lim, Y., Morris, M., Wang, L.: Comparison of regenerative braking energy recovery of a DC third rail system under various operating conditions. Int. J. Electr. Power Energy Syst. **155**(Part B) (2024). https://doi.org/10.1016/j.ijepes.2023.109575
4. Araúz, J., Martinez, S.: Methodology for assessing the impact of regenerative braking energy injection of a direct current railway system on the distribution grid. Electr. Power Syst. Res. **220** (2023). https://doi.org/10.1016/j.epsr.2023.109368
5. SNCF: Voyageurs. https://www.sncf-voyageurs.com/medias-publics/2025-03/dp_tgv-inoui_25-03-11-bd.pdf. Accessed 2 Mar 2026
6. Kikkawa, K., Tasaka, Y.: Effective utilization of SCiB™ lithium-ion battery to meet needs of rolling stock. TOSHIBA. **76**(4) (2021)
7. Poline, M., Gerbaud, L., Pouget, J., Chauvet, F.: Simultaneous optimization of sizing and energy management—application to hybrid train. Math. Comput. Simul. **158**, 355–374 (2019). https://doi.org/10.1016/j.matcom.2018.09.021
8. Poline, M.: Contribution aux méthodes de conception et de gestion des systèmes énergétiques multi-sources par optimisation systémique: application aux trains hybrides électrique autonomes. https://theses.hal.science/tel-02124030
9. Akli, C. R.: Conception systémique d'une locomotive hybride autonome, HAL Open Science. https://hal.science/tel-04425504
10. Akli, C.R., Roboam, X., Sareni, B., Jeunesse, A.: Energy management and sizing of a hybrid locomotive. In: 2007 European Conference on Power Electronics and Applications, Aalborg, Denmark, pp. 1–10 (2007). https://doi.org/10.1109/EPE.2007.4417333
11. Fu, Y., Abdallah, I., Deheuvels, F.: A simplification method for the harmonic overvoltage analysis of the railway infrastructure and the rolling stock. In: WCRR 2025, Colorado Springs (2025)
12. Pam, A., Letrouvé, T., Zhou, P., Yee, R., Pudney, P., Grellier, O.: Targeted traction power modulation of high-speed Trains for Stabilization of electric supply network with the electric flexibility. In: 2022 IEEE Vehicle Power and Propulsion Conference (VPPC), Merced, CA, USA, vol. 2022, pp. 1–6. https://doi.org/10.1109/VPPC55846.2022.10003344
13. Juston, M., Chamaret, A., Renault, M., Vulturescu, B.: Ecosystem analysis of the battery train, today and in the future. In: Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRAconference 2024 Lecture Notes in Mobility. Springer. https://doi.org/10.1007/978-3-031-89444-2_81

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Accelerating Public Charging Infrastructure: Micro-Level Approach Enables Efficient Planning of Charging Locations Based on Suitability of Public Space

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Abstract. Expanding public electric-vehicle (EV) charging infrastructure is a pressing municipal need, yet planning is slowed by site-specific public-space constraints. To address this challenge, we developed a method that considers all possible sites for charging infrastructure in public space and conducts a suitability analysis based on potential conflicts, including preservation orders, overlays with bike lanes, and vegetation protection. Our method incorporates demand data to identify hotspots for infrastructure placement. A buffer-based analysis is applied to each suitable site, assigning the best-scoring locations. We applied our method to a neighborhood in Berlin, Germany, and obtained a selection of sites that meet demand without generating conflicts in public space. This study delivers a high-resolution output and a flexible framework for diverse urban settings, making the charging infrastructure expansion process more efficient.

Keywords: Public charging infrastructure · Electric vehicles · Suitable location choice · Multi-criteria evaluation

1 Introduction

Switching motorized individual mobility to electric vehicles (EVs) reduces CO_2 emissions, local air pollutants, and noise, delivering public health [1, 2] and energy-security benefits [3].

Germany has 1.4 million BEVs and 2.9 million PHEVs in stock (1.1.2024) [4]. The country has the objective of 15 million EVs in 2030. While most charging occurs at home or work, dense urban areas often lack private parking, making publicly accessible chargers essential [5]. Expanding public charging infrastructure boosts local EV adoption [6, 7] and is a pressing public-sector priority. Recent public-sector initiatives and a growing body of research have produced robust forecasts of charging demand and a suite of meso-scale placement methods [8, 9]. Berlin, for example, has operated a science-driven, model-based planning programme for over a decade, involving the development of a location concept, contract awarding procedure, and user information platforms [10].

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Existing studies reliably estimate the number of public chargers needed and provide large and medium scale placement concepts. Nevertheless, translating these models into exact sites is still a time-intensive task, that involves multiple parties and factors such as historic preservation and vegetation protection. We present a method that integrates demand forecasting with a public-space suitability assessment, providing a decision-support tool to determine exact charging locations. By coupling these steps, the approach markedly reduces the effort required for site-specific planning. The approach is tested in a central district of the city of Berlin, Germany.

The paper is structured as follows: First, we describe the methodology of the approach. Second, we present and discuss the results. Third, conclusions are drawn.

2 Methodology

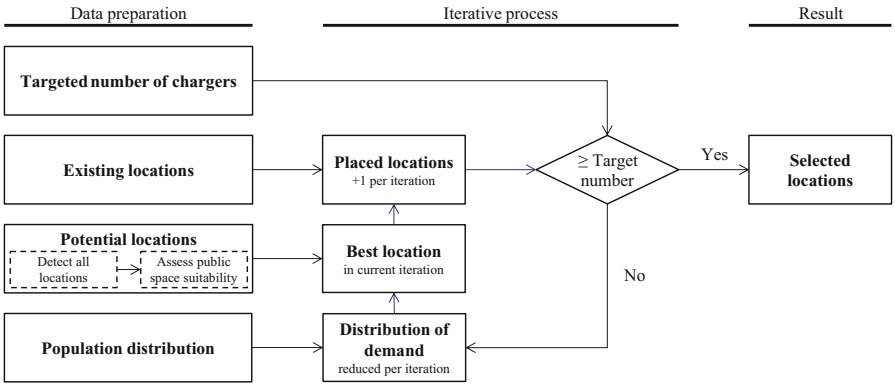


Fig. 1. Methodological approach.

The workflow (Fig. 1) comprises three stages: data preparation, an iterative placement process, and the final result. Data preparation involves gathering and preparing necessary input data, including the targeted number of chargers, the distribution of the existing charging infrastructure, the detection and suitability analysis of all possible sites for infrastructure expansion, and the distribution of the population in the study area. The iterative algorithm then calculates demand around each candidate location and assigns charging stations to the top-scoring locations, reducing demand in surrounding areas to ensure balanced coverage. The following section describes the steps in more detail and defines the input data. First, the case study area is introduced.

2.1 Case Study Description

We apply the method to a $\approx 1.5\ km^2$ part of Kreuzberg, Berlin (Fig. 2), with a population of 24,209 inhabitants in 2021 [11]. The area is dominated by dense early-20^{th}-century residential blocks, with some northern industry, cultural sites, and mixed-use ground floors. Street parking is prevalent because private backyard spaces are scarce. The river Spree forms the study area's northern boundary.

2.2 Data Preparation

The study adopts "neighborhood charging" [12], which comprises overnight charging in public parking close to the drivers' homes where private parking is limited. This service is provided by AC chargers with a maximum power of 22 kW [13]. Other charging behaviors, including workplace and retail charging, are excluded due to unavailability of proxy demand data required for street-scale allocation.

Targeted Number of Chargers. The method requires a targeted charger count, which may be set by policy or derived from demand-forecast models [14] and determines the infrastructure size needed to meet the foreseen demand. In our scenario, we assume 100 normal-speed chargers (two per station), resulting in 50 stations.

Existing Locations. Existing locations are obtained from public data from the German Federal Network Agency [15]. For this study, we retain only the 11 street-mounted normal-speed stations within the study area (as of 6.7.2024) (Fig. 2(c)).

Potential Locations. The method for selecting potential locations involves two successive stages: detection of all feasible sites and public space suitability assessment.

Detection of all Feasible Sites. Only street-side public parking bays are used; private yards and commercial lots (e.g., supermarket car-parks) are excluded because they fall outside municipal planning. An aerial-imagery detection algorithm provides georeferenced bays with capacity and orientation [16]. A GIS routine creates a point for every two adjacent bays and displaces the point 80 cm onto the sidewalk [17]. This procedure yields 2,920 potential locations within the study area (Fig. 2(a)).

Public Space Suitability Assessment. Each candidate is overlaid with the geometric representations of the spatial constraint layers listed in Table 1. The shape and size of every constraint buffer are defined by municipal preferences or literature-derived values. The set of criteria applied depends on data availability, data quality, and the relevance of each constraint to the study. Figure 2(a) presents the suitability analysis of all potential charging sites. It flags 53.5% (1,563) of the sites as conflicting and retains 46.5% (1,357) as conflict-free locations for the iterative placement process.

Population Distribution. We use address-level population data from the German Federal Agency for Cartography and Geodesy [11] as a spatial proxy for "neighborhood charging" demand [12]. Households with private garages, which typically enable home charging [23], are filtered out. The result is a set of georeferenced points representing the distribution of the relative demand. Parcel-level EV registration data would enhance accuracy, such data remain unavailable at sub-neighborhood resolution for Berlin. Our analysis operates at a finer scale than existing municipal datasets.

The relative demand distribution (Fig. 2(b)) shows a primary concentration in the study area center, with secondary clusters northwest/southeast. The demand distribution analysis is confined to study area limits, creating artificial central concentration. It is also crucial to consider the network accessibility, as hard borders impede the flow of connections. In this case, the data on the north side of the river was not considered.

Table 1. Criteria for public charging station suitability.

Criteria	Format	Value	Justification	References
Proximity to existing charging stations	Minimum distance	10 m	Qualified estimation after data analyses and observation	[18, 19]
Protection of tree roots	Minimum distance	Crown +1.5 m	[20]	[19]
Proximity to planting areas	Minimum distance	1 m	Buffer to enable use of station	[19, 21]
Conflict with road furniture	Minimum distance	2 m	Furniture size + utilization buffer	[22]
Proximity to memorials	Minimum distance	5 m	Qualified estimation after data analyses and observation	[21]
In front of protected buildings	Boolean attribute	No	Space occupying the sidewalk in front of protected buildings	[19, 22]
Conflict with bike lanes	Minimum distance	1.9 m	Standard lane width + utilization buffer	[17]
Reserved parking spaces	Boolean attribute	No	Information contained in parking space data	[22]
Insufficient sidewalk width	Minimum distance	1.8 m	Standard minimal sidewalk width	[17]

2.3 Iterative Placement

This step consists of four stages. The algorithm initiates by distributing demand proportionally to population density, then subtracts coverage from existing infrastructure. Iteratively, it selects the highest-demand candidate location and reduces demand within its area of influence. This cycle repeats until the target charger count is achieved, ensuring spatial coverage without over-concentration. The area of influence defines each station's service radius, while the demand reduction value quantifies its capacity to satisfy local charging needs.

Area of Influence. The area of influence defines each station's service radius, determined by the maximum 5-min walking distance from parked vehicles to residences [12, 23], assuming an average walking speed of 1.4 m per second [24]. The 5-min walking distance is then converted to meters, considering the urban fabric and walkability of the network [25]. As this study is applied to a dense urban environment, the area of influence around each charger is defined by a radius of 300 m.

Demand Reduction. The demand reduction value quantifies each charger's coverage capacity, calculated as total demand divided by target stations [26]. For 24,209 inhabitants in the area and 50 stations, each charger covers 484.2 inhabitants (24,209 ÷ 50). Upon station placement, this value is uniformly subtracted from demand units within the 300-m influence area, ensuring spatially balanced coverage.

Location Selection. The algorithm initiates by applying demand reduction around existing chargers to establish the residual demand field. This is then used to initiate the iterative placement process for additional charging infrastructure. The selection of the best placed location at each iteration depends on the quantity of demand calculated within the area of influence of each candidate location. The demand reduction method is applied to the selected location, updating the demand distribution, which is then used to select the next best located candidate. This iterative process continues until the targeted number of chargers is reached. The resulting dataset contains a selection of locations for the installation of new charging infrastructure.

3 Results and Discussion

The method identified 39 new charging locations (Fig. 2(c)) to complement the 11 existing stations, yielding a total of 50 stations as targeted. The resulting charging stations are concentrated in two major clusters. The bigger one is located in the center of the area, coinciding with the highest demand area, which also received the first placements (indicated by the number in Fig. 2(c)). Another cluster is located around the southeast corner. The northwestern area received minimal new stations due to existing infrastructure coverage. The selected locations tend to be distant from the boundaries of the study area, as demand outside these boundaries is not considered.

This contribution offers a high-resolution output, unlike earlier studies in this field [9, 27, 28]. The main advantage is the assessment of public space suitability, which allows for the inclusion of micro-scale barriers hindering charger placement. This approach provides a more detailed and accurate solution for charging infrastructure planning. The automated workflow excludes 53.5% of potential sites due to spatial conflicts, significantly reducing manual review burden for planners.

Nevertheless, the presented approach has limitations and undergoes iterative improvements. Currently, we cannot consider available connection power in the electricity grid, as obtaining this data is difficult in Germany due to confidentiality concerns.

Furthermore, the tool will be enhanced by integrating the results of a charging demand forecast model [14], which integrates spatially explicit EV penetration rates and charging behavior patterns, to generate dynamic targeted number of chargers as input, enabling the consideration of varying power requirements across future scenarios.

Currently, the spatially high-resolution distribution of charging demand is based on population density only. To further optimize the spatial distribution and draw a more realistic picture, the tool will also integrate data for other charging behaviors, such as charging at work or during shopping, facilitating a more complete and efficient planning approach.

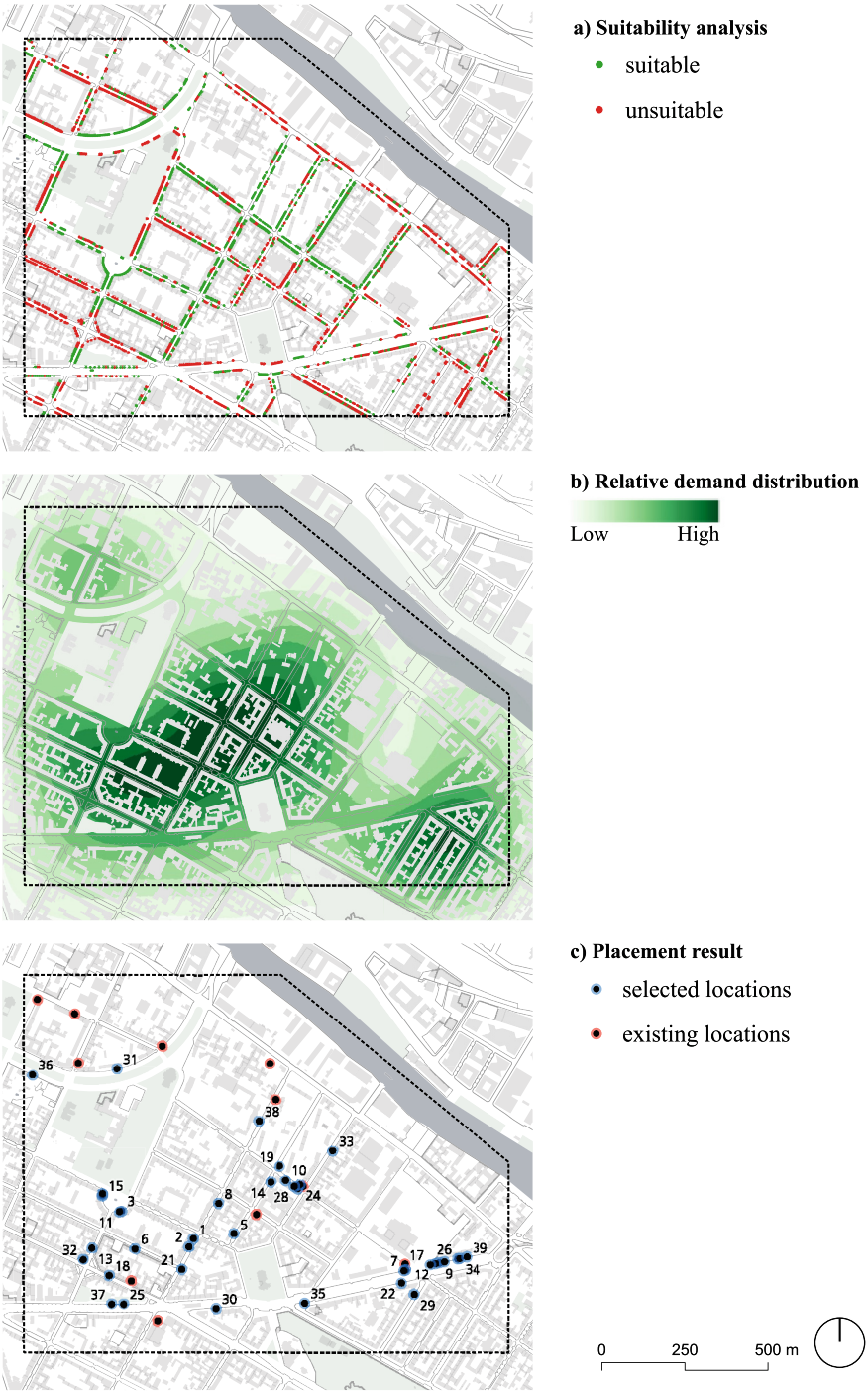


Fig. 2. Potential location suitability analysis (a), relative demand distribution based on population data (b), and result of the iterative charging infrastructure placement process (c).

4 Conclusion

In this study, an automated workflow for placing public charging infrastructure in a high spatial resolution is developed. The method includes on-site evaluations of the suitability of public space for placing charging infrastructure. An iterative placement process defines optimal exact sites. Results show that we can assess the local conditions in the public space and derive a subset of charging locations. Providing exact sites for the expansion of public charging infrastructure based on both, demand analyses and suitability of the public space is a new development and a significant added value towards earlier research. The approach therefore serves as a planning support and significantly simplifies the local effort for planning the expansion of public charging infrastructure. The proposed method is transferable and can be applied in diverse urban contexts and adapted to the framework conditions, needs and preferences of each municipality.

References

1. Chen, L., Ma, R.: Clean energy synergy with electric vehicles: insights into carbon footprint. Energ. Strat. Rev. **53**, 101394 (2024)
2. Masri, J., Amer, M., Salman, S., Ismail, M., Elsisi, M.: A survey of modern vehicle noise, vibration, and harshness: a state-of-the-art. Ain Shams Eng. J. **15**, 102957 (2024)
3. Zábojník, S., Steinhauser, D., Kráľ, P.: E-mobility in Slovakia by 2030—end of oil dependency? IET Smart Cities. **4**, 127–142 (2022)
4. Kraftfahrt-Bundesamt.: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Jahrebilanz_Bestand/fz_b_jahresbilanz_node.html (2025). Accessed 28 Sept 2025
5. Pardo-Bosch, F., Pujadas, P., Morton, C., Cervera, C.: Sustainable deployment of an electric vehicle public charging infrastructure network from a city business model perspective. Sustain. Cities Soc. **71**, 102957 (2021)
6. Illmann, U., Kluge, J.: Public charging infrastructure and the market diffusion of electric vehicles. Transp. Res. Part Transp. Environ. **86**, 102413 (2020)
7. Levinson, R.S., West, T.H.: Impact of public electric vehicle charging infrastructure. Transp. Res. Part Transp. Environ. **64**, 158–177 (2018)
8. Funke, S.Á., Sprei, F., Gnann, T., Plötz, P.: How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison. Transp. Res. Part Transp. Environ. **77**, 224–242 (2019)
9. Majhi, R.C., Ranjitkar, P., Sheng, M., Covic, G.A., Wilson, D.J.: A systematic review of charging infrastructure location problem for electric vehicles. Transp. Rev. **41**, 432–455 (2021)
10. Hardinghaus, M., Löcher, M., Anderson, J.E.: Real-world insights on public charging demand and infrastructure use from electric vehicles. Environ. Res. Lett. **15**, 104030 (2020)
11. Bundesamt für Kartographie und Geodäsie: Haushalte einwohner bund. https://sg.geodatenzentrum.de/web_public/Datenquellen_HH-EW-Bund.pdf (2025). Accessed 29 Sept 2025
12. Charly, A., Thomas, N.J., Foley, A., Caulfield, B.: Identifying optimal locations for community electric vehicle charging. Sustain. Cities Soc. **94**, 104573 (2023)
13. Saraswathi, V.N., Ramachandran, V.P.: A comprehensive review on charger technologies, types, and charging stations models for electric vehicles. Heliyon. **10**, e38945 (2024)
14. Wulff, N., Steck, F., Gils, H.C., Hoyer-Klick, C., van den Adel, B., Anderson, J.E.: Comparing power-system and user-oriented battery electric vehicle charging representation and its implications on energy system Modeling. Energies. **13**, 1093 (2020)

15. Bundesnetzagentur: Ladesäulenkarte. www.bundesnetzagentur.de (2024). Accessed 6 July 2024
16. Hellekes, J. et al.: Parking space inventory from above: detection on aerial images and estimation for unobserved regions. IET Intell. Transp. Syst., 1–13 (2022)
17. Ahrend, C., Schwedes, O., Böhme, U., Kettner, S.: Final Report e-Mobility. Berlin Technical University (2011)
18. Banegas, J., Mamkhezri, J.: A systematic review of geographic information systems based methods and criteria used for electric vehicle charging station site selection. Environ. Sci. Pollut. Res. **30**, 68054–68083 (2023)
19. Khalife, A., Fay, T.-A., Göhlich, D.: Optimizing public charging: an integrated approach based on GIS and multi-criteria decision analysis. World Electr. Veh. J. **13**, 131 (2022)
20. Landeshauptstadt Wiesbaden: Elektromobilitätskonzept der Landeshauptstadt Wiesbaden für den Individualverkehr (2019)
21. Wirges, J.: Planning the Charging Infrastructure for Electric Vehicles in Cities and Regions. Karlsruher Institut für Technologie (2016)
22. Schubert, F.: Ladeinfrastruktur im urbanen Kontext. TU Berlin (2021)
23. Anderson, J.E., Bergfeld, M., Nguyen, D.M., Steck, F.: Real-world charging behavior and preferences of electric vehicles users in Germany. Int. J. Sustain. Transp. **17**, 1032–1046 (2023)
24. Bartels, B., Erbsmehl, C.T.: Bewegungsverhalten von Fußgängern im Straßenverkehr - Teil 1 (2014)
25. Schön, P., Heinen, E., Manum, B.: Associations of street network and urban form with walking frequencies. Eur. J. Transp. Infrastruct. Res. **25**, 107–132 (2025)
26. Lehmann, J.: Methodology for the Optimized Localization of Charging Infrastructure for Electric Vehicles in Urban Environments. TU Berlin (2025)
27. Pagany, R., Ramirez Camargo, L., Dorner, W.: A review of spatial localization methodologies for the electric vehicle charging infrastructure. Int. J. Sustain. Transp. **13**, 433–449 (2019)
28. Hardinghaus, M., Seidel, C., Anderson, J.E.: Estimating public charging demand of electric vehicles. Sustainability. **11**, 5925 (2019)

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Experimental Results of a Liquid Hydrogen Storage System Prototype for Railway Systems

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Abstract. In the framework of IPCEI Hy2TEch (Important Project of Common European Interest), Alstom is studying the possibility to use liquid hydrogen as fuel for green railroad transportation. Alstom is a leader in developing gaseous hydrogen railway vehicles for the European market. Liquid hydrogen has the great advantage over gaseous hydrogen that it allows a much larger quantity of fuel to be carried onboard for a given volume. It also brings engineering challenges that must be carefully analyzed before it can be used on a train. This paper presents the experimental results obtained from testing a prototype Liquid Hydrogen Fuel System (LHFS) built with Chart Industries. Characteristics including gas flow, dormancy time, boil-off rate, and heat used for hydrogen vaporization are discussed, in the context of operating a shunting locomotive. These results suggest that an LHFS can be designed to supply fuel cells for railroad transportation, and that the operational constraints imposed on operators can be appropriately mitigated. Liquid hydrogen appears today to be a very promising alternative to electrification for CO_2-free, high-power rolling stock – that cannot use battery solutions due to storage limitations. This technology is an opportunity for the replacement of many diesel rolling stock material worldwide.

Keywords: Green transportation · rolling stock · liquid hydrogen · hydrogen storage

1 Introduction

Hydrogen is widely considered as one of the most promising options to achieve, at least partially, the decarbonation of the transportation industry. Several hydrogen rolling stocks are being put in service worldwide – see [1] for a comprehensive review. Hydrogen can provide excellent gravimetric power density and can be used in fuel cells or combustion engines. Nevertheless, hydrogen also has drawbacks, one of which is its low volumetric density compared to fossil fuels. While mass is a key parameter for train manufacturers, volume is typically a greater limiting factor for hydrogen use on board hence the denser the hydrogen, the better. Liquid hydrogen can have a volumetric density of up to 70 g/L, whilst gaseous hydrogen at 700 barg has a density of about

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40 g/L. Additionally, the higher density of liquid hydrogen can be achieved at low pressures, typically between 1 and 20 barg. The lower pressure requirement allows the use of cylindrical steel tanks which are cheaper and easier to manufacture than carbon fiber tanks. Details of the physics of cryogenic storage can be found for example in [2–4]. For a high-level review of hydrogen storage topics see [5]. For a comparison of different hydrogen storage technologies for mobility applications, see [6].

Liquid hydrogen brings some challenges that must be managed; the main one is boil-off. Boil-off is the inevitable process where some of the liquid fuel is vaporized due to ambient heat transfer through the insulated tank to the cold hydrogen. As vapor is produced inside the tank, the pressure increases. In practice, this is not an issue when hydrogen is used: the act of removing hydrogen from the tank to feed fuel cells naturally lowers pressure and cools down gas in the tank. When fuel cells are not used, for example when the train is parked, this phenomenon must be considered.

Other drawbacks of liquid hydrogen are related to availability of components, molecule cost and availability in specific regions, but they will not be discussed in this paper. Full economic analyses of liquid hydrogen usage are complex and very much dependent on the use and geographical localization of the railway. For a first analysis of costs related to hydrogen production and transportation, see [7] and references therein.

Alstom believes that liquid hydrogen has distinct advantages over other carbonless fuels that can be beneficial to its use on rolling stock. With the objective of quantifying these gains, Alstom has built, with its partner Chart Industries, a prototype LHFS. This article presents the main experimental results of the validation tests done on this prototype.

2 Target Performances for a Shunting Locomotive

The hypothetical vehicle for this study is a shunting locomotive powered by batteries and fuel cells and fueled by liquid hydrogen. The performances required from the LHFS depend on the train and its fuel cell system; for this prototype, among the targets that were defined, the following ones are described in this paper:

- Gas flow: at least 5 g/s.
- Gas temperature: between −40 and + 85 °C.
- Gas pressure: between 9 and 11 barg.
- Heating power: the power used to provide gaseous hydrogen at the correct temperature can be taken from the fuel cells without requiring extra electrical power.
- Dormancy time: at least 12 h, to avoid boil-off at nighttime when the locomotive is parked. See Sect. 4.2 for a description of this topic.
- Hydrogen density onboard: a minimum density of 50 g/l is targeted, with an objective of reaching at least 62 g/l in ideal conditions.

3 Experimental Setup

The experimental setup is shown in Fig. 1. The LHFS prototype functionality was demonstrated at the Chart Industries hydrogen test facility. The setup is composed of:

– a liquid hydrogen tank;
– a hydrogen handling system, including a control unit and responsible for managing pressure inside the tank;
– a vaporizer, delivering heat through a heat exchanger to the liquid hydrogen to vaporize it and raise its temperature to the desired value;
– an electrical heater, a pump and a heating fluid circuit to deliver heat to the vaporizer (to simulate the use of waste heat from a fuel cell);
– a flow controller to measure and regulate the mass flow of gaseous hydrogen exiting the system (to simulate the demands of a fuel cell);
– a scale to measure mass variations in the system during operations;
– a refueling system, to fill the LHFS as needed.

It must be noted that the electrical heater would not be needed on a rolling stock application, as heat would be provided by the fuel cells' thermal management system. In this setup an external source of heat was needed. By monitoring the power drawn by the heat source, it was verified that heat generated by the fuel cells would indeed be enough to power the LHFS. Please consider that this description is not exhaustive; details of several subsystems (notably related to safety, control, monitoring etc) cannot be shared, to protect the companies' intellectual property.

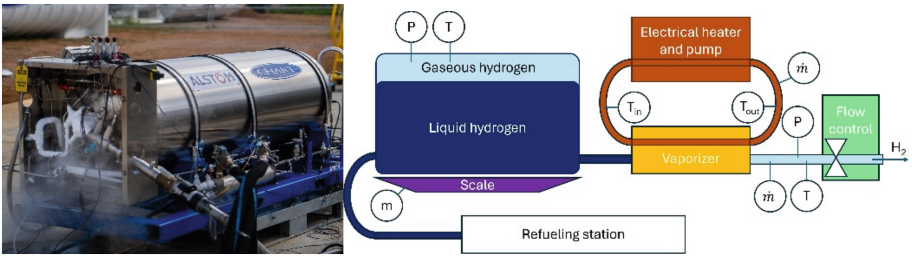


Fig. 1. Picture of the LHFS prototype (left) and schematic representation of the test setup (right).

4 Experimental Results

The following sections describe the main results obtained during the experiments. Uncertainties for the different quantities are estimated based on the sensitivity of the sensors, except for the mass (and thus density). Mass uncertainty is more complicated to evaluate due to the impact of environmental temperature and sometimes due to the formation of ice over valves, which slightly increase measured mass notably during defueling tests. The following uncertainties are applicable to the results shown in this paper:

– Hydrogen flow: $\pm 1\%$
– Hydrogen temperature: $\pm 1°$ Celsius
– Hydrogen pressure: 0.5%
– Heating power: 3.5%
– Mass and density: 3%

4.1 Hydrogen Usage: Hydrogen Gas Characteristics and Heating Power

The purpose of this test was to ensure that the LHFS could supply a steady stream of gaseous hydrogen at acceptable pressure and temperature to the fuel cells. A mass flow controller was used to test this performance at different flow rates or fuel cell powers. An external heat source was connected to the vaporizer to provide the heating of the supply hydrogen, and the heating power consumption of the LHFS monitored. Before looking at results, there are two important additional topics to discuss: the estimation of available heating power, and the dynamics of pressure buildup in the tank.

To properly vaporize liquid hydrogen and condition it to the right temperature on a train, it is desirable to use heat that is rejected by the fuel cells during operation, as it is provided by the train at no cost. It was demonstrated that it is indeed possible to capture enough power to perform this task, without needing other active heating element that would reduce available power for traction. As this performance will be very specific to the train installation, it cannot be evaluated precisely; nevertheless, a simple estimation of its order of magnitude will be sufficient. Consider a hydrogen flow q, with a lower heating value of 120 MJ/kg. Now suppose that the fuel cell has an efficiency of 50% (that is, half of the hydrogen's chemical energy is lost as heat) and that 50% of this heat is captured. Also consider 20% of thermal losses during the heat distribution. The available heating power in watts will then be calculated as $W_{avail} = q \bullet LHV \bullet 50\% \bullet 50\% \bullet 80\%$. As long as power required by the LHFS is well below this value (that is a function of q), the system will be able to work correctly. All excess power will have to be dissipated by the fuel cell's power system.

The pressure dynamics inside liquid hydrogen tanks are quite different from gaseous hydrogen storage. Liquid hydrogen is stored at low pressure, slightly above the fuel cell's working range. When hydrogen is removed from the tank, pressure and temperature inside it will decrease. While this is good as it allows the management of heat intake during use (see sect. 1), if left unchecked pressure will quickly fall below the lower acceptable limit of the fuel cells, causing the whole system to halt. To prevent this, a pressure buildup system injects enough heat (taken from the vaporizer) to increase pressure and compensate for this effect. The pressure buildup system is regulated by two solenoid valves that release heat inside the tank if the pressure reaches a minimum threshold and stop releasing heat once the pressure reaches a maximum threshold. An example of such dynamics is shown in Fig. 2. The system managed several pressure cycles in each configuration without issue.

The results of these tests are shown in Table 1.

Table 1 shows that performances required in sect. 2 were all fulfilled. Without going into details due to space limitations, we would like to briefly discuss two interesting points. Firstly, while the system was not tested coupled to fuel cells, its response to sudden changes in hydrogen withdrawal were measured. The prototype appears to have very well-behaved response, showing a fast response dynamics that should be in line with fuel cell usage. Secondly, there is an interesting and specific case that will only be briefly discussed in this paper: the cold start. Indeed, when the train starts at the beginning of its mission, the fuel cells are off and the only heat available to the LHFS is the heat capacity of the heating system. The prototype LHFS was forced to test this

Table 1. Results of defueling tests on the LHFS prototype.

H_2 flow	H_2 pressure (min-max)	H_2 temperature (min-max)	Heating power	Available heating power
g/s	**barg**	**°C**	**kW**	**kW**
5,6	9,1-10,3	26–36	22	130
4,2	9,3-10,4	39–50	17	100
3,3	9,4-10,5	44–56	13	80
1,65	9,5-10,6	49–56	6	40
0,53	9,5-10,6	41–57	1,3	13
		Objectives		
0,5 to at least 5,5	**9 to 11 barg**	**−40 °C to 85 °C**	**< available power**	**/**

condition and shown to be able to start correctly and work several minutes without an external heat source, more than enough to start the fuel cells and the heating system.

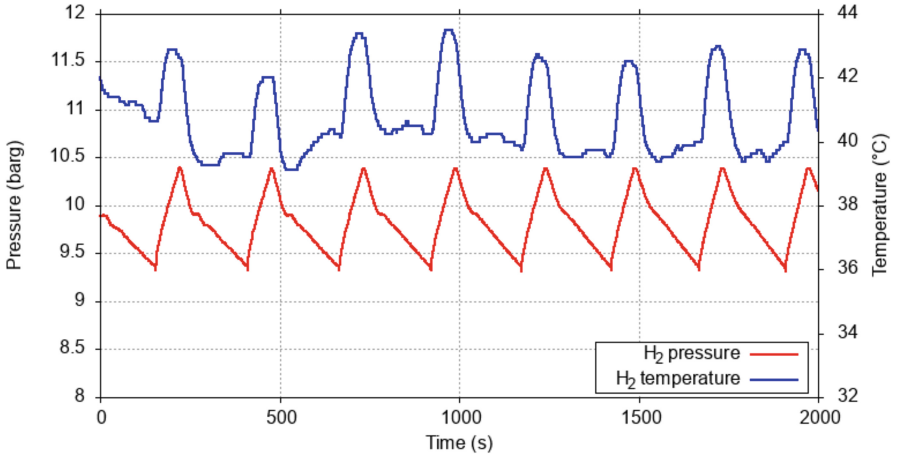


Fig. 2. Dynamics of hydrogen pressure and temperature supplied by the storage system, for a specific test at 4,2 g/s.

4.2 Dormancy Time and Boil-off Rate

As previously discussed, one of the most interesting performances to look at while discussing cryogenic storage is the system's capacity to remain cold. This is done by letting the system stand without adding or removing fuel and observing how pressure evolves inside the tank. Once it reaches a given threshold value, the BOG valve will

open and vent some hydrogen into the atmosphere. The time that it takes for the system to start venting is called dormancy time. When the train is parked and left unused for some time, heat will creep inside the vessel and, at the end of dormancy, start to release gas in the atmosphere. While this is not a safety concern, if correctly considered, it is a waste of energy and resources that one may want to avoid or at least minimize. For an in-depth discussion of the pressure buildup dynamics see [8].

Dormancy depends on many parameters, but the most important ones are the quantity of heat entering the system (related to the design of the tank) and the thermodynamical state of the system. Due to this, dormancy is not a fixed value, as it strongly depends on the quantity, pressure and temperature of the hydrogen inside the tank.

During the validation of our prototype, three different filling conditions at 10 bar were tested: tank initially full, tank initially half-full and tank initially almost empty.

Table 2. Results of insulation performance tests on the LHFS prototype.

Initial pressure	Initial density	Dormancy
barg	**kg/m3**	**hr:min**
9,9	62	1:40
10,2	30	27:19
10,0	14	17:15

Experimental results are shown in Table 2. These values show how different performance can be depending on the hydrogen's initial state. These values are most useful to verify that calculation schemes can correctly predict dormancy, which is out of the scope of this article. At the end of the dormancy period, boil-off gas rates between 50 and 150 g per hour were measured.

Globally, it is key to avoid parking the train at the wrong moment, notably with completely full or completely empty tank. If this can be done, very reasonable dormancy times well above the targeted 12 h could be achieved. It must be noted that larger tanks will have even better dormancy performances, due to a more favorable surface-to-volume ratio.

4.3 Hydrogen Refueling: Filling Time and Hydrogen Density

Refueling a pressurized container is always challenging, especially when dealing with cryogenic temperatures. Before refueling, the tank may have some liquid hydrogen inside, with the rest of the volume filled with gaseous hydrogen. When adding more liquid, pressure will increase until either the refueling station is not able to further increase pressure or the target internal pressure is reached. This means that, depending on the thermodynamical state of the hydrogen inside the tank, we may not be able to add much liquid to the tank, if the process is not well controlled. For example, a tank that has only gas inside, already at high pressure, will only be able to accept a little quantity of new liquid before pressure rises too much. In our experimental setup, the refueling

station's tank is first conditioned to ensure the hydrogen is sufficiently cold (below 25 K). The pressure of the liquid in the source tank is then increased by adding heat to the vapor phase. Once stratified, the liquid reaches a subcooled state and is ready to be transferred. See [9, 10] for more details on subcooled hydrogen refueling. The total hydrogen mass is measured with a high-precision scale. Results of four different refueling operations at different initial pressure and density are shown in Table 3. Temperature can be estimated from state equations (between 28 and 31 K).

Table 3. Results of refueling tests on the LHFS prototype.

Initial pressure	Initial density	Final pressure	Final density	Refueling time
barg	**kg/m3**	**barg**	**kg/m3**	**min:sec**
10,1	6,8	10,6	55,3	6:30
10,0	30,1	9,6	50,3	2:50
4,0	22,7	10,0	60,2	3:35
1,4	3,7	9,9	62,0	4:10

In the first case, the tank has no liquid hydrogen inside, only gas, and the pressure is in line with the tank's working pressure. A final density of about 55,3 kg/m3 was obtained, which is surprisingly good given the starting condition. The second case is representative of a train that decided to refuel even though the tank was already half full. Even in this non-ideal case, the target density of 50 kg/m^3 was achieved. In the third and fourth cases, some gas is removed from the tank (ideally fed back to the station) to lower pressure before the refueling. This results in higher final densities at the expense of removing some of the gas from the tank before refueling. The average refueling rate was measured at about 6,6 kg/min, but reached almost 10 kg/min in the most favorable case. This performance is nevertheless driven by the refueling station's design and could be further optimized for an industrial application.

5 Conclusions

The development of CO_2-free alternatives to replace polluting diesel trains is actively progressing. Liquid hydrogen has been identified as one very promising fuel across various sectors, particularly in aviation, as well as for high-power and high-capacity rolling stock. Due to space limitations, this paper can only cover technical results obtained on the demonstrator, while a more complete analysis would include at least safety, cost, supply chain, lifecycle emissions, comparison to other green solutions in different use cases. This article shows that the LHFS prototype that was built by Chart Industries and Alstom could meet the basic necessary requirements for rail applications, notably regarding defueling, refueling, dormancy. The prototype design can be scaled up to fit the needs of different types of rolling stock; ongoing work is related to the scaling-up of the system for rolling stock beyond 1 MW of power. The main challenges will be related to safety acceptance, dimensioning of valves, piping, refueling interfaces and evaporators, dimensioning of the heating system and reliability.

Overall, liquid hydrogen is closer than ever to be a crucial solution for transitioning to sustainable options for heavy-duty rail vehicles, an area currently lacking viable alternatives.

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References

1. Böhm, M., Fernández Del Rey, A., Pagenkopf, J., Varela, M., Herwartz-Polster, S., Nieto Calderón, B.: Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies. Int. J. Hydrog. Energy. **47**(89), 38003–38017 (2022). https://doi.org/10.1016/j.ijhydene.2022.08.279
2. Leachman, J.W., Jacobsen, R.T., Penoncello, S.G., Lemmon, E.W.: Fundamental equations of state for parahydrogen, Normal hydrogen, and orthohydrogen. J. Phys. Chem. Ref. Data. **38**, 721 (2009). https://doi.org/10.1063/1.3160306
3. Leachman, J.W., Wilhelmsen, Ø., Matveev, K.I.: Cool Fuel: the Science and Engineering of Cryogenic Hydrogen. Oxford University Press, Great Britain (2025). https://doi.org/10.1093/9780198936688.001.0001
4. Boryaev, A.A., Chernyaev, I.O.: & Zhu Yuqing: heat and mass transfer and hydrodynamics in cryogenic hydrogen fuel systems. Fuel. **321**, 124004 (2022). https://doi.org/10.1016/j.fuel.2022.124004
5. Godula-Jopek, A., Jehle, W., Wellnitz, J.: Hydrogen Storage Technologies: New Materials, Transport and Infrastructure. Wiley-VCH, Germany (2012). https://doi.org/10.1002/9783527649921
6. Rivard, E., Trudeau, M., Zaghib, K.: Hydrogen storage for mobility: a review. Materials. **12**(12), 1973 (2019). https://doi.org/10.3390/ma12121973
7. Fang, L., Dong, X., Wang, H., Gong, M.: Economic analysis of compressed gaseous hydrogen, liquid hydrogen, and cryo-compressed hydrogen storage methods for large-scale storage and transportation. Int. J. Hydrog. Energy. **162**, 150725 (2025). https://doi.org/10.1016/j.ijhydene.2025.150725
8. Matveev, K.I., Leachman, J.W.: The effect of liquid hydrogen tank size on self-pressurization and constant-pressure venting. Hydrogen. **4**(3), 444–455 (2023). https://doi.org/10.3390/hydrogen4030030
9. Pizzutilo, E., Acher, T., Reuter, B., Will, C., Schäfer, S.: Subcooled liquid hydrogen Technology for Heavy-Duty Trucks. World Electr. Veh. J. **15**(1), 22 (2024). https://doi.org/10.3390/wevj15010022
10. Maus, S.: Technology pitch: subcooled liquid hydrogen (sLH2), NOW & CEP Heavy Duty Event (2021). https://www.now-gmbh.de/wp-content/uploads/2021/05/Heavy-Duty-Event-Subcooled-Liquid-Hydrogen-sLH2-Schaefer-Linde-Maus-Daimler.pdf. Accessed 6 Mar 2026

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Enhancing Pre-standardization of Alternative Drive Trains for Improved Future Efficiency in Railways

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Abstract. In recent years, alternative drive trains—such as battery-powered trains and hybrid systems combining diesel/battery or hydrogen/battery technologies—have been developed to foster zero-carbon emission mobility in the railway sector. With the increasing deployment of these vehicles, standardizing their technologies is crucial for ensuring efficient, safe, and cost-effective solutions. Under the Europe's Rail Joint Undertaking (ERJU) and the "RAIL4EARTH" project and his work package 1 (WP1), experts are actively engaged in defining future requirements and suggesting modifications of standards and regulations to enhance interoperability, safety, and performance of these systems. Additionally, studies to create a methodology to compare alternative drive trains and related systems technologies have been achieved. The methodology will consider several criteria to have a systemic evaluation of the technologies.

These initiatives collectively aim to streamline operations at both the vehicle and broader system levels, advancing sustainable railway transport solutions.

Keywords: Railway · Decarbonization · Standardization · Energy management · Optimization of energy

1 Introduction

This work, produced after 48 months of the project, is part of the Flagship Project 4 (FP4) Rail4EARTH program under Europe's Rail initiative, which aims to accelerate the transition toward decarbonized rail mobility in Europe. The main objective of WP1 is to advance the pre-standardization of interfaces for alternative propulsion trains (Battery-Electric Multiple Units – BEMU, Hydrogen Multiple Units – HMU/HEMU, and hybrids Diesel/Battery Multiple Units – DBMU/DBEMU), optimize energy management at the railway system level, and support the integration of relevant standards for these emerging technologies.

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Within this framework, the consortium has conducted detailed analyses of existing technical and operational practices, identified key challenges in the deployment and interoperability of new propulsion systems, and engaged industry stakeholders in collaborative efforts to harmonize technical requirements. WP1 has focused on assessing current standardization gaps and recommending solutions that not only enhance the safety and performance of alternative drive trains but also facilitate scalable and cost-effective implementation across diverse European rail networks. By fostering innovation in energy management and promoting the adoption of unified standards, this research supports the broader goal of achieving significant reductions in greenhouse gas emissions and enabling the sustainable expansion of rail transport throughout Europe.

2 Pre-standardization of Interfaces

2.1 Objective and Structuration

The objective of this task was to analyze the current standardization landscape and regulatory framework related to alternative drive trains. Based on this analysis, improvements and recommendations will be proposed to support the development of alternative propulsion technologies. Pre-standardization activities have been structured into three main areas:

- Traction Battery Interfaces: addressing ease of maintenance and industrial competitiveness. A common standard would enable rapid module replacement, which is crucial for railway batteries.
- Train–Operation Interfaces: defining relevant operational data for railway operators and assessing methodologies for calculating the range of alternative drive trains.
- Train–Infrastructure Interfaces: specifying the impacts on standards for battery recharging, on-board power supply, and hydrogen refueling, in collaboration with operators, manufacturers, and infrastructure managers.

2.2 Pre-standardization of the Batteries

Regarding traction battery pre-standardization, an initial state-of-the-art review was carried out to identify and compare different types of traction batteries, also referred to as Energy Storage Units (ESU). Traction batteries are employed across nearly all categories of alternative drive trains, serving different purposes: as part of hybrid propulsion systems in combination with combustion engines or fuel cells, as the main energy source for battery-electric trains, or as auxiliary storage [1]. Moreover, traction batteries are also increasingly used in conventional electric trains operating on fully electrified lines. In this context, their primary role is to provide backup power in degraded operating conditions (e.g., substation failure), allowing the train to safely reach a station or another secure location [2]. Today, more than 1,200 railway vehicles in Europe have been identified as being equipped with on-board traction batteries (Fig. 1).

These traction batteries are built by several manufacturers, using references to different kinds of standards and specific requirements. The existing standards do not cover all the interface definitions but mainly provide requirements for tests. Therefore, the definition of interfaces has been realized, with the following mapping:

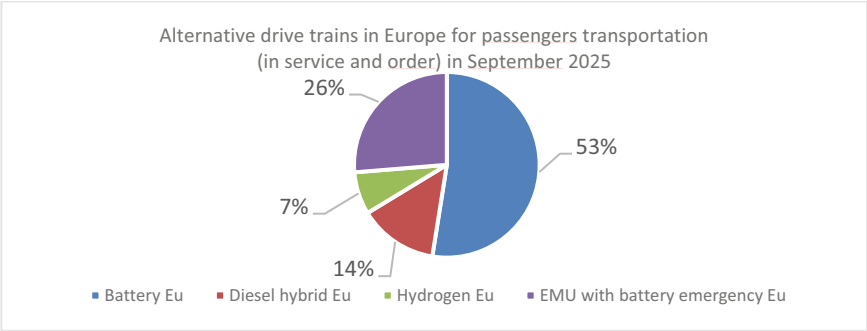


Fig. 1. Estimated trains with on-board traction batteries for passenger transportation in Europe

- Electrical interfaces (high voltage connection, low voltage connection)
- Cooling interfaces (heating and cooling of the energy storage unit)
- Mechanical interfaces (envelope of the ESU, mounting type)
- Communication interfaces (communication Protocol type, data content)

After this first step, comparison of the solutions used by the industry and exchange between train operators led to common agreements on some interfaces. The list below shows the consensus of the working group (Table 1):

Table 1. Example of interfaces and preferred solutions related to traction batteries according to RAIL4EARTH WP1 agreement

Interfaces	Recommendations for standardization
Communication	For BMS communication (inside ESU), CAN preferred. For communication between ESS and Vehicle, TCN preferred solution. Suggestion for updating IEC 62928 and IEC 62864–1
ESS parameters	Data exchanges are needed for several purposes (driver info, train operator, entity in charge of maintenance, battery passport, etc.). Identification of the parameters (name, unit, tolerance, sample rate, objective). Suggestion for updating IEC 62928 and IEC 62864–1

Several recommendations are impacting standardization with the development of new standards or the update of current standards.

2.3 Pre-standardization of Operational Interfaces

Regarding train operation interfaces, the studies focus on the Driver Advisory System (DAS) and range calculation. DAS is a solution well developed today for conventional railway vehicles. However, alternative drive trains have specific characteristics that require changes and extensions to the approach of existing DAS systems. This is especially relevant concerning the communication protocols used to exchange information

between board and ground systems. New data should be considered to provide properly optimized driving speed profiles, such as Energy Storage System state of charge (SoC) /state of energy (SoE), charging infrastructure maximum current allowed, etc. These parameters significantly affect the performance of alternative drive trains and should therefore be considered in the DAS. Concerning range calculation, the overview of functions for railway applications reveals two major findings:

– There is currently no standard for range calculation in rail applications.
– The methods used to calculate range on trains can vary significantly.
– The methodology for range estimation can be divided into three types:
– Simplified range calculation: Basic range estimation using fixed energy consumption values.
– Predictive range calculation: Advanced range estimation with pre-calculated energy consumption for a selected route.
– Real-time range calculation: Continuous range estimation considering route profile progression and factors affecting energy consumption (e.g. auxiliary loads) (Fig. 2).

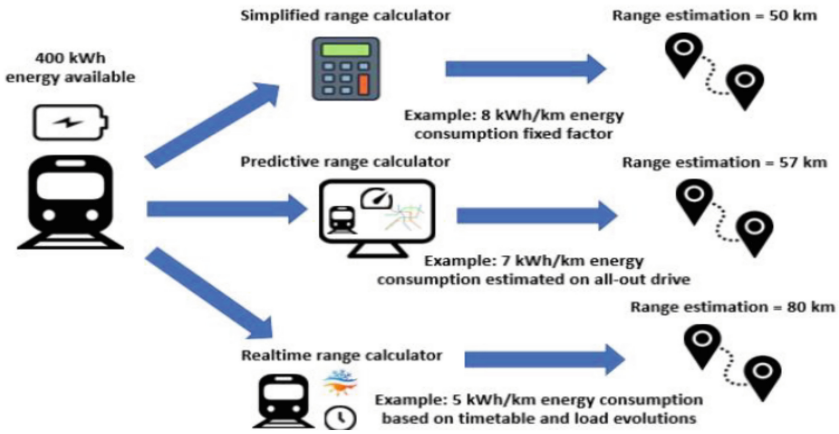


Fig. 2. Range calculator methodologies for battery train

2.4 Pre-standardization of Interfaces Between Train and Infrastructure

Regarding the interfaces between trains and infrastructure, hydrogen refueling has been thoroughly analyzed. This analysis relies on the work of several internal working groups and European projects, such as "FCH2RAIL" [3] and H2GoesRail, to examine hydrogen refueling protocols, mechanical requirements, and communication and safety needs. The study includes an exchange on the specification and impact analysis of standards for hydrogen refueling. This involves multi-stakeholder collaboration to define refueling protocols, mechanical requirements, and suitable charging profiles. Additionally, the study addresses the pre-standardization of the mechanical interface for hydrogen refueling. The hydrogen refueling requirements proposed are: 350 Bar pressure, mechanical

H35HF hydrogen receptacle according to EN ISO 17268:2020–05, Vehicle identification via GS1 tag. The conclusion emphasizes the need for an extension or adaptation of automotive standards to meet the specific requirements of rail applications.

All these recommendations on standardization and regulations will be collected and contribute to the goal of harmonization of the railway system [4] (ERJU, 2024).

3 Smart Energy Management

3.1 Objective and Structuration

The objective of this task is to enhance energy management functions and to compare various alternative drive train solutions and their associated systems (e.g., charging infrastructure, refueling stations, etc.) during the preliminary design phase. For energy management functions, the methodology applied is the state-of-the-art of the functions, with an analysis of these functions to suggest potential improvements and benefits for the application on alternative drive trains and for standardization. Concerning the comparison of alternative drive technologies, the methodology selected is the definition of a standardized process to evaluate each technology for a designated use case, considering several criteria representative of a systemic approach.

3.2 Energy Management Functions Identification and Improvements for Alternative Drive Trains

To improve alternative drive trains by increasing operational range and enhancing energy efficiency, while simultaneously reducing operational costs, effective energy management is essential. These energy management functions can be diverse and may impact traction systems, auxiliary loads (such as Heating Ventilation Air Conditioning – HVAC units), or other onboard equipment. Therefore, the proposed approach is to begin with a state-of-the-art of Energy Management Functions (EMF) for rolling stock. The following table gives some examples of functions prepared by the working group (Table 2):

The primary objective is to analyze the existing functions and determine whether improvements can be made to enhance their energy efficiency. Concurrently, recommendations for standardization or regulatory measures have been identified to:

- Ensure interoperability
- Define common requirements for interfaces and performance targets
- Establish methods to validate energy management functions, including applicable test protocols and acceptance criteria
- Reduce the costs associated with energy management functions through the implementation of common interfaces

Additionally, rolling stock hardware solutions might be used as well to improve energy efficiency. Several solutions can be applied to rail vehicles, such as defined by recent overview produced on energy savings for railway [5].

Table 2. Energy management functions list and description

Energy management functions	Description of the function	Estimated benefits
Eco-parking mode	Train mode when vehicle is at standstill. Reducing energy consumption through modifications of control systems (temperature regulation of the HVAC, lights reduction, etc.).	Energy savings up to 50% compared to standstill mode in service
BEMU charging	The traction batteries are charged during braking and from catenary via pantograph. The charging can have different strategies, based on prioritization of criteria (e.g. fast charging, optimized battery lifetime, optimized for energy costs, etc.).	Reduction of time to be ready for departure up to 3 (fast charging in DC), Battery ageing (optimized charging)

3.3 Optimization of Energy at System to Allow Fair Comparison Between Alternative Drive Technologies

An analysis of existing standards related to energy consumption calculations with IEC 63593 [6] and energy efficiency with IEC TS 63498 [7], as well as other relevant studies, was conducted to evaluate different types of traction technologies. Building on these sources, a comprehensive methodology was developed to be applied to all types of alternative drive trains and related systems. The methodological approach is structured as follows:

- Selection of a use case: describing a real or virtual railway line associated with an operational type (e.g., regional, suburban, intercity, etc.) and defining scenarios (e.g., BEMU first generation, BEMU first generation with charging station, HMU, etc.).
- Calculations are performed on an annual basis, extrapolating energy consumption over one or more cycles to establish a baseline and then combining it with operational data to determine energy consumption per day, week, and year.
- Definition of five criteria related to the railway system: Rolling Stock, Infra-structure, Operation, Energy Storage System, and Energy/CO_2.
- Each criterion is assessed using several parameters determined through the calculation process. A scoring system ranks each parameter from 0 to 10, with a maximum overall score of 50.
- The general evaluation is based on the combination of the scores across all criteria.

A summary table presents the results for the different scenarios tested within the use case. More detailed about the methodology can be found in the public deliverable of the project [8]. The table below provides an example of a general evaluation for various technologies within the same use case (Table 3):

Table 3. Evaluation table of alternative drive trains and related systems scenarios over the use case 1

Use case 1 (France)	Operation	Rolling stock	ESS	Infrastructure	Energy & CO2	System (Total)
DMU	8	5	5	8	1	27
BEMU 1st gen & New fast charging station	5	6	4	5	6	26
BEMU 2nd gen & EMF	8	5	6	9	8	36

This new methodology was initially tested on a regional railway line in France to compare three different scenarios: full electrification of the line with electric multiple units (EMUs), continued operation with diesel trains without infrastructure modifications, and battery electric trains with two options:

- First Generation BEMU (representative of current BEMUs in service, with an estimated range between 80 and 100 km) and an additional fast charging stations.
- Second Generation BEMU (so-called long-range BEMU, designed to achieve a 200 km range in battery mode) equipped with onboard energy management functions.

The evaluation identified the Second Generation BEMU as the preferred solution from a general perspective, achieving the highest scores in three main criteria: Energy Storage System, Infrastructure, and Energy/CO_2. The strong performance forecast for traction battery lifetime, the absence of required infrastructure investment, and the lowest estimated energy consumption on the route collectively indicate that the Second Generation BEMU scenario is the most promising option for this use case.

Further studies will focus on hydrogen-powered trains and other use cases to continue evaluating the effectiveness of the proposed methodology, in a similar way to other studies [9, 10].

4 Conclusion and Future Work

This paper has presented the results achieved through the RAIL4EARTH project and its work package 1. The main objectives of this working group have been accomplished, particularly in the areas of standardization and energy management. Pre-standardization activities have provided valuable input for future updates to standards and regulations concerning alternative drive trains. A total of 7 standards/regulations updates has been produced. Additionally, the exchange of experiences relating to traction batteries and hydrogen refueling has contributed to the development of new recommendations for the design of safer and more cost-effective solutions.

In the field of energy management, the analysis of functions currently implemented in both conventional and alternative drive trains has informed the definition of more advanced approaches. Seventy-seven requirements have been identified to improve the

functions on vehicles. These improvements will support the development of alternative drive trains with greater energy efficiency and extended operational range capabilities.

Concerning the comparison of alternative drive trains technologies, a future improvement by considering the full life cycle analysis, with production and recycling phases, could be developed.

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References

1. Thorne, R., Amundsen, AH., Sundvor, I.: Battery electric and fuel cell trains, maturity of technology and market status, TØI report (2019)
2. Kikkawa, K., Tasaka, Y.: Effective utilization of SCiB™ lithium-ion battery to meet needs of rolling stock. Toshiba. **76**(4) (2021)
3. Rodriguez, E., Calderon, BN.: FCH2RAIL Del. D7.4–Complementary gaps in analysis framework, FCH2RAIL deliverable (2024)
4. ERJU: System Pillar EU-RAIL and harmonisation version 1, ERJU report (2023)
5. ERJU: Energy saving in rail: consumption assessment, efficiency improvement and saving strategies, overview report, report (2024)
6. IEC: IEC 63593 Specification and verification of energy consumption (draft). 9/3108/CD (2024)
7. IEC: IEC TS 63498 System energy efficiency. 9/3135/CD (2024)
8. ERJU: D1.2 Energy management & pre-standardisation for alternative drive trains and related railway system Intermediate report no 2, ERJU deliverable (2025)
9. Marjani, S.R., Motaman, S., Varasteh, H., et al.: Assessing hydrogen as an alternative fuel for rail transport – a case study. Sci. Rep. **15**, 6449 (2025). https://doi.org/10.1038/s41598-025-90887-3
10. Streuling, C., Pagenkopf, J., Schenker, M., Lakeit, K.: Techno-economic assessment of battery electric trains and recharging infrastructure alternatives integrating adjacent renewable energy sources. Sustainability. **13**, 8234 (2021). https://doi.org/10.3390/su13158234

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Analysis of Strategies for LH2 Management Onboard Aircraft During Overnight Parking

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Abstract. Liquid hydrogen is a key enabler for decarbonizing aviation, offering zero in-flight CO_2 emissions. However, effective cryogenic storage management, especially during extended ground operations, is essential to minimize losses from boil-off gas. This study explores strategies to reduce overnight hydrogen losses for an A320-type aircraft, which typically retains 10–15% of tank capacity after its final daily flight. Two refuelling strategies are analysed: leaving the tank at partial fill overnight, and immediate post-flight refuelling to full capacity. These are evaluated alongside two airside supply infrastructure configurations: centralized fixed cryogenic storage and mobile trailer-based delivery. The thermal behaviour of the system, including tank thermodynamics, pipeline transfer losses, and insulation performance, is modelled using multi-phase, reduced-order simulations. A sensitivity analysis investigates the effects of initial thermodynamic conditions, tank design, insulation quality, and hydrogen transfer parameters on total boil-off gas. Results show that hydrogen losses are minimized with 50–75% partial post-flight refuelling. This work offers practical guidance for airport hydrogen logistics and supports the integration of liquid hydrogen into commercial aviation fuel systems.

Keywords: LH2 tank simulation · Refuelling process · Airport BOG management · Hydrogen-powered aviation · Airport infrastructure

1 Introduction

The global aviation sector is undergoing a critical transformation to mitigate its environmental impact and achieve climate-neutral operations by 2050 [1]. In this paradigm shift, liquid hydrogen (LH_2) has emerged as a leading candidate for a clean, sustainable aviation fuel, principally because it yields zero in-flight CO_2 emissions [2]. However, its adoption introduces significant engineering and logistical challenges, primarily due to its cryogenic nature. Stored at approximately −253 °C, LH_2 is susceptible to heat leakage from the surrounding environment, which causes it to continuously vaporize into the so-called boil-off gas (BOG) [3].

When hydrogen is not extracted from the aircraft tank, the BOG pressure buildup might force venting to avoid overpressure. If not properly managed, vented BOG represents not just a loss of fuel, but also a significant operational and economic hurdle [3].

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The challenge is relevant during extended on-ground stay, such as overnight parking. For an A320-type aircraft, central to many airlines' short to medium-haul operations, managing the 10–15% of LH_2 remaining in the tanks after the final flight of the day is a critical issue [1]. Inefficient management can lead to substantial overnight losses, impacting the economic viability of hydrogen-powered flight.

To address this crucial gap, a comprehensive analysis of ground-based strategies is essential. This requires evaluating the interplay between on-board tank thermodynamics and airports' refuelling infrastructure. The choice between immediate post-flight refuelling to full capacity versus leaving the tank at a partial fill level overnight presents an operational trade-off. These strategies are assessed considering different airside supply configurations: (A) a centralized fixed cryogenic storage with pipelines or (B) a more flexible distribution based on mobile trailers [4]. This paper provides a detailed analysis of these scenarios, offering practical guidance for the development of efficient airport hydrogen logistics.

2 Methodology

The hydrogen released during overnight storage is governed by the combined, interdependent effects of tank dormancy, refuelling protocols, ground distribution options, and pipeline chill-down: BOG is generated in aircraft tanks due to heat ingress and pressure control, while additional evaporation occurs during hydrogen transfer via pipelines or trailers and during the chill-down of refuelling lines. This work combines a thermodynamic tank model with sub-models for distribution and chill-down to simulate those effects. The tank model includes cryogenic hydrogen properties, heat leakage, BOG generation, and tank pressurization. Hydrogen transfer from ground to aircraft tanks is assessed, as both pipelines and trailers contribute to venting. Furthermore, since pipelines warm up when idle, their initial chill-down generates hydrogen evaporation [5] that must be modelled [6].

2.1 Storage Tank Model

CFD can provide detailed predictions on pressurization and component functionality [7, 8] but is computationally expensive. For system-level studies, reduced-order models are preferred [9]. This work adopts and extends the open-source model of Adler et al. [10], which computes evaporation, condensation, heat leaks, fluid extraction and tank weight. The tank is divided into three control volumes (gas, liquid and interface), with conservation laws applied at each interface. The following modifications are implemented to enable simulating the refuelling and the impact of entering subcooled LH_2:

- $\dot{m}_{g,out}$ and $\dot{m}_{l,out}$ are now positive for extraction, negative for refuelling.
- The convective term in the energy conservation equation for the gas phase (Equation 8 in [10]), now includes the enthalpy of entering gas, $h_{g,\,ext}$:

$$\sum \dot{m}_g h = \dot{m}_{bo} h_g - \begin{cases} \dot{m}_{g,out} h_g & , if\ \dot{m}_{g,out} > 0 \\ \dot{m}_{g,out} h_{g,\mathrm{ext}} & , if\ \dot{m}_{g,out} \leq 0 \end{cases}, \tag{1}$$

where $\dot{m}_{bo}$ is the BOG mass flux, $h_{g,\,ext}$ is the enthalpy of the entering gas, and h_g and m_g refer to the tank.

- Similarly, the liquid energy balance (Eq. 5 of [10]), with entering $h_{l,\,ext}$, is:

$$\sum \dot{m}_l h = -\dot{m}_{bo} h_g - \begin{cases} \dot{m}_{l,out} h_l & , if\ \dot{m}_{l,out} > 0 \\ \dot{m}_{l,out} h_{l,\text{ext}} & , if\ \dot{m}_{l,out} \leq 0 \end{cases}. \tag{2}$$

Vacuum insulated tanks with multi-layer insulation (MLI) are assumed, as it minimizes heat leaks [11]. The tank structure has two aluminium shells separating hydrogen, vacuum, and environment, both sized to withstand pressure differences [10]. The inner shell is designed to withstand twice the venting pressure, and a safety factor of 2 is applied to wall thickness. MLI density is assumed to be 90 kg/m^3 according to [11].

GH_2 venting starts at pressure p_{vent} and stops once it drops by Δp to the operating pressure, p_{op}. During refuelling, it is assumed that the venting mass flow rate is proportional to liquid inflow $\dot{m}_{l,out}$ and increases with fill level FL, while during dormancy it is modelled only as a function of p_{vent}. The resulting equation for venting is:

$$\dot{m}_{g,out} = \begin{cases} 0.07 \left| \dot{m}_{l,out} \right| \sqrt{p_{vent} - p_{atm}} FL, & for\ refuelling \\ 0.25 \sqrt{p_{vent} - p_{atm}}, & for\ dormancy \end{cases} \tag{3}$$

Three overnight refuelling strategies are analysed: (i) full refuelling at arrival (tank full overnight), (ii) keep arrival level (15%) with full refuelling in the morning, and (iii) partial refuelling at arrival, final fill in the morning.

H_2 thermodynamics is simulated in both refuelling and dormancy phases. During refuelling (10–30 min), the LH_2 fill level rises quickly, compressing GH_2 and requiring intense venting. During dormancy, the BOG builds up pressure possibly triggering venting; filling subcooled LH_2 reduces BOG and venting may be avoided.

2.2 Ground Distribution Model

GH_2 losses also occur in the on-ground distribution system that supplies the aircraft.

Trailer tanks (supply configuration (B)), similar to aircraft tanks but with better insulation due to no weight limits, have minimal heat ingress and higher p_{vent}. Thus, it is assumed that during transport no venting occurs and the LH_2 temperature remains constant, matching ground tank temperature. GH_2 losses occur only during trailer refuelling, modelled after aircraft tanks, with different insulation and pressure conditions.

Alternatively, underground pipelines (supply configuration (A)) can deliver LH_2 directly to the aircraft parking stands. The assumed infrastructure concept from [12] consists of a supply pipeline and a recycle pipeline used to maintain the temperature by continuously cycling the LH_2, avoiding direct evaporation but slightly warming up the LH_2. The returning flow brings this heat into the ground tank, calculated as:

$$\dot{Q}_{GT} = \dot{q}_p^{"} \left(\pi D_s L_p + \pi D_r L_p \right) / 2 \tag{4}$$

In Eq. 4, $\dot{Q}_{GT}$ is the heat into the ground tank, $\dot{q}_p^{"}$ is the heat flux determined by the insulation, D_s and D_r are the supply and recycle pipe diameters, and L_p is the pipe length, which is twice the distance between the storage tank and the airport parking stand. This heat leads to BOG within the ground tank, operating at saturation conditions. The evaporation rate is calculated as $\dot{m}_{GH2} = \dot{Q}_{GT} / \Delta h_{fg}$, using the latent heat of vaporization, Δh_{fg}.

2.3 Hose Chill-Down Model

This sub-model considers hose chill-down between the on-ground distribution system (pipeline or trailer) and the aircraft. Losses during the chill-down of the refueling hose docking into the aircraft tank depend on pipe geometry, insulation properties, and LH_2 mass flow rate. At the start of each refueling, LH_2 at 20–25 K passes through an initially warmer hose. Most of the hose is vacuum insulated, but the final connection lacks insulation and is assumed to start at ambient temperature. The initial temperature of the insulated section is estimated from the following energy balance:

$$\int_{T_{w,i}}^{T_{w,f}} C(T_w)dT = \dot{q}_p^{"}\pi\left[(D_h + t_h)^2 - D_h^2\right]L_h\Delta t \tag{5}$$

where $C(T_w)$ is the steel heat capacity from [13], $\dot{q}_p^{"}$ is the heat flux from the environment, Δt is the time between two refuelling processes (up to 8 h), D_h, t_h and L_h are internal diameter, thickness and length of the flexible hose.

When the LH_2 flow enters a warmer hose, rapid boiling occurs creating a complex two-phase flow that cools down the wall to LH_2 temperature [14]. The boiling regime (single-phase, nucleate, transition, or film boiling) depends largely on the wall temperature [6], and strongly affects heat transfer and GH_2 generation. This process is modelled using the 1D model proposed by Darr et al. [15, 16], which assumes constant mass flow rate, known pressure along the hose, and axial wall gradients (thin pipe assumption) to estimate generated GH_2 mass, m_{evap}, and mean GH_2 temperature. See [15, 16] for further details on the model.

3 Results

3.1 Effects of Aircraft Tank Refuelling Parameters

The parameters of the aircraft tank refuelling simulations are defined considering an A320-type platform. The typical volume of kerosene tank (24 m^3) is converted into LH_2 volume based on equivalent energy content, resulting in approximately 100 m^3 of LH_2, split into two 50 m^3 tanks. The tank walls are made of aluminium, with properties from [17], having internal diameter of 3.5 m and insulation composed of 57 layers of MLI. Assuming a heat leakage multiplier of 2 to account for connections and supports, the resulting heat flux is approximately 1.5 W/m^2.

Each simulation includes initial refuelling, overnight dormancy, and final morning refuelling to 95%. The variable simulation parameters are summarized in Table 1. Initial tank conditions assume saturated LH_2 at the operating pressure, with a 15% fill level at the end of daily operations. Two different LH_2 mass flow rates are considered, corresponding to pipeline- (5.0 kg/s) and trailer-based (1.5 kg/s) supply [18]. The temperature of the entering LH_2 is 20.96 K, corresponding to the saturation temperature in the ground tank (assumed 1.2 bar). In total, 400 simulations were performed, considering all combinations of the variables.

The results of one such simulation are presented in Fig. 1, showing temperature, pressure, hydrogen mass, mass flow rates for liquid and gas, and fill level over time.

Table 1. Variable parameters for tank simulations

Name	Operating pressure	Pressure rise for venting	Overnight duration	Initial refuelling target fill level	Mass flow rate
Symbol	p_{op} [bar]	Δp [bar]	Δt_{tot} [h]	FL_i [%]	$\dot{m}_{LH_2}$ [kg/s]
Values	2, 3, 4, 5, 6	0.25, 0.5, 0.75, 1	6, 8	15, 25, 50, 75, 95	5.0, 1.5

Figure 1(a) shows that the inlet flow of subcooled LH_2 significantly affects the stored liquid temperature, and during early refuelling it delays pressure build-up and extends dormancy time. Venting occurs just before the morning refuelling, as highlighted in Fig. 1(d) and (e), which show pressure and flow rate variations. The venting during dormancy is less intense and lasts longer compared to the one during refuelling due to the lower GH_2 flow rate, as modelled in Eq. 3.

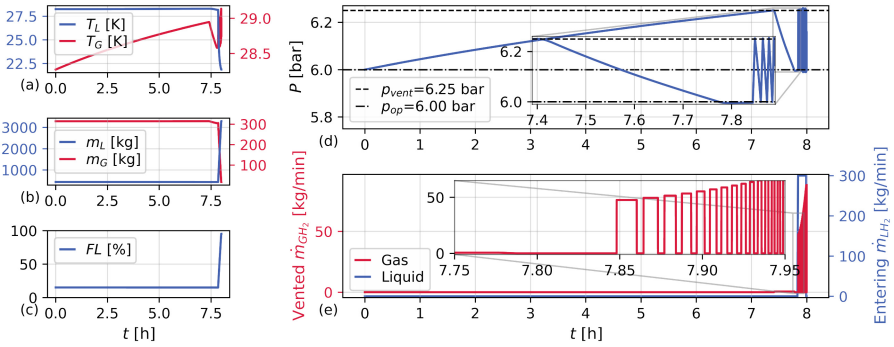


Fig. 1. Tank overnight simulation results with $p_{op} = 6$ bar, $\Delta p = 0.25$ bar, $\dot{m}_{LH_2} = 5$ kg/s, $\Delta t_{tot} = 8$ h and $FL_i = 15$ %.

The simulations also evaluate the total amount of hydrogen vented and the tank gravimetric efficiency, defined as $\eta_{eff} = m_{H_2}/(m_{H_2} + m_{tank})$, where m_{H_2} includes both the liquid and gaseous hydrogen masses after final venting to reach p_{op} while m_{tank} is the mass of the tank shells and insulation.

Key findings from the complete set of tank simulations are summarized in Fig. 2. Figure 2(a) shows the mass of vented GH_2 varying with initial fill level FL_i, for different p_{op} and Δp, with $\dot{m}_{LH_2} = 5$ kg/s and $\Delta t_{tot} = 8$ h. Results indicate that Δp has limited influence compared to p_{op} and refuelling strategy. Higher p_{op} results in greater vented mass, because of the large initial GH_2 mass. Evening refuelling to approximately 75% appears optimal, as it balances temperature control and pressure buildup. In fact, the ingress of subcooled LH_2 slowly lowers gas temperature, reducing pressure and delaying venting. This effect is not sufficient for the highest initial fill levels, where the GH_2 has no time for cooling from subcooled LH_2. In fact, filling completely the tank in the evening leads to the highest losses. Figure 2(b) displays the gravimetric efficiency η_{eff} across

the same range of p_{op} and Δp. As expected, lower operating and venting pressures yield higher η_{eff} since thinner tank shells are required, reducing overall tank weight. Figure 2(c) illustrates the influence of $\dot{m}_{LH_2}$ and Δt_{tot} on the vented GH_2, showing a minor effect compared to other parameters. The difference in the vented hydrogen between the two mass flow rates is negligible, except for $FL_i = 95$ %. In this latter case, for all p_{op}, not shown here, the difference remains below 10%.

The results for the configuration studied show that maximum η_{eff} and minimal BOG venting are achieved by operating at low p_{op} and by partial evening refuelling.

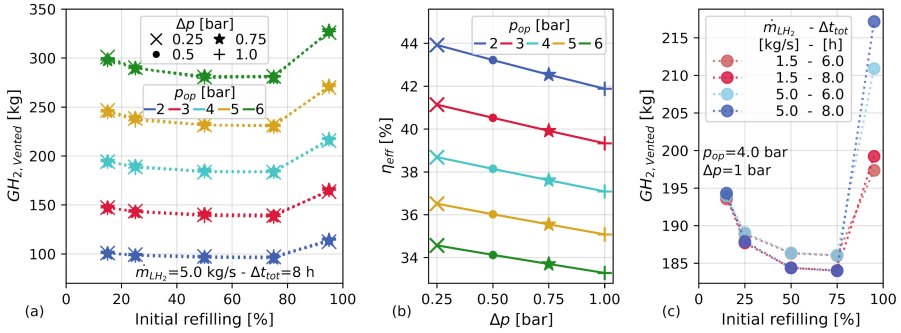


Fig. 2. Vented hydrogen and gravimetric efficiency for different set of parameters

3.2 Influence of On-Ground Distribution Options

LH_2 losses for the two on-ground distribution options, are compared. For the trailer-based configuration (B), it is assumed that one trailer fills one aircraft tank and vents GH_2 only during its own refuelling, as described in Sect. 2.2. One simulation is performed, assuming an initial pressure of 1.2 bar, $p_{op} = 10$ bar, and $p_{op} = 11$ bar. Under these conditions, each trailer vents approximately 51.2 kg of hydrogen. This amount is added to all cases involving the trailer-based distribution.

In the pipeline scenario (A), the ground storage (1.2 bar) is 2 km from the airport; considering supply and return, the total length is 4 km. Table 2 presents key simulation parameters (see also [12]) and the resulting hydrogen evaporation overnight.

The evaporated mass, eventually vented from the ground tank, is distributed among all aircraft parked. Therefore, the pipeline option results in less vented GH2 compared to the trailer-based if the number of overnight-parked aircraft is at least 10 for $\Delta t_{tot} =$ 6 h, and at least 13 for $\Delta t_{tot} = 8$ h. This comparison allows for a qualitative evaluation of the two options based on airport size. Although subject to multiple assumptions, it can provide a conceptual design guideline, as trailer-based losses are fixed per aircraft, while pipeline losses scale more favourably with the number of aircraft.

Table 2. Parameters and evaporated hydrogen mass for pipeline-based distribution

$\dot{q}_p^{"}$	D_s	D_r	L_p	Δh_{fg}	$\dot{m}_{GH_2}$	$m_{GH_2,6h}$	$m_{GH_2,8h}$
5.0 W/m^2	0.45 m	0.20 m	4 km	445.75 kJ/kg	0.0458 kg/s	**990 kg**	**1319 kg**

3.3 Contribution of Refuelling Hose Chill-Down to GH_2 Generation

The hose connecting aircraft and on-ground distribution is 6.0 m long, with the final 0.25 m without insulation, heating up to 300 K after refuelling. The remaining insulated section warms up between refuelling events (Eq. 5), assuming the hose is emptied after each operation and starts at 20.96 K, the saturation temperature of LH_2 in the ground tank ($p_{sat} = 1.2$ bar). Two different $\dot{m}_{LH_2}$ values are considered, corresponding to pipeline and trailer options. Table 3 summarizes the simulation parameters.

Hose internal pressure of 2 bar is assumed, which results in the largest amount of generated GH_2 mass during chill-down. The evaporated GH_2 mass, calculated with a 8 h time interval between refuelling events, is 0.92 kg and 0.84 kg for trailer and pipeline option, respectively. Since these values are two orders of magnitude smaller than the ones estimated from the aircraft tank refuelling process, this effect is considered negligible.

Table 3. Refuelling hose simulation parameters

D_h [m]	t_h [mm]	L_h [m]	L_{end} [m]	$\dot{q}_h^{"}$[W/m^2]	$\dot{m}_{LH_2,pipe}$[kg/s]	$\dot{m}_{LH_2,trailer}$[kg/s]
0.10	2.0	5.75	0.25	2.0	5.0	1.5

4 Conclusions

This study analyses various strategies for managing hydrogen logistics overnight in airports. A set of simulation models estimates GH_2 losses and assess the influence of key parameters.

The results indicate that minimizing hydrogen losses requires operating aircraft tanks at low pressure and keeping venting pressure low to improve gravimetric efficiency. A peculiar result is that partial refuelling to 50–75% minimizes evaporation, whereas fully filling the tanks at once (in the morning or evening) increases vented hydrogen. Factors such as hose chill-down, refuelling mass flow rate, and overnight stop duration are found to have a comparatively smaller impact. The configuration of on-ground distribution has limited influence on overnight losses, and should be selected based on airport size and operational context.

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References

1. Melosevich, K.C.M.: Design of a Hydrogen near Zero Emission Passenger Aircraft. Hamburg University of Applied Science (2024)
2. Clean Aviation Joint: Hydrogen-powered (2020). https://www.clean-aviation.eu/news-events/hydrogen-powered-aviation
3. Naquash, A., Agarwal, N., Lee, M.: A review on liquid hydrogen storage: current status, challenges and future directions. Sustainability. **16**(18), 8270 (2024)
4. Gordon, J.: The Role of Hydrogen in Aviation Decarbonization. NASA (2023)
5. Brennan, J.A., Brentari, E.G., Smith, R.V., Steward, W.G.: Hydrogen as a Possible Fuel for Aircraft, NASA Technical Note D-4030. NASA (1966)
6. Hartwig, J., Hu, H., Styborski, J., Chung, J.: Comparison of cryogenic flow boiling in liquid nitrogen and liquid hydrogen chilldown experiments. Int. J. Heat Mass Transf. **88**, 662–673 (2015)
7. Wang, L., Li, Y., Li, C., Zhao, Z.: CFD investigation of thermal and pressurization performance in LH2 tank during discharge. Cryogenics. **57**, 63–73 (2023)
8. Molkov, V., Ebne-Abbasi, H., Makarov, D.: Liquid hydrogen refuelling at HRS: description of sLH2 concept, modelling approach and results of numerical simulations. Int. J. Hydrog. Energy. **93**, 285–296 (2024)
9. Al Ghafri, S.Z., et al.: Modelling of liquid hydrogen boil-off. Energies. **15**, 3 (2022)
10. Adler, E.J., Martins, J.R.: Liquid hydrogen tank boil-off model for design and optimization. J. Thermophys. Heat Transf., 1–15 (2025)
11. Huete, J., Pilidis, P.: Parametric study on tank integration for hydrogen civil aviation propulsion. Int. J. Hydrog. Energy. **46**(74), 37049–37062 (2021)
12. Krog, S., H., et al.: Large-scale LH2 pipeline infrastructure concept for airports. Int. J. Hydrog. Energy. **163** (2025)
13. NIST, webpage: Material properties – cryogenics technologies group. https://trc.nist.gov/cryogenics/materials/materialproperties.htm
14. Hu, H., Chung, J.N., Amber, S.H.: An experimental study on flow patterns and heat transfer characteristics during cryogenic chilldown in a vertical pipe. Cryogenics. **52**(4–6), 268–277 (2012)
15. Darr, S.R., et al.: Numerical simulation of the liquid nitrogen chilldown of a vertical tube. In: 53rd Aiaa Aerospace Sciences Meeting (2015)
16. Darr, S.R., Hartwig, J.W.: Two-phase convection heat transfer correlations for liquid hydrogen pipe chilldown. Cryogenics. **105**, 102999 (2020)
17. Durr, C.: Cryogenic Fluid Management Technology Development for Propulsion Applications, NASA/TP-2006-214296 (2006)
18. Mangold, J., et al.: Refueling of LH2 aircraft-assessment of turnaround procedures and aircraft design implication. Energies. **15**(7), 2475 (2022)

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Hydrogen Train Scenarios in Passenger and Freight Transport from Europe and North America: Simulation of Thermal Management

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Abstract. Hydrogen-powered trains present a sustainable alternative to diesel-powered trains for railway transport of passengers and freight. Hydrogen as an energy carrier is cost-intensive, which is why energy demand should be reduced in all relevant operational scenarios. Since thermal losses are one of the main reasons for efficiency reductions, the presented work investigated the research question: Can hydrogen-powered trains combined with targeted energy management strategies be simulated and potential energy efficiency gains be quantified for European and North American scenarios?

A digital railway vehicle simulation framework is developed, which models longitudinal dynamics and energy management. The framework is built with standardized functional mock-up interfaces (FMI) for component sub-models to enable a co-simulation with models from different entities. As input for the simulations, different passenger and freight transport scenarios from Europe and North America are used. Requirements for hydrogen-powered trains vary greatly for different use cases of passenger and freight transport, as well as the location with its surrounding climate. Recuperation of braking energy in freight transport is challenging and remains an opportunity for further enhancement. For passenger transport, metal hydride cooling systems can provide additional cooling capacity and reduce electrical energy demand for air conditioning.

Keywords: Hydrogen trains · Energy management · Passenger transport · Freight transport · Simulation framework

1 Introduction – Hydrogen Trains and their Characteristics

In recent years, hydrogen trains have been steadily developed and tested so that they are now a possible option for providing rail transport on track sections without catenary. Some hydrogen trains are developed as hybrid trains, which makes it possible for them to use the external power supply from catenary as well as the internal power supply from the hydrogen-based power train [1]. In Germany, three fleets of hydrogen trains

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are operational in regional passenger transport in 2025 with 7 to 27 vehicles [2]. Even for the smallest of these fleets around 1 million train km/year with a hydrogen demand of over 200 t/year are stated [3]. In North America, the first hydrogen passenger train started its service in September 2025 [4]. Components specific for hydrogen trains compared to other rail vehicles are fuel cells and hydrogen tanks. Most rail vehicles use 350 bar hydrogen storage compared to 700 bar storage, which is established for passenger cars [5]. For the optimization of hydrogen vehicles different components are under development to increase efficiency. The pressure difference between tank and fuel cell can be leveraged by an expansion engine to recover additional energy [6]. The pressure difference can also be used by metal hydride reactors to provide an additional cooling capacity which can be used for air conditioning in the cabin of hydrogen trains [7]. These systems are referred to as HyPAC (Hydrogen Powered Air Conditioning).

Overall, the energy management of hydrogen trains is challenging as it is necessary to satisfy the energy demands from the power train and auxiliaries under a wide range of operational conditions. Especially at very low or high ambient temperature the thermal management of rail vehicles must take into account high energy demand to cool or heat the cabin [8]. For a regional train the thermal power demand for heating can be up to 92 kW [9]. To evaluate all kinds of conditions, simulation models of rail vehicles are widely established. They are used to optimize speed profile and power control of the vehicles in a digital environment [10]. Especially, the trajectories of the vehicles can be optimized utilizing a direct method solver to find the minimum energy trajectory [11]. Simulations tools are also used to size hybrid traction systems, especially fuel cells and batteries, the key components in the energy management [12]. The sizing process for hydrogen trains is sensitive to input parameters such as the environmental conditions, which vary over the climate zone and the continent of operation. In Europe for example, a lot of tracks are equipped with catenary whereas in North America mostly catenary-free operation is performed by rail vehicles. The configuration of the train and propulsion system is also different if it is designed for passenger operation or for freight transport. Freight transport is mainly performed by locomotives which pull freight wagons. In North America they can reach a length of up to 3 km, whereas in Europe they are normally maximum 750 m long. Passenger transport is mainly performed with multiple units which have an integrated traction system and a large cabin for passengers.

The state-of-the-art analysis shows that optimization for hydrogen trains is focusing on reducing the energy demand in operation. Thermal management is a key component in this optimization process as HVAC systems require up to 30% of energy demand [13]. Nevertheless, the conditions for the operation of hydrogen trains vary greatly, so that the research question for this work is: Can hydrogen-powered trains combined with targeted energy management strategies be simulated and potential energy efficiency gains be quantified for European and North American scenarios?

2 Methodical Approach - Simulation Framework for Rail Vehicles

To study the energy management in hydrogen trains a simulation framework called *pySimRail* is developed in Python. The framework uses parameter sets of environmental conditions, track profile and vehicle parameters as input to calculate the energy demand

of the vehicle. As environmental conditions, the ambient temperature, radiation and wind speed can be taken into account among other parameters. As track profile input, the different stations are listed with the intervals to the next station in terms of time and distance. In addition, the speed limit and gradient needs to be specified over the track distance. As vehicle parameters, the length, mass and Davis coefficients are listed in the input parameters set among other specifications of components such as efficiency or maximum power output.

Hydrogen tanks, fuel cells, batteries, traction motors and auxiliaries are sub-systems which are modelled in the simulation framework of a hydrogen train (see Fig. 1). The losses of these sub-systems are captured by using standard efficiency ratios for the components. The motor is represented by a steady-state equivalent-circuit model augmented with control logic that adjusts voltage and frequency to minimize losses. The model is used to calculate both motor operation for acceleration and alternator operation for regenerative braking. The battery model uses an equivalent-circuit model to estimate terminal voltage, ohmic losses, and to update state of charge. In addition, sub-systems like the hydrogen powered air-conditioning (HyPAC) can be included to study their effects on efficiency on vehicle level. The sub-models can be integrated as functional mock-up units (FMU) based on the functional mock-up interface (FMI) standard. This standardized interface allows a high flexibility in changing the implemented sub-models and enables co-simulation for component models from different parties. The code and equations of the model are not visible if it is packed as FMU, which makes it possible to share sub-models without disclosing intellectual property. In the simulation framework setup for this work, the models for battery, traction motor and traction motor inverter are developed by NRC as FMUs. Tank, fuel cell, HyPAC, auxiliaries, converters and other inverters are modelled by DLR. All sub-models are combined in the same simulation framework to perform the simulations.

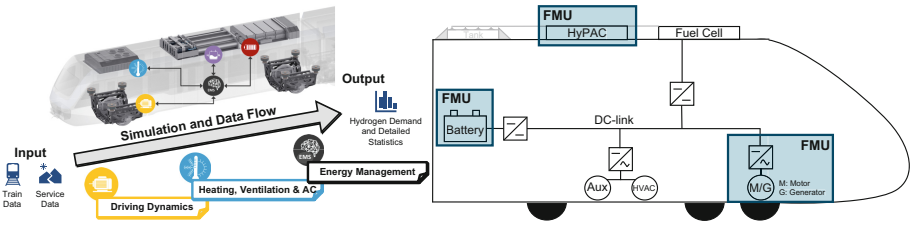


Fig. 1. Sub-models and simulation process of the rail vehicle simulation framework

The simulation process begins with loading the input parameter sets into the simulation framework. The simulation is then performed in three stages. The first stage simulates the driving dynamics. The vehicle trajectory is calculated by taking into account the track profile and the driving resistance based on the Davis coefficients. In the second stage the thermal power demand for HVAC is calculated based on the vehicle trajectory. In the simulation's third stage, energy demand for traction and HVAC is used to compute component-level energy demand and to run the energy management strategy. The energy management determines, based on vehicle state and operating conditions,

whether the battery or the fuel cell supplies the required power. Like in a finite state machine, the power output of the fuel cell is determined based on the current traction and auxiliary demand, as well as the state of charge of the battery. The battery then aims to meet the remaining demand or absorbs any excess power, thereby stabilizing the main DC-link voltage. All three stages of the simulation framework are combined to calculate the overall energy demand of a rail vehicle in a specific scenario.

As scenarios for this work, six track profiles from Europe and North America are defined in Table 1. The length of this scenarios varies from 165 km to 2,070 km. The meters climbed with positive elevation gain from start to final destination is only 118 m in track scenario 1 as it describes a scenario in Northern Germany where the landscape is flat. In comparison to this the scenarios from Spain and Canada show higher differences in elevation which must be considered when calculating energy demand.

Table 1. Track scenarios.

Track scenario	1	2	3	4	5	6
Country	Germany	Spain	Spain	Canada	Canada	Canada
Type	Pass.	Pass.	Pass.	Pass.	Pass.	Freight
Length in km	165	1,343	442	2,070	1,492	1,127
Stations	33	49	27	7	33	3
Meters climbed	118	4,842	1,578	5,472	1,959	1,720

In addition to the track scenarios, vehicles parameter sets are defined in Table 2. Vehicle parameter set 1 is used for the simulation of passenger use cases in combination with track scenarios 1 to 5. Vehicle parameter set 2 is used for the simulation of Canadian freight transport in track scenario 6.

Table 2. Generic hydrogen rail vehicle parameter sets.

Vehicle parameter set	1	2
Type	Passenger	Freight
Vehicle length	42 m	3,000 m
Vehicle mass	95 t	24,000 t
Number of cars	2	164
Passenger seats	120	–
Max. speed	140 km/h	40 km/h
Hydrogen capacity	200 kg	10,000 kg
Battery capacity	300 kWh	5,244 kWh
Max. fuel cell power	400 kW	7,200 kW

The passenger transport vehicle set describes hydrogen electric multiple units (HEMU) with 2 cars in the vehicle. The freight transport vehicle parameter set 2 describes a freight train with 6 locomotives, 6 tenders and 152 freight cars. The vehicle length, mass as well as the power levels of the components are higher for this scenario as the energy demand rises with the overall vehicle mass. The presented track scenarios are simulated with the *pySimRail* simulation framework in combination with the respective vehicle parameter sets. The scenarios are simulated at summer conditions at 30 °C and at winter conditions at −20 °C. For all conditions a reference simulation is performed to calculate the overall energy and hydrogen demand. In addition, an option with optimized thermal management is simulated. For summer conditions, it takes into account the exemplary usage of HyPAC to cool the cabin in the vehicle. However, this model is not optimized for the focused cabin and therefore, the cooling power reduction cannot be assessed quantitatively, as the metal hydride mass is at least five times lower than expected for this application. The usage of this model demonstrates how this simulation frameworks allows to implement various energy improvement strategies. For winter conditions, the optimized option considers the fuel cell waste heat to heat the cabin. The comparison of these scenarios will be presented in the results of the following Sect. 3.

3 Results and Discussion - Energy Demand of Hydrogen Trains in Europe and North America

The scenarios introduced in Sect. 2 are simulated to determine the energy demand accordingly. The hydrogen demand is presented in Fig. 2 for the track scenarios 1, 2 and 3. For the reference passenger transport cases the hydrogen demand is between 13.56 kg/100 km and 15.03 kg/100 km in the base case of the blue bars, which corresponds to the order of magnitude stated by the FCH2RAIL project [14].

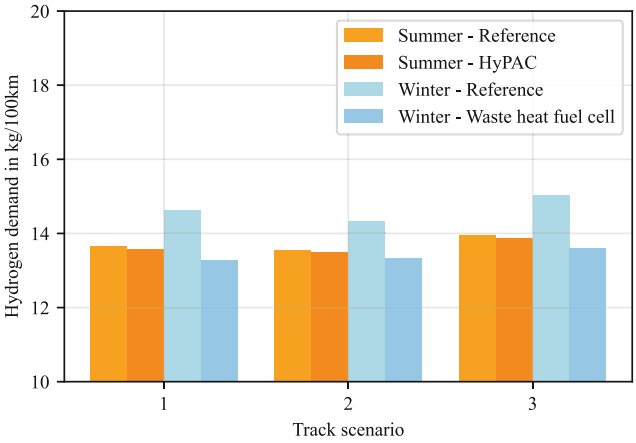


Fig. 2. Hydrogen demand for track scenarios from Table 1 in reference case and optimized case with HyPAC and utilization of waste heat from the fuel cell

The hydrogen demand varies over the three presented track scenarios as the gradients and mean velocities are different. The overall hydrogen demand for these cases is between 22.6 kg and 192.3 kg and is mainly depending on the length of the scenario. For the freight case from Table 1, the overall energy demand sums up to around 10,000 kg of hydrogen. The presented case represents an extreme energy demanding edge case because of the high vehicle weight, length and the gradient on the track as it was parametrized as a fully loaded train driving from the mountains to the coast. This results in an average hydrogen demand of 873.0 kg/100 km.

The orange bars in Fig. 2 compare the summer reference case with the summer HyPAC case. The difference between the bars is the potential reduction in energy demand if HyPAC systems are used as part of the thermal management. For the three passenger cases this leads to a reduction in energy demand by 0.4% to 0.6% for the overall vehicle. An energy reduction potential is shown, but these values do not correlate with expected values of such a vehicle, as the HyPAC's metal hydride mass is at least five times lower than expected for the cooling demand in this passenger carriage. The blue bars compare the winter reference case with a winter case where the waste heat from the fuel cell is used to heat the cabin. The energy demand is reduced by 6.8% to 9.2% by the utilization of the fuel cell waste heat.

For the freight case, the potential for a reduction of energy demand is lower. The energy demand for HVAC is lower and the demand for traction is higher compared to the passenger transport scenarios. As HyPAC systems and waste heat utilization reduce HVAC energy demand, passenger transport cases represent the main intended application for these technologies. For freight trains the share of recuperated energy from braking is low currently, but a re-sizing of batteries for regenerative braking could be part of future work for optimized energy management in hydrogen freight trains.

For a more detailed analysis of the energy demand the split in energy of scenario 1 is presented in Fig. 3. The provided energy is visible on the left of the figure by hydrogen, battery discharge and recuperation. Energy is provided to the DC-link of the vehicle and distributed from there into the energy demand of different parts.

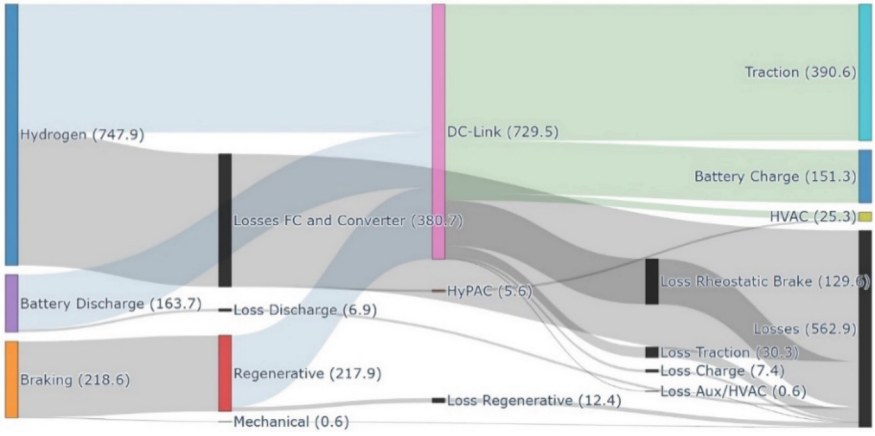


Fig. 3. Energy split in the hydrogen train in kWh in scenario 1 as Sankey diagram

The overall energy demand consists of the losses in the different components, the charging of the battery, the traction and HVAC. All losses are marked in black in the Sankey diagram. Over the scenario the losses sum up to 562.9 kWh. Most of these losses occur in the fuel cell system and the corresponding converter with 380.7 kWh.

HVAC energy demand sums up to 25.3 kWh in scenario 1. The HyPAC system can provide 5.6 kWh out of the HVAC energy demand. This leads to a reduction of HVAC energy demand from the DC-link of 22%. Therefore, HyPAC systems represent an innovative technology as part of a thermal management strategy to reduce energy demand in hydrogen trains for passenger transport.

4 Conclusion

Hydrogen train scenarios from Europe and North America are simulated in this work and the corresponding energy demand is calculated. For the simulation the *pySimRail* simulation framework is used, which is able to implement sub-models for individual components from several parties. The simulation results show that the hydrogen demand for passenger use-cases is significantly lower than for freight use-cases. For passenger use-cases, a hydrogen demand between 22.6 kg and 192.3 kg was calculated. An optimized thermal management strategy based on metal hydride cooling systems (HyPAC) can reduce electrical energy demand for HVAC in hydrogen trains. However, a detailed study how much this technology can reduce the energy demand with a custom design needs to be assessed. For freight trains this technology leads to less improvements as the energy demand for cooling is lower. Overall, freight trains represent a demanding scenario for decarbonization as the vehicle weight and length are high. For the simulated case in this work an overall hydrogen demand of up to 10,000 kg were calculated for a track length of around 1,100 km. New hybridization strategies between fuel cell and battery show potential to reduce this energy demand by taking advantage of regenerative braking also in freight trains. The investigation of better leveraging braking energy for higher efficiency as well as thermal management strategies for high ambient temperatures represent future work based on the presented results.

References

1. Kühlkamp, F., et al.: The FCH2RAIL project: a demonstration of a modular fuel cell hybrid power pack. Transp. Res. Procedia. **72**, 1491–1498 (2022). https://doi.org/10.1016/j.trpro.2023.11.615
2. Wieser, S., Brünner, L., Böhm, M., Soto, M., Rodríguez, E.J.: Development, application and optimization of hydrogen refueling processes for railway vehicles. Int. J. Hydrog. Energy. **124**, 331–344 (2025). https://doi.org/10.1016/j.ijhydene.2025.04.040
3. Herwartz, S., Pagenkopf, J., Streuling, C.: Sector coupling potential of wind-based hydrogen production and fuel cell train operation in regional rail transport in Berlin and Brandenburg. Int. J. Hydrog. Energy. **46**(57), 29597–29615 (2021). https://doi.org/10.1016/j.ijhydene.2020.11.242
4. Global Railway Review: US' first hydrogen passenger train ZEMU to debut this weekend. https://www.globalrailwayreview.com/news/230200/us-first-hydrogen-passenger-train-zemu-to-debut-this-weekend/ (2026). Accessed 28 Apr 2026

5. Böhm, M., Del Fernández Rey, A., Pagenkopf, J., Varela, M., Herwartz-Polster, S., Nieto Calderón, B.: Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies. Int. J. Hydrog. Energy. **47**(89), 38003–38017 (2022). https://doi.org/10.1016/j.ijhydene.2022.08.279
6. Wieser, S., Muck, N., Scharmach, M.: Hydrogen expansion work in fuel cell electric passenger and heavy-duty vehicles by simulative assessment: a comparison. IEEE Ind. Appl. Mag. **29**(2), 59–69 (2023). https://doi.org/10.1109/MIAS.2022.3214021
7. Kordel, M., Heeland, M.M., Knetsch, K.: Waste energy AC technologies in H2-multiple units. In: Nießen, N., Schindler, C. (eds.) IRSA 2023 Proceedings (2024). https://doi.org/10.18154/RWTH-2024-00257
8. Wieser, S., Schenker, M., Schwurack, H., Hoffmann, F., Donner, S., Konrad, M.: Efficient air conditioning of battery-electric multiple units (BEMU): Modeling and optimization. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Lecture Notes in Mobility. Transport Transitions: Advancing Sustainable and Inclusive Mobility, pp. 485–491. Springer Nature, Switzerland (2025). https://doi.org/10.1007/978-3-031-89444-2_71
9. Wieser, S., Naveau, L., Kraft, W., Beristain, R.A., Anson, A.: Modeling and simulation of thermal management in battery electric rail vehicles for the sizing of thermal storage systems. Energy Convers. Manag. **346**, 120489 (2025). https://doi.org/10.1016/j.enconman.2025.120489
10. Schenker, M., Kühlkamp, F.: Optimization model for operation of battery multiple units on partly electrified railway lines. In: 2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), pp. 1–8. IEEE (2021). https://doi.org/10.1109/EVER52347.2021.9456608
11. Schenker, M., Schirmer, T., Dittus, H.: Application and improvement of a direct method optimization approach for battery electric railway vehicle operation. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. **235**(7), 854–865 (2021). https://doi.org/10.1177/0954409720970002
12. Pugi, L., Berzi, L., Cirillo, F., Vecchi, A., Pagliazzi, V.: A tool for rapid simulation and sizing of hybrid traction systems with fuel cells. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. **237**(1), 104–113 (2023). https://doi.org/10.1177/09544097221092622
13. Buonomano, A., Forzano, C., Giuzio, G.F., Palombo, A., Russo, G.: Energy efficiency and indoor thermal comfort of railway carriages: development of an innovative passenger-centric-control framework for HVAC systems. Energy. **307**, 132440 (2024). https://doi.org/10.1016/j.energy.2024.132440
14. Pagenkopf, J., et al.: FCH2RAIL deliverable D6.1 – Report on KPI assessment. FCH2RAIL Project Report. https://fch2rail.eu/project-results/fch2rail-deliverable-d6-1-report-on-kpi-assessment/ (2024). Accessed 28 Apr 2026

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Bremen's Approach to Hydrogen and PtX Applications - A Comprehensive Overview

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Abstract. Bremen, Germany's smallest federal state, consists of the city of Bremen and, 57 km to the north, the city of Bremerhaven on the mouth of River Weser with one of Europe's largest container terminals. Both the city of Bremen and Bremerhaven are integrated into three Trans-European Transport Network (TEN-T) corridors. With their strategic location and advanced multimodal infrastructure, Bremen and Bremerhaven serve as essential hubs for European freight transport. In 2020, total CO_2 emissions from final energy consumption in the federal state of Bremen amounted to 7.972 million tonnes, mainly attributed to the ArcelorMittal steelworks located in Bremen and the transport and mobility sector. In order to reduce this carbon footprint, Bremen initiated a number of initiatives and projects in different contexts like production, transport, mobility, and maritime logistics on regional, national, and European level. Based on a literature analysis, this paper provides a comprehensive overview of Bremen's respective activities related to carbon footprint reduction by applying hydrogen-based technologies and puts them into the European context. In the next step, the drivers of the green energy transition in Bremen are identified following a qualitative content analysis approach. The paper's focus is on hydrogen and Power-to-X applications in transport and mobility related to goods and passengers as well as maritime logistics.

Keywords: Carbon Footprint Reduction · Hydrogen Valley · Power-to-X · Mobility · Maritime Logistics

1 Introduction

In 2019, the European Commission (EC) launched the European Green Deal [1], outlining a vision for a sustainable, competitive, and climate-neutral Europe. The goal was to achieve net-zero greenhouse gas emissions by 2050 while fostering economic growth independent of resource consumption. To support this transition, the 'Fit for 55' legislative package [2] sets the framework for reducing the EU's net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. In July 2020, the EU H_2 Strategy [3] was adopted to facilitate clean hydrogen production in Europe and by the first quarter of 2022, all of its 20 action points were implemented and delivered. The REPowerEU

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plan [4] delivered in May 2022 assigns to renewable hydrogen a pivotal role to replace natural gas, coal and oil in transport and industry towards a hydrogen economy with a target of production of 10 million tonnes of domestic renewable hydrogen and 10 million tonnes of renewable hydrogen imports by 2030. Finally, the Clean Industrial Deal (CID) [5], which was presented by the European Commission in February 2025, is a transformative strategy aimed at making Europe's industry more competitive, circular, and climate-neutral. As a key pillar of the European Green Deal, it seeks to balance decarbonization, reindustrialization, and innovation while reinforcing Europe's resilience in a shifting global economy.

Bremen, Germany's smallest federal state and also referred to as the Free Hanseatic City of Bremen, consists of the city Bremen with about 585,000 inhabitants and, just 57 km to the north, the city of Bremerhaven on the mouth of River Weser with about 119,000 inhabitants and one of the world's largest container terminals. Bremen as well is a leading hub in the space as well as aviation and aerospace sector, featuring an international airport and renowned companies such as Airbus, Ariane Group, and OHB Space Systems. Additionally, the city is home to the ArcelorMittal Bremen steel plant. Bremen occupies a strategically vital position within the Trans-European Transport Network (TEN-T) [6]. With their strategic location and advanced multimodal infrastructure, Bremen and Bremerhaven serve as essential hubs for European freight transport, further strengthening Bremen's role as a key logistics and transport centre in Europe. As the second largest port location in Germany, the Bremen and Bremerhaven ports in 2024 moved 62 million tonnes of cargo. In total, 4.4 million standard containers were shipped.

In 2020, the total CO_2 emissions from final energy consumption in the state of Bremen amounted to 7.972 million tonnes. The largest share was attributed to steelworks, which accounted for 4.042 million tonnes. Actually, the city is home to the steel plant ArcelorMittal Bremen, a major industrial site that emits roughly 50% of Bremen's total annual CO_2 emissions. The mobility sector as a whole contributed 1.202 million tonnes (15%), with road transport being the dominant source at 1.054 million tonnes. Other mobility-related emissions included 58,000 t from coastal and inland shipping, 36,000 t from aviation, and 54,000 t from rail transport [8]. This paper to a part bases on information contained in the H2B:IMPACT project application.

2 Methodology

This paper provides a comprehensive overview of Bremen's activities related to carbon footprint reduction by applying hydrogen-based technologies obtained through a literature analysis. In the next step, the drivers of the green energy transition in Bremen are identified following a qualitative content analysis approach [9], followed by a description of the strategies and plans with regard to the establishment of a Hydrogen Valley in Bremen.

3 Literature Analysis

In order to reduce the mentioned CO_2 emissions, the state of Bremen in November 2019 adopted the North German Hydrogen Strategy [10] in conjunction with the other four North German states. In reaction to the abovementioned European strategy in 2020,

the Bremen senate in December 2021 adopted the "State of Bremen Hydrogen Strategy" [11]. Furthermore, the current Innovation Strategy of the State of Bremen "Key to Innovations 2030 – Strategy for Innovation, Services and Industry" identified hydrogen technology as an innovation driver and central element for sustainable economic management and efficient use of resources [12].

Hydrogen is already being utilized on a smaller scale across various industries in the state of Bremen. Looking ahead, hydrogen's potential as an energy source will be expanded across multiple sectors. The transition to a hydrogen economy will be prioritized in industries where replacing fossil fuels with renewable electricity is not feasible. In Bremen, this applies particularly to the steel industry, which is expected to have a significant hydrogen demand. Additionally, hydrogen will play a crucial role in decarbonizing the shipping, aviation, and heavy goods vehicle (HGV) sectors, which are key pillars of Bremen's economy.

In this context, the Bremen Hydrogen Strategy integrates various initiatives into a comprehensive framework aimed at decarbonizing hard-to-abate sectors such as steel production, maritime and aviation industries, logistics, and transportation [11]. This has led to the deployment of new hydrogen production units. In particular the Hy.City.Bremerhaven initiative has established two 1 MW PEM and alkaline electrolysers, which contribute significantly to green hydrogen production in the region. Additionally, the Fraunhofer Institute for Wind Energy Systems (IWES) in Bremerhaven hosts an electrolyser test field, currently featuring two electrolysers with a total production capacity of 2 MW [13]. Both electrolysers serve a wide variety of off-takers, including seven hydrogen busses, a pilot scale e-methanol plant currently under construction and expected to produce 200 t of green methanol per year for maritime purposes, fuelling a newly built methanol vessel, and a publicly accessible refuelling station, operating at 350 and 700 PSI for refuelling hydrogen-based mobility solutions [14].

Furthermore, Bremen together with relevant stakeholders is part of the following ongoing Important Projects of Common European Interest (IPCEI) and other projects:

- The IPCEI DRIBE [11] focuses on decarbonizing steel production through hydrogen-based processes in a clear follow-up to the deployment of an electrolyser planned at the steel plant by deploying an additional 50 MW electrolyser and implementing Direct Reduced Iron (DRI)-technology in the steelmaking process. The project is cofounded by the federal state of Bremen with 1.3 billion euros and will end in 2042 when a planned 130.000 t of green hydrogen is used in the DRI installations.
- The IPCEI Clean Hydrogen Coastline [15] aims to establish a comprehensive hydrogen infrastructure along the northern coast, facilitating large-scale production, distribution, and utilization of green hydrogen. The first electrolyser in the city of Emden will become operational in 2026.
- The IPCEI WopLin initiative [11] is dedicated to integrating hydrogen into aviation infrastructure in Northern Germany, promoting sustainable air travel.
- The German national project hyBit [16] aims to accelerate Bremen's hydrogen economy by fostering innovation and collaboration across industries.
- The German national project MariSynFuel [14] aims at implementing a local production of synthetic methanol as marine fuel for shipping in Bremerhaven.

4 Identification of Drivers of the Green Energy Transition in Bremen

This chapter identifies the drivers of the green energy transition in Bremen, following a qualitative content analysis approach based on the literature analysis provided in the previous chapter together with an analysis of the related project documentation. On that basis, six drivers were identified, which are described in the following.

- DRIVER 1: Availability of strategic logistics assets and infrastructures within Bremen, being at the cross of three TEN-T corridors. Furthermore, Bremerhaven features the eighth busiest EU container port, and Bremen is home to an international airport and features an extensive network of companies operating in international logistics. As potential hydrogen importer as well as producer, the state of Bremen will play a crucial role in transporting green hydrogen to industrial centres across Germany.
- DRIVER 2: Renewable energy production based on locally available resources - Bremen is actively involved in the successful use and development of on- and offshore wind energy capacities to support and implement the ambitious expansion targets set by the German government [17].
- DRIVER 3: Fertile industrial ecosystem with key actors in particular in the steel industry, aviation, heavy transport, and other industries attracting new businesses and investments. Hydrogen has the potential to be utilized both as energy source and as feedstock in different industries with high need to be decarbonized.
- DRIVER 4: Well established public-private partnership facilitating the development of new business and governance models to turn decarbonization challenges into a great opportunity for socio-economic territorial growth.
- DRIVER 5: Driving Emission-Free Transport: Bremen is raising relevant interest from road, air and waterway transport operators towards free emissions transport. With port capabilities and ongoing naval fleet expansion, hydrogen is positioning more and more as a viable alternative to meet the demands from the evolving landscape.
- DRIVER 6: Exploiting high-quality knowledge: Bremen owns extensive knowledge and experience on safe transport, fire safety and management, store, process and transit fuels, including excellent R&I facilities, clusters and hubs working on hydrogen.

The conditions as described by the drivers clearly highlight the promising strategic situation of the German Federal State of Bremen with regard to the green energy transition and especially the establishment of a Hydrogen Valley.

5 H2B:IMPACT – The Bremen Hydrogen Valley

Hydrogen Valleys are expected to play a key role on advancing the global hydrogen economy, contributing to the REPowerEU targets by scaling up renewable hydrogen production, supply and consequently to meet the growing demand from industry, energy, transport, and other sectors, by identifying and overcoming the technological and non-technological barriers with respect to production, distribution, storage, and utilization of hydrogen at large scale.

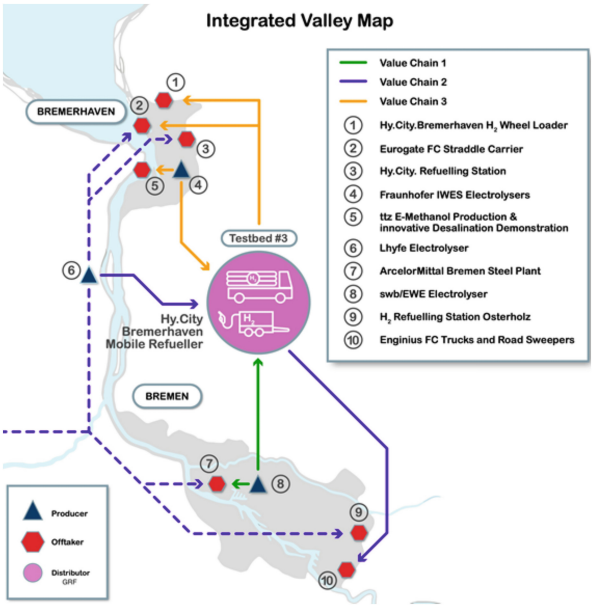


Fig. 1. Overview of the Bremen Hydrogen Valley.

5.1 Overview

To support this process, the state of Bremen together with a respective consortium in spring 2025 submitted the H2B:IMPACT project proposal to the Clean Hydrogen Partnership, which was approved in August 2025. H2B:IMPACT has the strategic objective to create a Hydrogen Valley centred in the state of Bremen as depicted in Fig. 1. The setup of the Hydrogen Valley follows a concept as laid out in [18], comprising renewable energy sources, hydrogen production and storage, transportation/distribution, and end use. Within H2B:IMPACT, three new value chains will be demonstrated, integrating three hydrogen production systems, related distribution infrastructure and five test-beds with innovative use cases, demonstrating a newly built green regional hydrogen production and innovative offtake of in the industrial, heavy transport, maritime logistics, and construction sectors.

The mentioned value chains will operate in an integrated way. H2B:IMPACT will provide advanced balancing infrastructure in the form of a mobile refuelling station with advanced Internet of Things (IoT) capabilities and related control mechanisms, allowing artificial intelligence (AI)-based logistics optimization ensuring interoperability. All this indicates the ports' central economic functions both on regional and national level. The ports of Bremen pursue continuous improvement measures beyond the statutory environmental standards to develop and implement innovative environmentally friendly technologies and processes in the industrial sectors of ports and shipping. Ongoing activities aim to further decrease emissions to reduce the proportion of compensation certificates required. To this end, it is planned to convert facilities, vehicle fleets, and

port vessels to emission-free propulsion and renewable energy supplies with the goal of making the ports of Bremen a CO_2-neutral and low-emission port location by 2035 [7].

5.2 Overall Concept of H2B:IMPACT

H2B:IMPACT aims to drive large-scale demonstration efforts from both the public and private sectors through an industry led flagship initiative strategically focused on establishing a Hydrogen Valley ecosystem centred in the state of Bremen. The Bremen Hydrogen Valley will be developed as an integrated hydrogen ecosystem, connecting industrial, mobility, construction, and logistics sectors through a coordinated network of hydrogen production, distribution, and storage facilities feeding many end-use applications. By leveraging Bremen's existing infrastructure, industrial base, and ongoing hydrogen initiatives, the project will serve as a scalable and replicable model for hydrogen deployment, supported by key industrial players, demonstrating added value in terms of upscaling potential and improvement of EU industrial competitiveness.

The H2B:IMPACT project will present three value chains, demonstrating five innovative test beds beyond the state of art in the industrial, construction, transport and logistics sectors. The ambition is to accelerate the transition to a hydrogen-based economy, while enhancing energy security, competitiveness, and sustainability, providing key knowledge and roadmaps for further upscaling across the EU and the rest of the world. The implementation of the Bremen Hydrogen Valley will take place in three phases:

(1) detailed design and planning, including the licensing, deployment of initial production facilities, storage infrastructure, and distribution networks,
(2) integration and commissioning of hydrogen applications across industrial and transport sectors, and
(3) performance monitoring and impact assessment.

The latter phase will include a scaling and replication strategy, engaging new stakeholders and expanding hydrogen adoption across additional industrial and transport sectors and will confirm the testbed at final technology readiness level (TRL) 8.

The H2B:IMPACT testbeds are interwoven through a network of infrastructure, production sources, and shared innovation goals, creating a circular and mutually reinforcing hydrogen ecosystem in the Bremen Valley. The synergies emerge not only through common supply chains - such as the shared usage of electrolytic hydrogen from different producers - but also through technological interdependencies that drive efficiencies across applications.

A clear example of cross-sector interaction is the linkage between hydrogen producers and downstream applications. As an example, hydrogen produced and stored at the production sites is routed to the e-methanol facility, where it is synthesized into carbon-neutral fuel. This fuel then powers vessels, thereby completing a closed energy loop. Moreover, the CO_2 required for e-methanol synthesis is captured from a wastewater treatment plant, forming a perfect instance of circularity. Mobile refuelling infrastructure developed under testbed 3 further binds the ecosystem together. The mobile unit not only refuels hydrogen powered trucks (testbed 1) and hydrogen powered construction equipment (testbed 4) but also serves future port operations needs (testbed 2), effectively connecting decentralized applications to centralized hydrogen sources. This logistical

versatility reduces the need for duplicate infrastructure while ensuring energy availability where it is most needed, and irradicates the need for deployment of decentralized storage and refuelling infrastructure at the operational sites of non-road going mobile machinery.

6 Conclusion

This paper gives an overview over hydrogen-related initiatives in the German federal state of Bremen based on a literature analysis, and identifies six drivers of the green energy transition in Bremen following a qualitative content analysis approach. The latter were found to be related mainly to Bremen's strategic geographical position at the cross of three TEN-T corridors, featuring the eighth busiest EU container port and an international airport, as well as access to renewable energy production provided by on- and offshore wind energy production on the North Sea coast. Furthermore, Bremen features a well established public-private partnership and a fertile industrial ecosystem comprised of steel industry, aviation, heavy transport and other industries attracting new businesses and investments, thus facilitating the development of new business and governance models to advance decarbonization efforts. A raising interest from road, air, and waterway transport operators towards carbon free emissions transport supports this development as well. A sound basis for this process is provided by extensive knowledge and experience in green technologies by Bremen's industry as well as research communities. These facts highlight the promising strategic situation of the German Federal State of Bremen with regard to the green energy transition and especially the establishment of a Hydrogen Valley. The paper as well introduces the new Bremen Hydrogen Valley to be implemented within the H2B:IMPACT project. It briefly describes project activities, value chains, and testbeds foreseen in the project, which during the writing of this paper was expected to start in February 2026. More detailed information is to be provided in additional papers during the runtime of the project.

References

1. The European Green Deal: Striving to be the first climate-neutral continent. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (2025). Accessed 29 Sept 2025
2. Fit for 55: Delivering on the proposals. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en (2025). Accessed 29 Sept 2025
3. Key actions of the EU hydrogen strategy. https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/key-actions-eu-hydrogen-strategy_en (2025). Accessed 29 Sept 2025
4. REPowerEU: energy policy in EU countries' recovery and resilience plans. https://www.consilium.europa.eu/en/policies/repowereu/ (2025). Accessed 29 Sept 2025
5. Clean industrial deal - a plan for EU competitiveness and decarbonisation. https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en (2025). Accessed 29 Sept 2025
6. Trans-European Transport Network (TEN-T). https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en (2025). Accessed 29 Sept 2025

7. Bremenports: Umweltpolitische Erklärung der bremischen Häfen, Bremen/Bremerhaven (2024)
8. Energiestatistik, Energiebilanzierung und CO2-Emissionen. https://www.statistik.bremen.de/themen/energiestatistik-energiebilanzierung-und-co2-emissionen-1914 (2025). Accessed 29 Sept 2025
9. Mayring, P.: Qualitative content analysis: theoretical foundation, basic procedures and software solution. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-395173 (2014)
10. Norddeutschland: Treiber der Wasserstoffwirtschaft. https://norddeutschewasserstoffstrategie.de/ (2025). Accessed 29 Sept 2025
11. Hydrogen Strategy: The State of Bremen. https://www.wfb-bremen.de/sixcms/media.php/49/Broschu%CC%88re_Wasserstoffstrategie_EN_Web.pdf (2025). Accessed 29 Sept 2025
12. Schlüssel zu Innovationen 2030 – Strategie für Innovationen, Dienstleistungen und Industrie Land Bremen. https://www.bremen-innovativ.de/wp-content/uploads/2021/10/Broschu%CC%88re_Schlu%CC%88ssel-zu-Innovationen-2030_Web.pdf (2025). Accessed 29 Sept 2025
13. Vervoort, J., et al.: First experience in operation and data acquisition at the hydrogen lab Bremerhaven. J. Phys. Conf. Ser. **3025**, 012024 (2025). https://doi.org/10.1088/1742-6596/3025/1/012024
14. Meyer-Larsen, N., Schories, G.: Practical approach towards green methanol as maritime propellant. In: McNally, C., et al. (eds.) TRAconference 2024, LNMOB, pp. 1–7 (2025). https://doi.org/10.1007/978-3-031-89444-2_108
15. Clean Hydrogen Coastline - geballte Vorteile durch Technologie und Kompetenz in der Küstenregion https://www.clean-hydrogen-coastline.de/de/ (2025). Accessed 29 Sept 2025
16. Wasserstoff – der Energieträger von morgen, https://hybit.org (2025). Accessed 29 Sept 2025
17. Windenergie in Bremen. https://umwelt.bremen.de/klima/klima-energie/windenergie-24764 (2025). Accessed 29 Sept 2025
18. Bampaou, M., K.D.: Panopoulos: an overview of hydrogen valleys: current status, challenges and their role in increased renewable energy penetration. Renew. Sust. Energ. Rev. **207** (2025). https://doi.org/10.1016/j.rser.2024.114923

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A Heuristic Approach for Estimating Charging Demand from Long Distance Trips at Fast Charging Stations

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Abstract. In this paper, we propose a method for determining future charging demand at public fast charging stations. The method links charging behavior with existing traffic and energy demand models. This results in a prediction of demand for public fast charging from long-distance trips on a nation-wide level. To validate the model, we compare with observed charging sessions in Norway, and the results show that the model is able to provide a decent approximation of charging patterns with average R^2-values of 0.72 and 0.76 for the energy demand and traffic volume hourly profiles.

Keywords: Fast charging · Battery electric vehicle · Charging demand

1 Introduction

The global stock of battery electric vehicles (BEVs) reached 58 million in 2024, with projections indicating an increase to approximately 390 million BEVs by 2035 [1]. The anticipated increase in BEVs necessitates extensive development of the charging infrastructure. A report by [2] estimates that Norway will need 9,000 public fast charging points by 2030, more than double the infrastructure available in 2021. However, factors such as battery technology development, charging technology advancements, power grid capacity, and charging behavior introduce significant complexity and uncertainty for future infrastructure investments.

Several methods for modeling charging demand have been developed. Activity-based and agent-based models have been widely used to estimate BEV charging profiles and infrastructure needs [3–7]. Charging decisions are crucial in BEV modeling. Strategically, users choose between home, workplace, or public charging. Operationally, they plan when and where to charge, and for how long [8]. used the analytic hierarchy process (AHP) to help BEV drivers select the most appropriate charging station based on their needs and preferences [9]. provided a comprehensive review of methodologies and technologies for BEV charging infrastructure planning. Additionally, research

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on the willingness to pay for reducing waiting time at charging stations highlights the importance of minimizing delays for EV users [10].

While previous studies have successfully modeled BEV charging behavior using activity-based and agent-based approaches, most focus on urban mobility, short-distance trips, or rely on household travel surveys with limited geographic scope. Few studies have addressed nation-wide charging demand from long-distance inter-city travel, particularly in rural areas where public fast charging infrastructure is critical. Additionally, existing models often lack integration with detailed transport network data and do not account for real-world charging behavior derived from large-scale user surveys. Our study addresses these gaps by combining transport demand modeling with a heuristic charging behavior framework, validated against observed charging station data.

2 Methodology for Predicting Charging Demand

The approach is illustrated in Fig. 1, which outlines the decision-making process for each modeled trip regarding where to charge along the route. The primary source for these decisions is the survey conducted by the Norwegian EV Association. This survey provides valuable insights into the charging behavior and preferences of BEV users, which are crucial for accurately modeling charging demand.

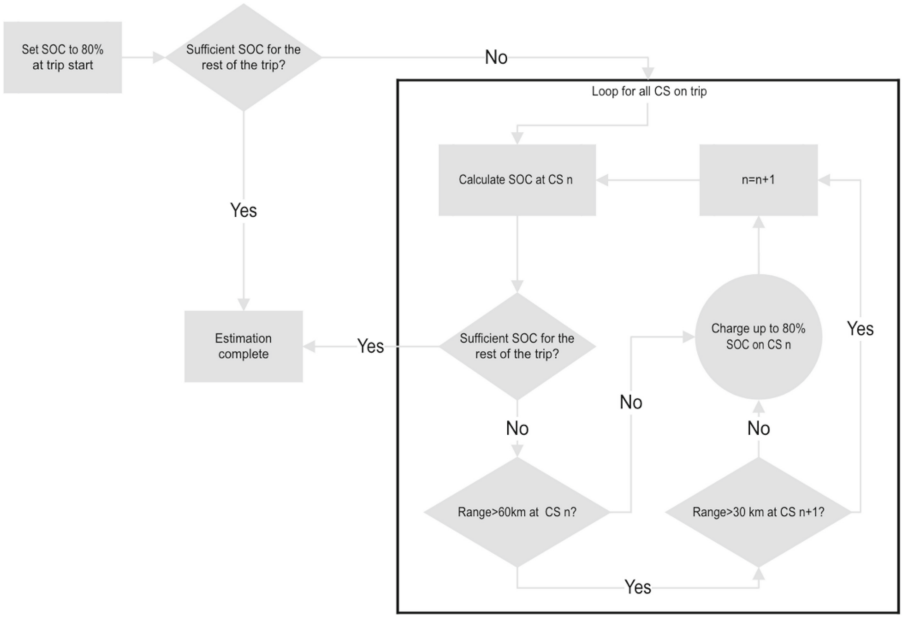


Fig. 1. Simulated behavior for estimating where vehicles are charged on a long-distance trip.

The starting point is estimating the state of charge (SOC) of the battery at the beginning of the trip. According to the survey, respondents reported an average SOC of 80%

before long trips. This value is used for all trips to estimate the initial energy stored in the battery for different vehicle categories. The required energy for the entire trip is then calculated according to the methodology presented in [11]. This resulted in an energy consumption profile for each estimated trip, giving detailed information about the change in SOC along the route as input for the next step in the method. If the energy stored in the battery exceeds the total energy required for the trip and the remaining range at the end of the trip is more than 30 km, no charging sessions are needed. The 30 km threshold represents the range anxiety of BEV users and is consistently applied throughout the estimation process. If the SOC is insufficient to complete the trip without charging, the SOC at available charging stations along the route is estimated sequentially. The availability of fast charging stations is sourced from a publicly available database [12], which includes information on the location, number of charging points, maximum power, and charging technology of all publicly available charging stations. For simplicity, we assume that BEV drivers have access to this information when deciding where and when to charge. The decision to charge at a station is based on the estimated SOC at the next two charging stations in the sequence. If the range is less than 60 km at the next station or less than 30 km at the station after that, the driver decides to charge up to an SOC of 80%. This decision pattern allows the model to simulate the spatial and temporal distribution of charging demand for each trip. The values representing range anxiety (60 km and 30 km) are derived from survey responses regarding comfortable SOC levels during trips, as highlighted in the introduction.

To represent the travel demand in Norway, we used the results from a national transport model, NTM6. The NTM6 model provides detailed projections of transport demand in terms of origin-destination (OD)-matrices, which are essential for estimating future charging needs. To estimate the time of arrivals at charging stations, more information about travel behaviour which exceeds the daily resolution of NTM6 is required. The Norwegian National Household Travel Survey was used to determine the time of day for the start of all trips in the OD-matrix. As the battery pack size varies between brands and even within model type, it is not straightforward to use technical data to estimate a representative car park. Therefore, data from a survey by the Norwegian EV association has been used. Here, the respondents are asked about the size of the battery pack of their BEV in kWh. The questions in the survey are grouped into sociodemographics, car ownership, travel habits, BEV car choice, BEV range, charging choices, and environmental issues. With approximately 10 000 respondents, we consider this to be representative of the actual Norwegian BEV fleet. This study considers two scenarios: the baseline scenario with 2020 as the reference year, and a prognosis for 2030 based on expected developments in population, car ownership, and road infrastructure, modeled by NTM6. For the 2030 scenario, we also include two additional permutations with BEV range increases of 20% and 40% to investigate the impact on charging station usage. These improvements assume that the trend of increasing BEV range will continue towards 2030, inspired by similar projections from [13], who expect the average range to increase from 380 km in 2020 to 562 km in 2030. The final output of this step is an hourly frequency of charging sessions and energy transfer at each charging station for an average day in the scenario used in the underlying transport model. Data is collected from a charging point operator (CPO) in Norway to validate the model results. This data set consists of the number

of charging sessions and the energy transferred per hour at 13 fast charging stations in Norway, covering a total of 23 months. This is processed to a data set consisting of up to 24 data points for each of the 13 CS, including both number of visits (veh/h) and energy transfer (kWh/h).

3 Results from the Analysis

The main result from the methodology presented in the previous section is a temporal distribution of estimated charging demand at all publicly available fast charging stations in Norway. The results are estimated for a basis situation (2020) and a predicted situation (2030). First, we present an analysis of one trip to visualize the charging behaviour. Then, aggregated results and a validation of the basis situation is presented.

3.1 Example Trip, Bergen - Oslo

The driving route from Bergen to Oslo used in the National Transport Model is 477 km and starts along the Ev16 route from Bergen, Voss and through the 24.5 km Lærdal tunnel. Then, the route turns into the Hemsedal mountain pass with the road summit 1136 m above sea level. There are several other routes available, but the transport model uses this route as the best in terms of generalised cost. Three different vehicle types are used in this example, based on the socket type (CHAdeMO, CCS or Tesla). This reflects the situation in Norway in 2020 to align with the other data sets used in the study. The main differences between the vehicle types are weight and engine power. The total energy consumption is just below 70 kWh for the 20 and 40 kWh capacity cars and 81 kWh for the 70 kWh car. The difference in energy consumption is a direct consequence of differences in vehicle weight. On this route, regeneration represents about 6–8% of the energy consumption.

Table 1 shows the charging demand pattern for the trip for the three vehicle types. The 20 kWh CHAdeMO vehicle needs to charge six times during the trip with an average of 9.7 kWh on each CS. It also needs to charge on charging stations on each side of the mountain climb. With its higher battery capacity, the 40 kWh CCS car only needs to charge three times during the trip. The last charging session is higher than necessary in terms of energy delivered for both cars, because the charging model charge to 80% capacity no matter the distance to the final destination. The 70 kWh Tesla car only needs one charging session, just before the climb up the mountain.

3.2 Aggregated Nation-Wide Results

Table 2 shows overall statistics of the estimated daily energy demand and daily visit for a total of all of the 707 publicly available fast charging stations in the Norwegian dataset. Based on the presented methodology, results for 2030 were estimated. Here, only the transport demand was changed, using the long-distance transport model to create a reference 2030 scenario. The main change of input was the population prognosis from [14] and a county wide BEV vehicle fleet prognosis for 2030. The other steps were unchanged, including the network of charging infrastructure. To investigate the

effect of change in battery capacity, the 2030 scenario was also run with an estimated improvement in battery efficiency, i.e. by increasing the energy capacity by 20% and 40% without increasing the weight of the battery pack. In Table 2, the results from 2030 with an increase in range of 0%, 20% and 40%, respectively, are compared with the 2020 scenario. The increase in demand in 2030 is mainly due to the expected increase in transport demand, while the other two scenarios also include changes in vehicle range. Most of the result's values increase by a factor between 3 and 5.5.

Table 1. Breakdown of fast charging model, Bergen - Oslo.

	CHAdeMO		CCS		Tesla	
Distance (km)	Range (km)	Charge (kWh)	Range (km)	Charge (kWh)	Range (km)	Charge (kWh)
10	–		114		–	
11	117		113		–	
22	108		104		296	
32	94		90		–	
58	71		67		–	
60	68		64		–	
80	49	9	45	26	–	
102	92		201		–	
103	–		–		213	
120	70		180		–	
146	51	9	160		–	
173	87		131		143	
198	63		106		119	36
220	28	12	71	22	–	
278	51	9	161		–	
305	103		148		–	
309	–		–		216	
337	73		117		–	
358	51		96		–	
370	39	11	84		157	
398	87		55		–	
422	63		203		–	
430	56	8	196		–	
459	88		–		–	
461	86		165		–	
465	81		160		–	

(*continued*)

Table 1. (*continued*)

	CHAdeMO		CCS		Tesla	
Distance (km)	Range (km)	Charge (kWh)	Range (km)	Charge (kWh)	Range (km)	Charge (kWh)
471	75		154		–	
477	69		148		53	

– indicates socket type not available at charging station

Table 2. Nation-wide results for the reference and prognosis scenarios with an increase in battery capacity of 20% and 40%.

	2020	2030	2030 + 20% range	2030 + 40% range
Energy demand for all charging stations (kWh/day)	68 357	388 113	299 192	225 685
Mean energy demand per CS (kWh/day)	96.69	548.96	424.39	319.67
Median energy demand per CS (kWh/day)	34.44	211.11	161.03	115.89
Maximum energy demand per CS (kWh/day)	1227	7217	6160	4680
Minimum energy demand per CS (kWh/day)	0.00108	0.00763	0.02776	0.00257
Total vehicles (sum all CS veh/day)	3672	20838	13173	8787
Mean vehicles per CS (veh/day)	5.19	29.47	18.69	12.45
Maximum number of vehicles per CS (veh/day)	55	309	241	178
Minimum number of vehicles per CS (veh/day)	0.00003	0.00021	0.00062	0.00003
Mean energy delivered (kWh/session)	18.61	18.63	22.71	25.68

3.3 Validation of Results for 2020

An overall comparison between observed and estimated charging profiles is shown in Fig. 2, where the deviation in kWh/h and veh/h hour is plotted for 13 charging stations with detailed charging data provided by a Norwegian CPO. For both plots, we see that there are two charging stations where the deviation is fairly low. The demand is overestimated at one station, but for most stations, the energy demand is underestimated.

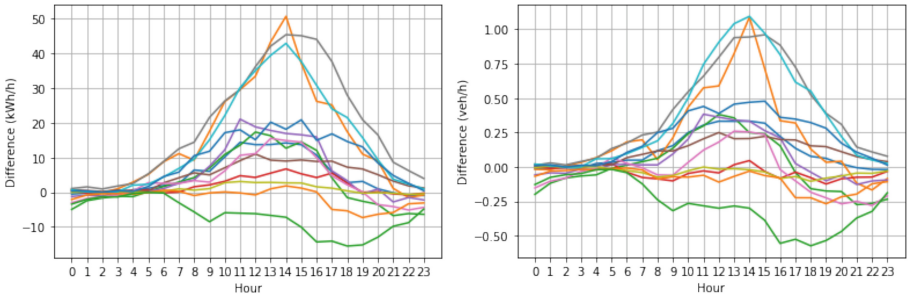


Fig. 2. Difference in modelled and observed demand distributions at 13 fast charging stations. Energy demand (left) and visiting traffic volume (right).

To further quantify the deviation, we calculate the coefficient of determination in each plot, as done by [6]. For the energy demand, the average value of R^2 is 0.72, while the corresponding value for the traffic volume is 0.76.

4 Discussion and Conclusions

The proposed methodology in our study resulted in an estimation of the average behaviour of the population of Norwegian BEV drivers and their charging preferences. On a trip level, the charging strategies seem reasonable, for the following reasons. The BEV types with smaller batteries have a higher number of charging stops due to a lower range. It is also apparent that the elevation profile affects the charging strategy, as there are charging stops directly before or after the highest peak in the middle of the trip. Average energy per session aligns with battery capacity and observed station data. In addition, an increase in battery capacity increases the energy delivered per session. These are results within the range of expectation, assuming that BEV drivers will seek to minimize their charging stops on a long distance trip.

The results show that the utilization rate of the capacity at charging stations is low in general. In 2020 the average energy demand is 96.69 kWh/day. There are some locations with a higher utilization rate, with the highest value being 1227 kWh/day, which translates into 51.1 kWh/h on average. However, the maximum hourly value will be much higher due to daily variation. This indicates that some charging stations are close to the power capacity of the grid connection in some periods. Looking at the future scenarios, this is even more prevalent, reaching 7217 kWh/day at the most visited station. The most extreme values would probably change if the model also included the queuing

aspect, forcing BEV drivers to consider adjacent charging stations in hours with a high possibility of charging queues. Moreover, the vehicles visiting in the same hour interval does not necessarily charge at the maximum power simultaneously. Nevertheless, we see that the majority of charging stations have a low daily energy demand. Model results moderately match observed charging station usage. In general, the energy charged and vehicles visited are underestimated by the model. This is most prominent at daytime, with a peak around 14.00, as shown in Fig. 2.

There are some areas where the model could be improved. Firstly, only the AADT is modelled. It is apparent that there will be deviations from this, which at times will increase the demand and cause queuing. In order to quantify this, a model that can differentiate between type of day should be developed. Secondly, our results represent an average day, also for ambient temperature. Since the temperature in Norway can be drop far below 0 °C in the winter, and towards 30 °C in the summer, the increase in energy demand due to cabin heating, ventilation and air condition can affect the charging demand. Thirdly, the model only includes trips from the National transport model. By including the regional transport demand, we would be able to give better estimations for fast charging demand in urban areas. With less availability of home charging, the need for fast charging will increase, in our case represented by the SOC at the start of the trip. This would increase the demand at charging stations. Fourthly, the charging behaviour model should be refined to also include additional facilities at the charging stations, as well as the interaction effect between nearby charging stations. Fifthly, the survey results from the EV Association were not weighted or cross-checked for inconsistencies, which might affect the input parameters to the study. Finally, the charging profiles show that the demand for fast charging varies throughout the day. Any measures that can help to distribute the demand and thereby reduce the peak demand will help especially to reduce queues. In our study, we have only looked at an average day of the year. However, there will be occasions where the demand is significantly higher, such as cold days and holidays.

References

1. Global EV Outlook 2024. https://www.iea.org/reports/global-ev-outlook-2024 (2024). Accessed 25 Mar 2026
2. Kunnskapsgrunnlag om hurtigladeinfrastruktur for veitransport. https://www.regjeringen.no/no/aktuelt/kunnskapsgrunnlaget-om-utbygging-av-ladeinfrastruktur-er-klart/id2902606/. Accessed 25 Mar 2026
3. Daina, N., Sivakumar, A., Polak, J.W.: Modelling electric vehicles use: a survey on the methods. Renew. Sust. Energ. Rev. **68**, 447–460 (2017)
4. Crozier, C., Morstyn, T., McCulloch, M.: Capturing diversity in electric vehicle charging behaviour for network capacity estimation. Transp. Res. Part D Transp. Environ. **93**, 102762 (2021)
5. Hu, L., Dong, J., Lin, Z.: Modeling charging behavior of battery electric vehicle drivers: a cumulative prospect theory based approach. Transp. Res. Part C Emerg. Technol. **102**, 474–489 (2019)
6. Pareschi, G., Küng, L., Georges, G., Boulouchos, K.: Are travel surveys a good basis for ev models? Validation of simulated charging profiles against empirical data. Appl. Energy. **275**, 115318 (2020)

7. Márquez-Fernández, F.J., Bischoff, J., Domingues-Olavarría, G., Alaküla, M.: Assessment of future EV charging infrastructure scenarios for long-distance transport in Sweden. IEEE Trans. Transp. Electrif. **8**(1), 615–626 (2021)
8. Oliveira Farias, H.E. et al.: Combined framework with heuristic programming and rule-based strategies for scheduling and real time operation in electric vehicle charging stations. Energies. **14**(5), 1370 (2021)
9. Qin, H., Su, X., Ren, T., Luo, Z.: A review on the electric vehicle routing problems: variants and algorithms. Front. Eng. Manag. **8**(3), 370–389 (2021)
10. Hoen, F.S., Díez-Gutiérrez, M., Babri, S., Hess, S., Tørset, T.: Charging electric vehicles on long trips and the willingness to pay to reduce waiting for charging. Stated preference survey in Norway. Transp. Res. Part A Policy Pract. **175**, 103774 (2023)
11. Hjelkrem, O.A., Arnesen, P., Bø, T.A., Sondell, R.S.: Estimation of tank-to-wheel efficiency functions based on type approval data. Appl. Energy. **276**, 115463 (2020)
12. Statistikk fra NOBIL. https://info.nobil.no/statistikk Accessed 25 Mar 2026
13. Paradies, G.L., Usmani, O.A., Lamboo, S., van den Brink, R.W.: Falling short in 2030: simulating battery-electric vehicle adoption behaviour in the Netherlands. Energy Res. Soc. Sci. **97**, 102968 (2023)
14. Statistics Norway: National population projections. https://www.ssb.no/en/befolkning/befolkningsframskrivinger/statistikk/nasjonale-befolkningsframskrivinger Accessed 25 Mar 2026

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Hybrid Train: Validation Process and Experimentation Insights Regarding Decarbonization and Operation Robustness

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Abstract. Régiolis Hybrid project involves modifying an existing dual-mode Régiolis train by replacing 2 of the 4 powerpacks with high-power lithium-ion batteries. The main aim of this project is to reduce energy consumption by 20% by recovering and exploiting electrical braking energy, previously dissipated as heat in the braking choppers.

For the first time in France, a train equipped with Li-Ion batteries was able to carry passengers. Fitted with a datalogger that continuously sends all the necessary monitoring data, it then travelled more than 60,000 km, enabling a precise assessment of the overall performance.

Environmental performance was measured by a test bench campaign to replay the data collected during commercial operation. This made it possible to assess the precise gain in CO2 emissions and pollutants without bias, and find up to −25% CO2, −52% HC, −41% CO, −41% NOx, −39% PM. Furthermore, performance with biofuels was also evaluated.

Finally, reliability was studied from two angles: the ability to keep the timetable compared to the rest of the dual-mode trains fleet, but also by analyzing the new operating points of the remaining powerpacks to ensure that the usage profile doesn't degrade the train reliability.

Keywords: Decarbonization · hybridization · biofuels · robustness assessment · experimentation outcomes

1 Introduction

Given global environmental challenges and the climate emergency, all transport sectors are now concerned with improving their energy performance and emissions. In France and for the railway sector, a first step in reducing the carbon emissions of regional trains was carried out in 2004 with first dual-mode diesel-electric trains. Dual-mode trains can run on electrified lines thanks to their pantograph or on non-electrified lines thanks to their diesel powerpacks (genset providing electric power to electrical motor). This is the case of Régiolis trains, which began commercial operation in 2014. Today, dual-mode trains are extensively deployed across Europe, supported by a highly electrified railway network that accounts for nearly 57% of the total [1].

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Hybrid technology represents an additional improvement to further reduce Greenhouse Gas (GHG) and pollutant emissions [2–6]. SNCF, in partnership with Alstom and CAF, has developed a hybrid train based on a dual-mode Régiolis train, incorporating batteries. The concept behind this hybridization is to remove 2 out of 4 powerpacks (PWPs) and replace them with high power Li-ion batteries (LTO chemistry). This will enable the recovery of electrical energy from braking, storage and then release it during the following acceleration phases in order to reduce fuel consumption.

This innovative train has been also equipped with a system that collects a large amount of data, enabling accurate assessment of its energy performance and the robustness of the hybrid technical solution (timetable compliance and impact on remaining PWPs).

The objective of this paper is to present the validation process and experimentation insights regarding decarbonization and operation robustness of a retrofitted hybrid train in commercial operation, with a specific focus on PWPs.

The outline of the paper is organized as follows. Section 2 describes the methodology used and the environmental performances of the Régiolis hybrid train. A test bench is used to measure fuel consumption and pollutant emissions of the PWPs of a hybrid and non-hybrid Régiolis train, whose behavior was recorded during real commercial missions. Section 3 presents an assessment of operational reliability in terms of schedule adherence and powerpack reliability by analyzing data from Régiolis Hybrid among Régiolis fleet over a period of several months.

This will lead to discussions and conclusions about the Régiolis hybrid experimentation insight, especially comparing other decarbonization solutions.

2 Environmental Performance

To compare pollutant emission levels between hybrid trains and conventional trains during commercial operation, a portable emission measurement system (also known as PEMS) is required. This type of equipment has already been used for tests carried out on a train on the Czech rail network [7]. Unfortunately, as the equipment selected was not originally designed to be installed on a train, a number of issues arose during the validation of its location: the system's vulnerability to shocks and vibrations on the roof, the addition of significant weight to the train, an increased risk of parts being lost while in service, severe operational constraints (train roof access for calibration device is necessary every day) in railway production context, etc.

To overcome these problems, a two-stage solution was adopted:

- Stage 1: recording of the diesel engine's operating parameters via the powerpack's CAN network during commercial service and especially the following parameters: Engine Percent Load At Current Speed, Actual Engine Percent Torque and Engine Speed.
- Stage 2: reproduction of the various phases of diesel engine operation on a dynamic test bench.

The acquisition device that was installed allows the parameters circulating on the powerpack's CAN communication network to be viewed and recorded in accordance with the SAE J1939 standard. To increase the number of acquisitions, all the powerpacks

on the hybrid train and the conventional train were equipped with this system. To obtain comparable data between the operation of the hybrid train and that of the conventional train, the principle multiple units' operation (conventional train + hybrid train) was adopted. With these two trains coupled together, the dynamics of the train are the result of the performance of each of the trains, and the traction instructions given by the driver are applied identically to each of them.

The commercial testing of the hybrid Régiolis started in December 2023 and has been extended until 2027. To date, it has run over 80,000 km in 4 different regions (Occitanie, Nouvelle Aquitaine, Grand Est and Centre Val de Loire). Dozens of routes were therefore covered, each with their own specific characteristics in terms of length, gradient, time constraints, etc.

Certain criteria were considered when selecting the route to be used on the engine test bench: consistency between theoretical and actual timetables according to the stations served, no significant delays, traction battery charge level of the hybrid train between departure and arrival less than +/− 10%, etc. "La Rochelle – Bordeaux – La Rochelle" and "La Rochelle – Poitiers – La Rochelle" were selected to be reproduced on the test bench.

A second selection was then made to retain only one representative PWP per train, comparing the various data proving correct operation in multiple units. To this end, we selected the powerpack whose engine speed was closest to the maximum and minimum engine speeds specified by the engine manufacturer.

For bench testing, an engine with 12,000 h of operation from a Régiolis' powerpack was used with its after-treatment system. The engine was coupled to a generator to perform dynamic loads and thus simulate actual commercial operation [8]. This setup allows for very accurate reproduction of the train's journeys with the power associated with the engines.

Measurements taken during a test (depending on the type of train, route and fuel used) provide information on fuel consumption and total regulated emissions (CO, HC, NOx, PM and PN) from an engine on a given route. To determine total emissions (per train), it was assumed that the powerpacks for each train operated in a similar manner: the values were therefore multiplied by 4 for the conventional train, while the values were multiplied by 2 for the hybrid train.

Figure 1 shows comparisons of fuel consumption, Greenhouse Gas emissions and pollutant emissions between the conventional train and the hybrid train on the "La Rochelle – Bordeaux – La Rochelle" and "La Rochelle – Poitiers – La Rochelle" routes.

In addition, the use of biofuel being part of the decarbonization solutions, bench tests made it possible to compare performance and emissions with Diesel B7 fuel and B100 biofuel (fuel composed of 100% methyl esters of fatty acids based on rapeseed).

Figure 1 highlights several points on the impact of the train's hybridization, but also on the effects of using B100 compared to B7.

The reduction in fuel consumption and CO2 emissions is due to the use of recovered braking energy by batteries, which is reused when needed (−18% to 25%).

As shown in Fig. 3, the operating points of the diesel engines in the hybrid train achieve higher load points, which have been observed in the pollutant emissions per



Fig. 1. Comparison of fuel consumption and pollutant emissions of return journeys between "La Rochelle - Poitiers" and "La Rochelle - Bordeaux" in Diesel B7 and B100

engine. In terms of the train as a whole (2 PWPs vs. 4 PWPs), total emissions are lower for the same power delivered to the trains (i.e particulate matter −21% to 39%).

B100 reduces CO2 emissions in the same way as B7 but differs in terms of certain pollutants due to the properties of the fuel. However, in a "well-to-wheel" analysis, B100 permits to reduce by 60% GHG emissions compared to fossil fuel.

This test campaign clearly showed that the use of PWPs differed between the two configurations, which could potentially have an impact on its maintenance schedule (optimization required), as explained in chapter 3.

3 Operational Reliability

3.1 Hybridization Impact on Timetable Robustness

Fuel savings and reduced emissions were demonstrated in the previous section. However, it is important to ensure that hybrid technology does not degrade the train's traction performance, particularly about its ability to respect timetables.

The collection of Infrastructure Manager operational data allowed the study of, in real environment, the impact of hybridization on the train's ability to follow paths designed for non-hybrid trains. Of course, train operation is subject to high variability due to various external and internal factors. Nevertheless, based on several months and thousands of km

performed, it was possible to draw clear and interesting conclusions from this somewhat confused picture:

– On average, the running delay of trains operated by the hybrid train did not differ from that of non-hybrid trains, as illustrated in Fig. 2.
– In the event of a delayed departure and without occurrence of further operational obstacles, the hybrid train is able of use the margin included in its path and recover the delay

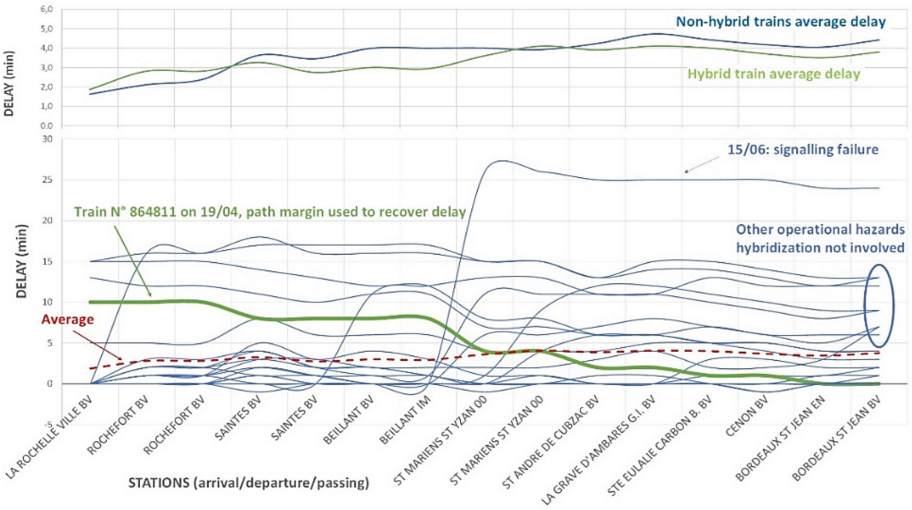


Fig. 2. "La Rochelle – Bordeaux"; Above: average delay at each station, either hybrid train or non-hybrid; Below: delay at each station for each train operated by the hybrid train.

3.2 Hybridization Impact on Powerpack Reliability

Régiolis hybridization has been designed so that scheduled maintenance operations can take place at the same frequency as for the original Régiolis trains. This makes it possible to maintain the same organization as with the classic dual-mode Régiolis trains, thereby streamlining costs without additional constraints. Regarding corrective maintenance, one of the objectives of hybridization was also to ensure that the modification would not compromise the reliability of the remaining components, particularly the two PWPs. To determine whether specific maintenance/monitoring was required for the hybrid train, a comparison was made between the remaining powerpacks of the hybrid train and those of a dual-mode train to characterize the evolution of the operating profile. The comparative data used was collected via remote transmission and selected over sufficiently long periods of use that were representative of the trains' nominal operation on "Bordeaux – La Rochelle" and "La Rochelle-Poitiers".

The results in Fig. 3 show some differences, notably a slightly higher full load rate for the hybrid train's powerpacks. Nevertheless, the overall performance of these

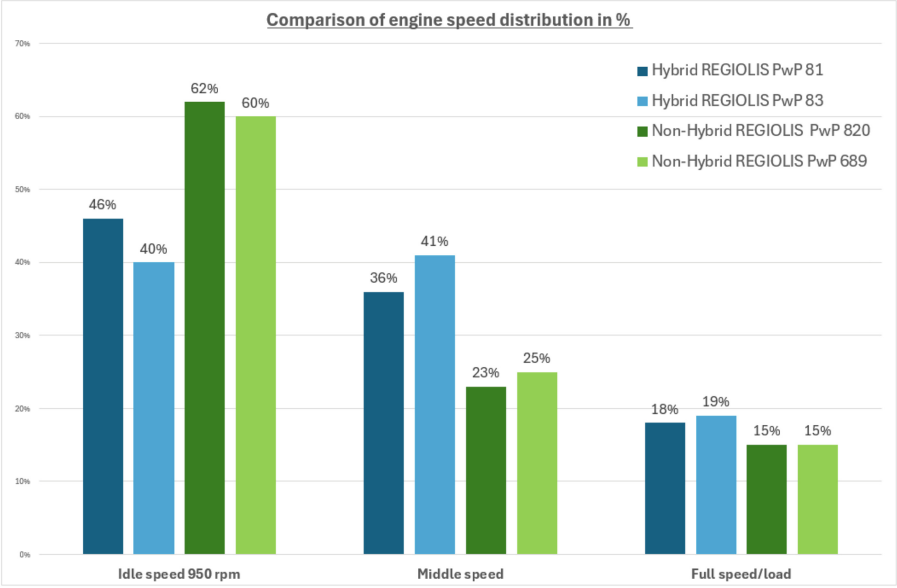


Fig. 3. Comparison of the speed distribution of 2 engines on hybrid trains and on conventional dual mode trains

powerpacks remains quite similar to that of dual-mode trains. Consequently, at this stage, no changes to the hybrid powerpacks maintenance have been recommended.

Finally, given the implementation of a new "stop & start" function on the hybrid train's PWPs, an additional analysis was carried out to characterize the evolution of the occurrence of internal combustion engine start-up/shutdown between the hybrid train and the conventional dual-mode train. The analysis of these data identified a concern on the starter side, because a factor of 2 was observed in the occurrence of starts/stops per hour of operation for the hybrid train's powerpacks. As a result, close monitoring during maintenance was recommended to maintain a good level of robustness.

4 Conclusion

Commercial operation of a regional hybrid train has confirmed, through various sources, that the fuel consumption reduction target of 20% has been achieved. By reproducing and comparing the operation of two powerpacks used in hybrid and non-hybrid trains on two representative railway lines, it has been demonstrated significant reductions in pollutant emissions, which, combined with the ability to operate on batteries alone in densely populated areas, significantly reduces the exposure of passengers and local residents to pollutants.

Based on the analysis of operating data over more than 80,000 km and illustrated in this paper by the analysis of traction performance on the "La Rochelle - Bordeaux" line, hybridization did not degrade operational robustness.

Other decarbonization solutions besides hybridization can be considered and are being, or will be, tested by SNCF. The use of biofuels is the most transparent solution in terms of impact on operations, infrastructure adaptation, and investment costs. However, although they reduce CO2e emissions by 50 to 80% from well to wheel [11], the bench tests presented in this paper demonstrate that local pollutant emissions persist.

The complete electrification of railway lines is the most energy efficient and the least carbon-intensive due to the French energy mix. Electrification, however, is too expensive and takes a long time to implement.

The use of dual-mode battery-powered trains is a relevant solution from an environmental perspective and would reduce CO2e emissions by 80% without any local emissions. However, the operational impacts, given the limited range (approximately 100 km with current technologies) and the significant investment and time required to establish a network of new charging points or upgrade existing infrastructure, are hindering the fast industrialization of this solution.

The use of hydrogen is also a viable solution that could reduce CO2e emissions by approximately 70% compared to the use of diesel. However, the investment costs for hydrogen stations, the adaptation of maintenance facilities, and the price of hydrogen are currently limiting its use on long lines without alternative decarbonization solutions.

Hybridization is a solution that reduces fuel consumption and local CO2 emissions by 20%. It only requires modifications to the rolling stock and no dedicated infrastructure. It can also be combined with the use of biofuel. Showing a positive balance between deployment difficulty and benefits, hybridization can be considered as an interesting long-term solution capable of making rail an even more environmentally friendly means of transport. Furthermore, recent research has shown its potential to reduce fuel consumption by optimizing the use of batteries alone and by prioritizing battery charging via the catenary, allowing fuel savings of 25% to 51% compared to conventional diesel train [12].

References

1. Eurostat Article Electrified railway lines increased by 31% since 1990. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240313-1. Accessed 4 May 2026
2. Saeed, M., Briz, F., Guerrero, J.-M., et al.: Onboard energy storage systems for railway: present and trends. IEEE Open J. Ind. Appl. **4**, 238–259 (2023)
3. Fedele, E., Iannuzzi, D., Del Pizzo, A.: Onboard energy storage in rail transport: review of real applications and techno-economic assessments. IET Electr. Syst. Transp. **11**(4), 279–309 (2021)
4. Olmos, J., Gandiaga, I., Lopez, D., et al.: Li-ion battery-based hybrid diesel-electric railway vehicle: in-depth life cycle cost analysis. IEEE Trans. Veh. Technol. **71**(6), 5715–5726 (2021)
5. Amokrane, F., Elbachir, M.-I., Depature, C., et al.: Energy management solution of the future dual-mode electric train. In: IEEE International Conference on Electrical Systems for Aircraft Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), pp. 1–6. IEEE, Naples (2024)
6. Depature, C., Renault, M., Crispiani, D., et al.: Hydrogen and battery trains, which Technologies for Future Light Trains? In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRAconference 2024 Lecture Notes in Mobility, pp. 226–232. Springer, Cham (2025)

7. Vojtisek-Lom, M., Jirků, J., Pechout, M.: Real-world exhaust emissions of diesel locomotives and motorized railcars during scheduled passenger train runs on Czech railroads. Atmos. **11**(6), 582 (2020)
8. Cárdenas, M., Armas, O., Mata, C., et al.: Performance and pollutant emissions from transient operation of a common rail diesel engine fueled with different biodiesel fuels. Fuel. **185**, 743–762 (2016)
9. Depature, C., Dégardin, F., Riezu, I., et al.: Characterization of the french railway line difficulties for diesel and hydrogen hybrid trains. Transp. Res. Procedia. **72**, 1475–1482 (2023)
10. Khalid, M., Yousif, M., Kazmi, S., et al.: Coordinated scheduling and multi-energy storage planning for electric train operations. Results Eng. **27**, 106751 (2025)
11. ADEME: Analyse de cycle de vie attributionnelle d'un trajet en train sur 100km de ligne non-électrifiée. https://librairie.ademe.fr/mobilite-et-transports/8405-acv-attributionnelle-d-un-trajet-en-train-sur-100-km.html. Accessed 4 May 2026
12. Aroua, A., Lhomme, W., Depature, C., Adam, P., Renault, M.: Fuel-saving potential of a retrofitted diesel hybrid dual-mode train. IEEE Open J. Veh. Technol. **7**, 402–417 (2026)

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Novel Metal Hydride Cooling System in a Hydrogen Demonstrator Train: Design, Implementation and Technology Assessment

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Abstract. Air-conditioning systems require up to 40% of the overall energy demand in railway vehicles, which need to be reduced, especially in hydrogen trains, where fuel capacity is limited. One approach is the utilization of metal hydrides as a pressure-driven refrigeration unit. Simulation studies suggest an energy reduction of up to 13226 kWh per year and coach. A corresponding lab-scale system is already demonstrated. However, one research question arises: How can we integrate and operate a metal hydride refrigeration system in a real hydrogen train? In such a system, the hydrogen is directed through two metal hydride reactors alternately absorbing hydrogen exothermically and desorbing endothermically, which results in a quasi-continuous cooling effect without consuming hydrogen. In this study the development of a 5-kW metal hydride refrigeration system and the integration approach in the *Talgo* test train 'TPH2' is presented. The system will meet the requirements for the train environment, such as operating temperatures and mechanical stability. Before installing the system in the train, it is tested on a setup simulating the train environment. First measurements at two static cooling cases based on the railway standard EN50591 demonstrate a successful operation and show an average cooling power of 428–435 W.

Keywords: HVAC · efficiency · fuel cells · hydrogen · metal hydride

1 Introduction

Air-conditioning of the passenger compartment is one of the major energy consumers among all auxiliary loads in railway vehicles [1]. For trains with battery or hydrogen powered traction it causes a significant decrease in driving range depending on the environmental conditions. Especially for hydrogen trains it is also essential to reduce the hydrogen consumption to minimize the operating costs. Moreover, hydrogen powered

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trains with high-pressure storage tanks carry an additional energy storage besides the chemical energy of hydrogen: the energy of highly compressed gas. This energy can be used to either by a mechanical expander [2] or directly in a solid-state reaction of metal hydride (MH) with hydrogen in order to drive an air-conditioner. The core of such as metal hydride based air-conditioning system (H2-A/C) consists of two reactors, that are filled with the reactive metal hydride. This thermochemical material is able to reversibly absorb and desorb hydrogen in its metal lattice during a chemical reaction, that is accompanied with a strong thermal effect. Thus, the reactors are built as pressure resistant fluid-solid heat exchangers to efficiently transport the heat of reaction to a heat transfer fluid (HTF).

Figure 1 shows the system layout with the two reactors arranged between the high-pressure tank and the fuel cell. The system is equipped with a bypass in parallel (not depicted) which acts in case of hydrogen flows higher than the design mass flow of the H2-A/C. In operation both reactors work in anticyclic mode in two half cycles by alternatingly absorbing and desorbing hydrogen: In the first half cycle reactor 1 is absorbing hydrogen on an intermediate pressure level, e.g. 80 bar as in the developed system of this study. This causes heat release at a temperature level above ambient, which is dissipated to the ambient. At the same time reactor 2 desorbs hydrogen to the fuel cell slightly above fuel cell supply pressure, e.g. 10 bar as in the target test train of this study. Since the desorption requires heat, and temperature and pressure of the reaction are coupled, heat uptake below room temperature occurs. Accordingly, useful cooling power is generated at reactor 2. As soon as the pressure in reactor 2 reaches the minimum fuel cell supply pressure (approx. after 1–3 min), the hydrogen and fluid valves are switched. Thus reactor 2 is regenerated by absorbing hydrogen and releasing heat to the ambient and reactor 1 is generating the cooling power. Through this anticyclic operation a quasi-continuous refrigeration machine is realized that is able to cool down the cabin air in a hydrogen-powered train.

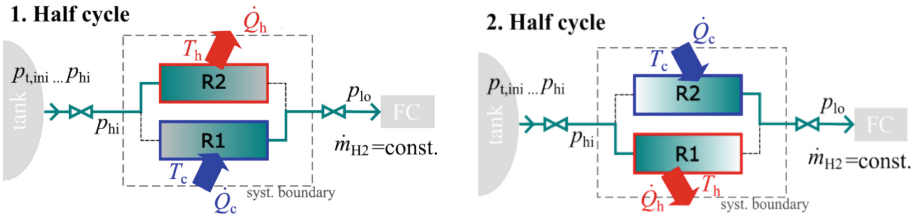


Fig. 1. Quasi-continuous operation principle of the H2-A/C in two alternating half cycles

The application of metal hydrides for thermal machines has been studied since the discovery of technically usable metal hydrides in the 1970s [3]. However, the open system configuration for fuel cell vehicles with a high-pressure tank was only proposed by Linder et al. [4]. Since then, a first demonstration of a working H2-A/C coupled with a fuel cell in a laboratory environment was published [5, 6]. Recent work on reactor side achieved drastic improvements in performance by a new sophisticated reactor design. With a specific power of up to 500 W/kg$_{MH}$ (at 20 °C cold and 30 °C hot side temperature) the power density compared to the previous prototype was approximately doubled. Based

on experimental results of the new reactor prototype an efficiency increase and therefore range increase and fuel saving potential in the range of 5–6% has been projected for a vehicle equipped with such a H2-A/C. Additional system simulations with a fuel cell multiple unit train on realistic tracks showed annual energy savings between 1547 kWh/a and 13226 kWh/a per coach depending on the climate zone [1].

However, due to the small lab scale, the current prototype has an absolute power of only 150 W, which is more than two orders of magnitude smaller than required for an application in a hydrogen train. Therefore, the current reactor prototype is scaled up to the kilowatt scale and packed with all necessary auxiliaries (pumps, valves and control unit) to a packed system. It is designed, considering the requirements of the vehicle environment, to enable its integration in a real fuel cell train. Moreover, the experimental results so far were only reached in laboratory conditions under steady-state conditions of hydrogen flow, cold load and simulated ambient temperatures. In order to gain more realistic results, a test facility is developed that is able to simulate dynamic thermal conditions, but also transient hydrogen mass flows from the tank to the fuel cell. First experiments with packed H2-A/C and the dynamic test facility are conducted for test cases according to EN 50591, under relevant temperature conditions. These tests are then analyzed in terms of the resulting cooling power.

2 Methodology

The H2-A/C as a packed module is depicted in Fig. 2 (detail view), showing dimensions of 958x395x446 mm in length, width and height respectively. It has a total weight of approximately 45 kg and its mechanical stability is designed according to the standard EN12663–1. After a finite element analysis with loads of 3 g in longitudinal, 1 g in lateral and 1 g in vertical direction, structural reinforcements were applied, leading to a figure of safety of 2.2. The module consists of two reactors, one placed in the left and one in the right space of the frame. Among the broad variety of MHs, an AB2-type is used, since it shows a low reaction temperature at typical fuel cell inlet pressures, thus being able to produce cooling power [7]. In order to conduct first tests of the H2-A/C, the reactor version 1.0 [8] is installed in the system. Each of these reactors is carrying approximately 1.5 kg of MH and has a rated thermal power of 1 kW. In a next step, reactor 2.0 will be installed. By means of an increased amount of MH and an improved reactor design based on the works in [9, 10], a rated power of 5 kW is aimed for. In between the reactors, the hydrogen and HTF section is arranged, in which valves ensure the proper switching between the two half cycles.

The back view in Fig. 2 (detail view) shows the corresponding connectors for the high-pressure hydrogen line coming from the tank and the outgoing low-pressure hydrogen line to the fuel cell. The hydrogen inlet and all hydrogen components inside the H2-A/C are designed for 80 bar, whereas the pressure of the outlet line can be set from 15 to 5 bar to meet the requirements of the fuel cell installed in the train. Figure 2 (detail view) additionally shows the HTF connectors on the backplate, through which the generated cold and waste heat is transported to air heat exchangers inside the train. The packed H2-A/C is completed by a controller and a signal conditioning box, not depicted. All the components in the electronic boxes fulfil the temperature requirements for the typical

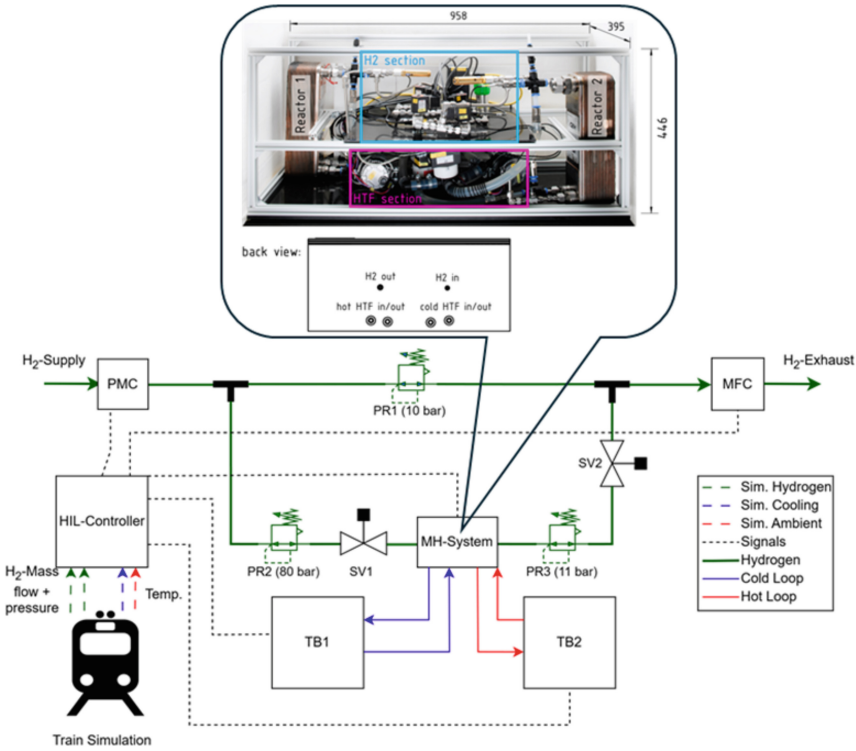


Fig. 2. The H2-A/C installed in the hardware in the loop test setup that simulates the train environment

operation range of a train of −25 °C up to 55 °C. Moreover, the critical components fulfil the fire resistance standard UL94 V0 for the first static tests of the train, and will fulfil the standard EN 45545–2 for future track tests in perspective.

The packed H2-AC is first tested in a hardware-in-the-loop (HiL) test facility, which is depicted in Fig. 2. In this case, hardware in the loop means that the H2-AC is available as a hardware component, and the coupling to the train is only simulated. For this purpose, the hydrogen pressure of the tank in the train is simulated by a hydrogen supply bottle and a subsequent pressure regulator (PMC), and the mass flow required by the fuel cell is simulated by a mass flow controller (MFC) letting hydrogen flow to the ambient. The cooling temperature for the cabin air conditioning and the recooling temperature as the outside temperature are controlled by the thermostatic baths TB1 and TB2. The actuators and sensors for simulating the train, as well as all actuators and sensors of the MH system, run together in a HiL controller. In addition to the simulated infrastructure in the train, a by-pass system is implemented as real hardware. This consists of three pressure reducers (PR1, PR2, PR3), whereby PR1 represents the originally installed pressure reducer of the train. PR2 and PR3 are additional pressure reducers. PR2 limits the pressure to the maximum 80 bar of the H2-AC and PR3 provides a slightly higher pressure for the output of the H2-AC to supply the fuel cell. Whenever the H2-AC cannot

provide enough hydrogen from desorption, the pressure downstream of PR3 drops below 10 bar and PR1 supplies the remaining hydrogen for the fuel cell system. With this setup a wide range of working points can be simulated. Moreover, it is possible to investigate dynamic hydrogen flows that can generate a variable cooling power.

3 Results

For the first test cases, static load profiles according to the standard EN 50591 were chosen. The temperature requirements for these are listed in Table 1. The two cooling cases, test cases 5 and 6, are most often occurring in climate zone 1 and climate zone 2, and therefore most relevant beyond all test cases in the standard EN50591 for evaluating the H2-A/C. In both cases the temperatures of the standard were used, whereby for the cooling temperature ($T_{cooling}$) the heat exchanger's efficiency of 5 °C was subtracted, and for the ambient temperature ($T_{ambient}$), the efficiency of 5 °C was added, in order to consider the influence of a real heat exchanger.

Table 1. Temperature levels and hydrogen mass flows of the applied test cases [1]

Test case of EN 50591	$T_{cooling;standard}$	$T_{cooling,test}$	$T_{ambient,standard}$	$T_{ambient,test}$	Hydrogen mass flow
5	22 °C	22 °C - 5 °C = 17 °C	22 °C	22 °C + 5 °C = 27 °C	4.86 g/min
6	25 °C	25 °C - 5 °C = 20 °C	28 °C	28 °C + 5 °C = 32 °C	4.86 g/min

In order to collect a sufficient amount of data, the tests were each carried out for 25 min. In these experiments the fuel cell inlet pressure is set to 5 bar. Figure 3 shows three representative cycles of the experiment, after the stationary operating point has stabilized. The grey horizontal lines mark the end of a full cycle, which is reached when the pressure at the desorbing reactor drops below 5 bar. The data show the basic principle of the H2-A/C, in which the reactors alternately provide the cooling capacity. This results in a quasi-continuous cooling output.

Negative peaks occur during the half cycle switching due to the temperature switching process. In order to be able to generate cold, the reactor, which has previously absorbed hydrogen, must first be cooled down. This process occurs between the two plateaus at 0 W at the beginning of a cycle. Those plateaus result from the time a valve needs to fulfil the switching process. To minimize losses, when the reactor must be cooled down, only the inlet valve is initially opened, while the valve at the outlet remains closed. Only after a few seconds is it also opened. This results in a staggered switching of the valves, that is beneficial for improving the average cooling power [11].

The cooling power then evolves until the cycle is ended due to the switching criterion. The maximum power of the H2-A/C in both static cases is around 1 kW. On average, a

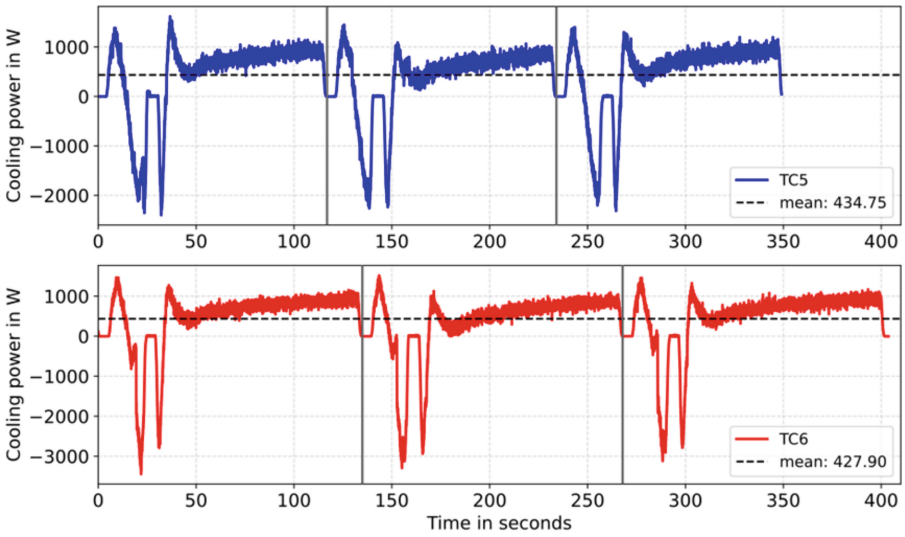


Fig. 3. Cooling power for test case 5 and 6 of EN 50591

lower power of 434.75 W for test case 5 and 427.90 W for test case 6 is reached, which is marked by the dashed black line. As seen in the data, the half cycle duration of test case 5 is shorter than of test case 6, which is due to the selected operating point. As the ambient temperature in test case 5 is closer to the equilibrium point, less hydrogen can be desorbed. But nevertheless, the average power of test case 5 is higher, despite the lower amount of desorbed hydrogen, because the temperature lift between hot and cold side temperature in test case 5 is lower. A lower temperature difference results in lower thermal losses during the temperature switch from the hot to the cold side, which leads to the higher average output.

4 Discussion and Conclusions

The MH-based technology H2-A/C can recover energy from high-pressure tanks in a fuel cell train to drive an innovative refrigeration process, and thus reduce hydrogen costs and increase driving range. At the example of the hydrogen test train TPH2 of the train manufacturer Talgo, a reasonable integration option is found. The hydrogen-side integration will be realized in parallel to the already installed pressure reducer between tank and fuel cell, along with two additional pressure reducers before and behind the H2-A/C. For the thermal integration, the H2-A/C will be equipped with a dedicated fluid-air heat exchanger at the hot and cold side each. The cold side heat exchanger will be placed in the air duct before the evaporator of the existing HVAC system, whereas the hot side heat exchanger will be integrated in parallel to the existing fuel cell radiator. Both integrations, the thermal one as well as the integration in the hydrogen path, are simulated in a developed test setup with HiL capabilities. It enables comprehensive tests of the H2-A/C in the train environment, including static load tests, but also dynamic scenarios consisting of real drive cycles with varying cold loads and ambient temperatures. The

H2-A/C is built up as a packed system comprising all auxiliaries, a controller and defined interfaces to the train. The system is designed for a rated power of 5 kW and fulfils the interface requirements for the hardware integration in the 'TPH2' train, as well as relevant railway standards regarding mechanical stability and fire protection for this prototype.

In a first test stage, existing reactors of a lower power class were installed in order to test the packed system and the HiL test facility. Two tests were conducted with these preliminary reactors at static operation points with constant inlet temperatures and with a constant hydrogen mass flow. The used temperatures represent the two most relevant cooling cases of the HVAC standard EN50591. The results show a successful operation of the H2-A/C over several half cycles and a maximum cooling power of approximately 1 kW. The characteristic power curves show a timely average of 428 W and 435 W of continuous cooling output in the two test cases, respectively. In the next step, the H2-A/C will be equipped with an improved reactor design and a higher amount of MH to reach a higher cooling power of 5 kW. Furthermore, dynamic tests on this test facility with realistic driving cycles are planned that will qualify the H2-A/C for the first hardware integration in the fuel cell test train 'TPH2' of Talgo.

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References

1. Kordel, M., Heeland, M.M., Knetsch, K.: Waste energy AC technologies in H2-multiple units. In: 4. International Railway Symposium Aachen (IRSA), pp. 561–581. RWTH Aachen University, Aachen, Germany (2023)
2. Singer, G., Köll, R., Aichhorn, L., Pertl, P., Trattner, A.: Utilizing hydrogen pressure energy by expansion machines – PEM fuel cells in mobile and other potential applications. Appl. Energy. **343**, 121056 (2023)
3. Schlapbach, L., Züttel, A.: Hydrogen-storage materials for mobile applications. Nature. **414**(6861), 353–358 (2001)
4. Linder, M., Kulenovic, R.: An energy-efficient air-conditioning system for hydrogen driven cars. Int. J. Hydrog. Energy. **36**(4), 3215–3221 (2011)
5. Weckerle, C., Nasri, M., Hegner, R., Bürger, I., Linder, M.: A metal hydride air-conditioning system for fuel cell vehicles – functional demonstration. Appl. Energy. **259**, 114187 (2020)
6. Weckerle, C., Nasri, M., Hegner, R., Linder, M., Bürger, I.: A metal hydride air-conditioning system for fuel cell vehicles – performance investigations. Appl. Energy. **256** (2019)
7. Skripnyuk, V.M., Ron, M.: Hydrogen desorption kinetics in intermetallic compounds C2, C51 and C52 with laves phase structure. Int. J. Hydrog. Energy. **28**(3), 303–309 (2003)
8. Weckerle, C., Bürger, I., Linder, M.: Novel reactor design for metal hydride cooling systems. Int. J. Hydrog. Energy. **42**(12), 8063–8074 (2017)
9. Wimmer, A., Kordel, M., Linder, M., Bürger, I.: High performance reactor of a metal hydride based cooling system for air-conditioning of fuel cell electric vehicles. Appl. Energy. **391**, 125911 (2025)

10. Wimmer, A., Linder, M., Bürger, I.: Metal hydride-based cooling system for fuel cell electric vehicles: achieving a temperature lift of 40 K. Appl. Energy. **398**, 126396 (2025)
11. Weckerle, C., Nasri, M., Hegner, R., Bürger, I., Linder, M.: A metal hydride air-conditioning system for fuel cell vehicles – functional demonstration. Appl. Energy. **259** (2020)

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Powering Ships, Cutting Carbon: The FuelSOME Approach to Multifuel SOFCs

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Abstract. The maritime sector faces an accelerated decarbonization trajectory driven by the International Maritime Organization's 2023 greenhouse-gas (GHG) strategy [1] and the European Union's FuelEU Maritime regulation [2]. Against this regulatory backdrop, the FuelSOME project develops and validates a multifuel solid oxide fuel cell (SOFC) system tailored to ocean-going vessels [3]. The system targets efficient operation on ammonia, methanol and hydrogen—preferably sourced from renewable energy or waste streams [4] —supported by a fuel supply and quality framework and by techno-economic and life-cycle sustainability assessments (LCSA) [5]. This paper outlines the project rationale, system concept and interim progress, while situating FuelSOME in the scientific and industrial state of the art. Key activities include (i) screening fuel pathways and defining SOFC-grade fuel quality requirements, (ii) advancing stack-level tolerance and degradation management under multifuel operation [6], (iii) designing a flexible 6 kW SOFC architecture with harmonized balance-of-plant for multiple fuels [7], and (iv) implementing an integrated TEA/LCSA to compare against conventional marine propulsion [8]. Initial results indicate successful design and manufacturing of stack modules suitable for multifuel operation, component validation under varying atmospheres, and development of reforming/cracking units for ammonia and methanol [9]. Socio-environmental and economic assessments are progressing, with no major risks identified to date. The near-term objective is the laboratory validation of a 6 kW system with ≥50% electrical efficiency and ≥500 h operation under marine-relevant profiles. Collectively, these outcomes point to the technical feasibility and sustainability potential of multifuel SOFC systems as a pathway to deep decarbonization in deep-sea shipping [10]

Keywords: solid oxide fuel cell · maritime decarbonization · Hydrogen · Ammonia

1 Introduction

International shipping accounts for roughly 3% of global greenhouse-gas emissions and is subject to increasingly stringent climate policies [11, 12]. In July 2023, the International Maritime Organization (IMO) adopted a revised GHG strategy that commits the sector to reach net-zero emissions by or around 2050, complemented by indicative

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checkpoints for 2030 and 2040 [13]. In Europe, Regulation (EU) 2023/1805 ('As outlined in the FuelEU Maritime regulation') establishes progressively tighter limits on the well-to-wake GHG intensity of energy used on board, applies to ships ≥5,000 GT calling at EU/EEA ports, and mandates onshore power use for certain ship types [14, 15]. These converging policy signals accelerate demand for high-efficiency, fuel-flexible propulsion solutions capable of utilizing scalable low- and zero-carbon energy vectors.

Among advanced options, solid oxide fuel cells (SOFCs) are attractive for deep-sea vessels due to their high electrical efficiency, combined heat-and-power capability and intrinsic fuel flexibility [16, 17]. Recent reviews emphasize that SOFCs can substantially reduce CO_2 and local pollutants (NO_n, SO_n, PM) relative to combustion-based systems, especially when integrated with waste-heat recovery or hybridized with batteries/turbines for transient load handling [18]. However, practical deployment requires credible pathways for fuels with higher volumetric energy density than compressed hydrogen—namely ammonia and methanol—and rigorous management of new safety and system-integration challenges [19, 20].

In this context, FuelSOME aims to develop and validate a multifuel SOFC concept for ocean-going vessels, covering fuel pathways and quality, stack- and system-level technologies, and prospective TEA/LCSA benchmarking against incumbent propulsion [21, 22]. This paper summarizes the project's concept and early progress and articulates next steps towards a laboratory-validated 6 kW system [23].

2 State of the Art and Rationale for SOFCs in Maritime

SOFC systems can exceed 55–60% electrical efficiency at stack level and achieve higher overall efficiency in combined heat-and-power configurations [24]. Their tolerance to CO and reformate streams enables operation on fuels such as natural gas, methanol and, via cracking, ammonia - offering a transition path from today's fossil fuels to renewable e-fuels [25]. Comprehensive reviews of maritime SOFC applications report promising performance across auxiliary and propulsion roles and high-light integration.

Ammonia provides carbon-free tank-to-wake operation and can be synthesized from renewable hydrogen and nitrogen; it also benefits from liquid storage at moderate conditions [27, 28]. Its hazards are dominated by toxicity and potential NO_n formation if combusted, necessitating robust leak prevention, detection and ventilation, and stack/system designs that avoid NO_n generation during cracking and electro-oxidation [29]. Methanol is liquid at ambient conditions with growing bunkering pilots; 'green' methanol can be produced from biomass or captured CO_2 plus renewable hydrogen, but supply scale-up and cost remain challenges [30]. These fuel characteristics motivate a multifuel SOFC architecture that can accommodate fuel availability dynamics while preserving high efficiency.

3 The FuelSOME Project: Objectives and Approach

FuelSOME's overarching objective is to demonstrate the technological feasibility of a flexible, scalable SOFC system able to operate on ammonia, methanol and hydrogen for deep-sea shipping. The project integrates four pillars: (i) fuel-pathway screening

and quality definition; (ii) stack-level R&D to expand tolerance windows and mitigate degradation under multifuel operation; (iii) design and build of a lab-scale, ~6 kW SOFC system with harmonized balance-of-plant (BoP); and (iv) an integrated techno-economic assessment (TEA) and prospective life-cycle sustainability assessment (LCSA). Key performance indicators include ≥50% electrical efficiency at system level, ≥500 h of operation on marine-relevant profiles, and evidence-based recommendations for port fuel supply backbones and fuel quality specifications (Fig. 1).

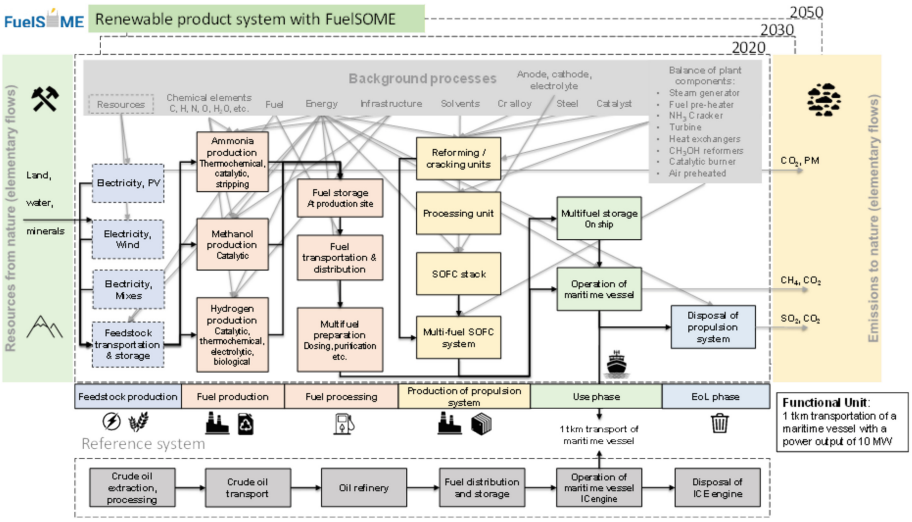


Fig. 1. System model of the FuelSOME system. On the bottom the different life cycle stages are shown. Inside the system model all processes considered in the LCA are depicted. Elementary flows are shown vertically, background processes and the functional unit are drawn horizontally. Source icons: Adobe Stock (Adobe Stock, 2022)

3.1 Fuel Pathways, Quality Requirements and Port Supply Backbones

A structured screening compiles industrial and emerging pathways for renewable hydrogen, ammonia and methanol. For each pathway, the analysis considers production routes, expected fuel quality (including sulfur, chlorine and trace species), logistics to ports, storage options and compatibility with SOFC operation. Where necessary, pre-conditioning steps (e.g., desulfurization, chloride removal, controlled steam-to-carbon ratios) are identified to meet SOFC-grade specifications. These data feed a supply-chain model for European ports that optimizes alternative fuel backbones under GHG, energy-efficiency and quality KPIs.

3.2 Stack-Level R&D and Multifuel Tolerance

At stack level, controlled tests map performance windows (temperature, current density, fuel utilization) using simulated reformate compositions representative of ammonia cracking and methanol steam reforming. Ex-situ component tests (seals, interconnects, coatings) in relevant atmospheres support identification of fuel-specific degradation mechanisms (e.g., nitriding under NH_3, carbon deposition risks with methanol) and mitigation strategies. A 2 × 3 kW stack module is designed as a building block for the 6 kW system.

3.3 System Architecture, Modelling and Prototype Test Bed

The system employs a harmonized BoP for multiple fuels, encompassing a configurable fuel-processing unit (ammonia cracker/methanol reformer), anode-off-gas recirculation, air management, thermal integration and safety systems. Zero-/low-order process models guide the P&ID, operating strategies (start-up, transient management) and controls. The lab prototype is exercised on marine-relevant load profiles, with exhaust analysis, fuel-consumption metering and closed-loop 'hardware-in-the-loop' of emulated subsystems where appropriate.

3.4 Techno-Economic and Prospective Life-Cycle Sustainability Assessment

TEA estimates CAPEX/OPEX across scenarios (current, near-term, mid-term) and accounts for fuel costs, cargo impacts and policy incentives. The prospective LCSA (environmental LCA, social LCA and life-cycle costing) quantifies cradle-to-grave GHG emissions, non-renewable energy demand, biodiversity impacts and social risk hotspots, benchmarking the FuelSOME system against conventional marine propulsion under EU-relevant trajectories.

4 Interim Results

Early project outcomes include: (i) design and manufacturing of SOFC stack modules capable of multifuel operation; (ii) component validation under varying fuel atmospheres; (iii) development of ammonia-cracking and methanol-reforming units sized for a 6 kW module and compatible with internal/external conversion strategies; and (iv) advancing socio-environmental and economic assessments without identification of major risks to date. A public report summarizes candidate technology concepts and fuel pathways, including indicative cost and readiness differences. Ongoing work refines fuel-quality envelopes and stack operating maps, and integrates these into the system-level controller.

5 Discussion

5.1 Safety and Compliance

Ammonia's primary hazard is toxicity; credible ship designs must incorporate double-walled piping, dedicated ventilation zones, continuous detection, hazardous-area classification and emergency-shutoff logic. Current guidance from classification societies and European agencies provides a risk-based framework for bunkering and engine-room integration. For SOFC use, maintaining near-complete NH_3 conversion upstream of the stack and avoiding high-temperature mixing of NH_3 with oxidant streams mitigates NO_n formation.

5.2 Fuel Availability and Cost

Methanol is gaining momentum through large dual-fuel engine orders and expanding bunkering pilots, yet the long-term role of 'green' methanol hinges on scaling sustainable carbon sources and e-fuel synthesis. Ammonia avoids the carbon-sourcing constraint, but requires green hydrogen at scale and stringent safety management. A multifuel SOFC architecture hedges supply risks by enabling operation on whichever sustainable fuel is locally available at acceptable cost and quality.

5.3 System Integration

Deep-sea profiles require careful thermal management and hybridization for transients. Anode off-gas recirculation, autothermal reforming/cracking options and waste-heat utilization are central to meeting $\geq$50% system electrical efficiency while maintaining component durability. As outlined in the FuelEU Maritime regulation framework's GHG-intensity metric underscores the importance of well-to-wake accounting and favors configurations that minimize upstream and onboard energy penalties.

6 Conclusion

Under rapidly tightening climate policies, multifuel SOFC systems represent a credible pathway to decarbonize ocean-going vessels while preserving operational flexibility. FuelSOME advances this vision by aligning fuel-pathway assessments, stack- and system-level engineering and holistic sustainability analysis. Early results are consistent with the feasibility of a 6 kW multifuel SOFC demonstrator and support further scale-up and standardization for maritime applications.

The immediate milestone is laboratory validation of a 6 kW SOFC system capable of operating on ammonia, methanol and hydrogen with $\geq$50% electrical efficiency and $\geq$500 h cumulative operation on marine-relevant cycles. Subsequent work will address: (i) extended durability testing to quantify degradation rates under each fuel; (ii) refinement of safety cases for shipboard integration; (iii) port-scale supply-chain scenarios aligned with As outlined in the FuelEU Maritime regulation implementation; and (iv) scaling design principles towards 500–1,000 kW modules suitable for hybrid prime-mover architectures in oceangoing vessels.

References

1. International Maritime Organization: Strategy on reduction of GHG emissions from ships. https://www.imo.org/en/MediaCentre/PressBriefings/pages/Decarbonization-strategy.aspx (2023). Accessed 11 Feb 2026
2. European Commission: Regulation (EU) 2023/1805 of the european parliament and of the council on the use of renewable and low-carbon fuels in maritime transport (FuelEU Mari-time). official journal of the european union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R1805 (2023). Accessed 17 Dec 2025
3. Van Veldhuizen, B., et al.: Solid oxide fuel cells for marine applications: opportunities and challenges. J. Power Sources. **525**, 231094 (2022). https://doi.org/10.1016/j.jpowsour.2022.231094
4. Osman, A.I., Hefny, M., Abdel Maksoud, M.I.A., Elgarahy, A.M., Rooney, D.W.: Recent advances in carbon capture storage and utilisation technologies: a review. Environ. Chem. Lett. **19**, 797–849 (2021). https://doi.org/10.1007/s10311-020-01133-3
5. Frehner, A., et al.: Life cycle sustainability assessment of a multi-fuel capable propulsion system based on SOFC technology. Energy Convers. Manag. **297**, 117456 (2024). https://doi.org/10.1016/j.enconman.2024.117456
6. Neubauer, R., et al.: Effect of multifuel approach on SOFC system performance and architecture requirements. J. Fuel Cell Sci. Technol. **20**(3), 031004 (2023). https://doi.org/10.1115/1.4056789
7. Alma Clean Power: Breakthrough in direct ammonia fuel cell technology: world's first 6 kW fuel cell system successfully tested. https://almacleanpower.com/news (2023). Accessed 17 Dec 2025
8. Lee, H., et al.: Comparative life cycle assessments and economic analyses of alternative marine fuels. Transp. Res. Part D: Transp. Environ. **105**, 103217 (2022). https://doi.org/10.1016/j.trd.2022.103217
9. Huhtinen, W., et al.: Testing platform for SOFC stack modules utilizing marine fuels. J. Power Sources Adv. **15**, 100095 (2023). https://doi.org/10.1016/j.powera.2023.100095
10. Farrukh, S., et al.: Pathways to decarbonization of deep-sea shipping: a review of alternative fuels and technologies. Renew. Sust. Energ. Rev. **169**, 112948 (2023). https://doi.org/10.1016/j.rser.2022.112948
11. Osman, A.I.: Nasr M, Lichtfouse E, Farghali M, Rooney DW: hydrogen, ammonia and methanol for marine transportation. Environ. Chem. Lett. **22**, 2151–2158 (2024). https://doi.org/10.1007/s10311-024-01757-9
12. Skuld: International maritime organization GHG strategy. https://www.skuld.com/globalassets/documents/imo-ghg-strategy.pdf (2023). Accessed 25 Sept 2025
13. International Maritime Organization: International maritime organization adopts revised strategy to reduce greenhouse gas emissions from international shipping. https://www.imo.org/en/mediacentre/pressbriefings/pages/revised-ghg-reduction-strategy-for-global-shipping-adopted-.aspx (2025). Accessed 25 Sept 2025
14. EUR-Lex: Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime). OJ L 234, 22.9.2023, pp. 48–100. https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng (2023). Accessed 26 Sept 2025
15. European Commission: Decarbonising maritime transport – FuelEU maritime. https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en (2023). Accessed 29 Sept 2025
16. van Veldhuizen, B.N., van Biert, L., Aravind, P.V., Visser, K.: Solid oxide fuel cells for marine applications. Int. J. Energy Res., 5163448 (2023). https://doi.org/10.1155/2023/5163448

17. HELENUS Consortium: High efficiency low emission nautical SOFC. https://www.helenus.eu/about-the-helenus-project/ (2024). Accessed 30 Oct 2025
18. Ellingsen, L. A.W.; Jenssen J.I.: LCA of marine propulsion. Asplan Viak for NCE Maritime CleanTech. https://maritimecleantech.no/wp-content/uploads/2020/11/Report-LCA-of-marine-propulsion-systems.pdf (2020). Accessed 30 Jan 2026
19. Global Maritime Forum: Zero-emission shipping fuels: a guide to methanol and ammonia. https://globalmaritimeforum.org/news/zero-emission-shipping-fuels-methanol-and-ammonia/ Accessed 1 Feb 2026
20. American Bureau of Shipping: Safety insights for ammonia as a marine fuel. https://ww2.eagle.org/content/dam/eagle/publications/ammonia-safety-advisory.pdf (2025). Accessed 10 Sept 2025
21. Neubauer R., Sztrinko P., Innerkofler M., Reiter B.: Effect of multifuel approach on SOFC system performance and architecture requirements. EFCF. https://fuelsome.eu/wp-con-tent/uploads/2023/12/EFC23_Effect_of_Multifuel_Approach_on_SOFC_System_Raphael-Neubauer_Submission.pdf. (2023). Accessed 10 Sept 2025
22. Huhtinen W., Saxelin S., Hopsu J.: Testing platform for SOFC stack modules utilising marine fuels. https://www.efcf.com/fileadmin/user_upload/P01_EFCF-2024_Paper_neuA1225_PlatformMarineFuelSOFC_Huhtinen_Werneri.pdf (2024). Accessed 10 Sept 2025
23. Alma Clean Power: Breakthrough in direct ammonia fuel cell technology: world's first 6 kW fuel cell system successfully tested. https://almacleanpower.com/news/alma-clean-power-announces-breakthrough-in-direct-ammonia-fuel-cells Accessed 12 Sept 2025
24. Lv, X., Hong, P., Wen, J., et al.: Highly efficient operation of an innovative SOFC-powered all-electric ship system using a quick approach for ammonia-to-hydrogen. Front. Energy. **19**, 365–381 (2025). https://doi.org/10.1007/s11708-025-0974-8
25. Eguchi, K.: Component materials and reactions for ammonia-Fueled SOFCs. In: Aika, K., Kobayashi, H. (eds.) CO_2-Free Ammonia as an Energy Carrier, pp. 427–446. Springer, Singapore (2023). https://doi.org/10.1007/978-981-19-4767-4_28
26. Reurings J.W.: A modeling study to investigate performance of SOFC-ICE hybrid systems for marine applications. MSc thesis, https://repository.tudelft.nl/record/uuid:7ff207b4-e7a8-4104-896a-91b27ceff34d, Delft (2019)
27. The Royal Society: Ammonia: zero-carbon fertiliser, fuel and energy store: https://royalsociety.org/green-ammonia Accessed 22 Oct 2025
28. Saygin, D., Blanco, H., Boshell, F., et al.: Ammonia production from clean hydrogen and the implications for global natural gas demand. Sustainability. **15**, 1623 (2023). https://doi.org/10.3390/su15021623
29. Dhawale, D.S., Biswas, S., Kaur, G., Giddey, S.: Challenges and advancement in direct-ammonia solid oxide fuel cells: a review. Inorg. Chem. Front. **10**, 6176–6192 (2023). https://doi.org/10.1039/D3QI01557B
30. Fasihi, M., Breyer, C.: Global production potential of green methanol based on variable renewable electricity. Energy Environ. Sci. **17**, 3503–3522 (2024). https://doi.org/10.1039/D3EE02951D

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Contribution of Electric Vehicle Chargepoints to the Flexibility of the Luxembourgish Energy System and the Absorption of Renewable Energy

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Abstract. The European Union (EU) member states are required under the Alternative Fuels Infrastructure Regulation (AFIR) to assess how electric vehicle (EV) uni and bidirectional chargepoints could enable EVs to contribute to the flexibility of the electricity system, including their participation in the balancing market, to reduce costs of the system and users, and to a better absorption of renewable electricity. An in-house perfect foresight optimisation model was used to simulate typical days of forecast 2030 electricity demand both nationally and regionally for Luxembourg, including seasonal and daily EV and non-EV demand, EV plug-in profiles, electricity day ahead prices, and requirement and prices for grid services, namely frequency containment reserve (FCR) and automatic frequency restoration reserve (aFRR). The available flexibility was quantified as connected EV battery energy and power in 2030 that can be charged and discharged per hour of day. EV charging was optimised to maximise cost savings in 2030 from day ahead electricity prices, from provision of grid services, and from postponement of grid reinforcements due to reduction of peak network capacity. EV charging was also optimised to increase the share of renewable electricity consumption in 2030. Recommendations for Luxembourg and other states are provided with regards to EV flexibility and bidirectional charging.

Keywords: Vehicle-to-grid · Electricity grid flexibility · Electric vehicles · Optimisation

1 Introduction

This paper is based on a project commissioned by the Institut Luxembourgeois de Régulation (ILR) to Cenex in response to obligations under the EU's AFIR Articles 15(3) and 15(4) [1]. Cenex is a non-profit research and consultancy organisation specialised in low emission transport and the associated infrastructure. AFIR Article 15(3) requires EU Member States to assess how the deployment and operation of EV chargepoints could enable EVs to contribute more to the flexibility of the energy system, including their participation in the balancing market, and to a better absorption of renewable electricity.

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Article 15(4) requires the regulator to assess the potential contribution of bidirectional charging to reducing the costs of the electricity system and users and to increasing the share of renewable electricity in the electricity system. Cenex conducted this study, which will be used by the Luxembourgish Government to take measures to adjust the geographical distribution and availability of chargepoints and take any relevant related measures. The full report is now available [2].

2 Methodology

Data was collected from publicly available sources in addition to data provided by ILR and a report from Creos [3], the main distribution network operator (DNO) in Luxembourg. This data includes EV registrations [4], EV chargepoint deployment by type and region [5], travel surveys [6], regional electricity generation and demand, and prices from wholesale electricity and flexibility services.

A perfect foresight optimisation model developed by Cenex [7] was used to simulate typical days of electricity demand both nationally and regionally for Luxembourg. The perfect foresight method assumes a perfect knowledge of future events and efficient dispatch of flexibility, so results presented are optimistic and should be viewed as a theoretical upper bound on what is possible.

Winter and summer days of both high and low renewables generation output were selected from historical data to provide a variety of conditions in which EV charging flexibility could operate within. On high renewables output days, the flexibility can be tested to see how much renewable generation can be absorbed. On low renewables output days, the impact of flexibility on price optimisation and grid service provision can be tested without the need for renewables absorption.

The model was applied to a 2023 scenario and a forecast scenario in 2030. EV uptake rates, EV plug-in behaviour, and renewable generation capacities were varied within the forecast scenario. EV plug-in profiles for cars, vans and heavy goods vehicles (HGVs) [8] were created, with plug-in events at home, workplace, destination, or high powered (e.g. en route) locations. The electricity demand profile for 2030 was forecast using a combination of historical demand shapes and the Creos report. Electricity prices for 2030 were forecast with a 9 EUR/MWh reduction from 2023 in line with expert predictions [9].

Three charging scenarios were used to test the sensitivity of how frequently vehicles plug-in, reflecting the availability of vehicle-to-grid (V2G) and incentivisation of users to plug-in, when possible, even if they do not need to charge. This paper considers only the "Incentivised" plug-in behaviour in order to demonstrate the potential of what smart charging and V2G could achieve in terms of flexibility. Recent demand-side response trials in the UK have demonstrated that plug-in frequency and duration were significantly increased via incentivisation through availability payments (increase in plug-in time was 18–26% compared to non-incentivised) [10]. A sensitivity analysis on all scenarios is available in the full report.

Much of the analysis was done by running a scenario at the national level. This provided results for total impact of EV charging and EV flexibility. However, to address issues of regional capacity constraints or renewables absorption, regional versions of the model were run. These regional versions were based on the six grid zones in Luxembourg.

The simulation results in this report need to be viewed as optimistic upper boundary estimates of the theoretical flexibility assessment. Realistically achievable practical flexibility is expected to be substantially lower due to technical and practical limitations in the real world. Examples of technical limitations include connection constraints at workplaces; imperfect interoperability between vehicles, chargers, and energy management systems; sleep mode on some EVs if charging current is low; or standards for EV-charger communications being compulsory only from 2027. Examples of practical limitations include limited adoption of optimized charging, V2G, and automation software; or user concerns about accelerated battery degradation associated with V2G. Further iterations of this study will account for these limitations, which were not in scope of this initial study.

3 Results

From a total of approximately 218 thousand electric cars, vans and HGVs estimated to operate within Luxembourg in 2030, the number of vehicles connected to chargers is expected to peak overnight, reaching a maximum of around 130 thousand in the incentivised scenario. In 2030 the connected charging power (for the incentivised plug-in scenario) peaks at around 1.700 MW. A maximum discharge power of around 370 MW is also available. Figure 1 shows the corresponding average charging power and V2G discharging power of all connected vehicles in each hour of the day. This metric is based on the rated charger power for each vehicle and does not account for the state of charge (SOC) present in each vehicle battery at the time of connection.

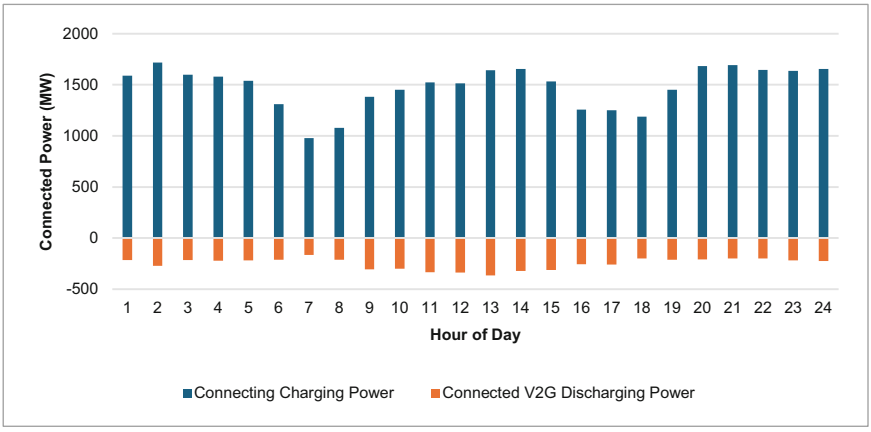


Fig. 1. Sum of Charger Power of all Connected Vehicles per Hour of the Day, 2030 Incentivised Weekday Profile

In 2023 based on the current number of EVs and current plug-in behaviours, up to 88 MW of EV charging demand could be shifted from the times of day with the highest

EV charging demand to other times of the day. In 2030 with the incentivised plug-in behaviour this rises to 878 MW.

As per Table 1, in 2030 if EV charging is optimised for day ahead wholesale energy prices, they could provide daily energy cost savings of up to 299 k EUR for smart charging alone. Savings could become 403 k EUR if V2G is included, and 427 k EUR if both V2G and grid services are included (FCR and aFRR). In 2030 an EV fleet could be expected to contribute to aFRR and FCR grid services, based upon existing technical demonstrations of the technology and an expected technology readiness level (TRL) of 9 in 2030. Modelling of 2030 suggests that, with the incentivised plug-in scenario, the EV charging portfolio can offer close to and sometimes more than the transmission system operator (TSO) grid services requirement.

Table 1. Summary of Potential Savings against Unmanaged Charging in EUR, 2030 Incentivised

Reference Day	Winter High-Generation	Winter Low-Generation	Summer High-Generation	Summer Low-Generation
Baseline National Consumption Costs at Day-Ahead Pricing (Unmanaged EV Charging)	1650 k EUR	4677 k EUR	1417 k EUR	2532 k EUR
Saving Cost-Optimised Smart Charge	299 k EUR	256 k EUR	141 k EUR	235 k EUR
Saving Cost-Optimised V2G	403 k EUR	291 k EUR	195 k EUR	280 k EUR
Saving Combined Grid Services & Cost Optimised V2G	427 k EUR	322 k EUR	249 k EUR	326 k EUR

There is potential for the optimisation of EV charging to contribute to network reinforcement postponement. Modelling demonstrates that in 2030, if EV charging is used solely for the purpose of reducing network peak capacity, then network reinforcements that would otherwise be required can be postponed. All regions within Luxembourg, with the exception of Southeast and Southwest, could keep the maximum network demand below 2023 capacity levels on the typical days simulated, resulting in a deferral of 566 M EUR of reinforcement costs. This result should be interpreted in the theoretical and optimistic upper boundary context that the assumptions of the study represent. Several simplifications were made, such as ignoring the electricity distribution requirements inside each of the six regions, excluding safety margins for network capacities, assuming

that network operators could rely on the flexibility that EV users could provide in the real-world, or any post-2030 grid planning considerations.

If the 2030 costs savings above are split equally across all residents, this results in the following daily savings per resident depending on the source:

- Day ahead wholesale energy price optimisation: between 0,19 EUR and 0,61 EUR
- Additional savings from grid service provision: between 0,03 EUR and 0,08 EUR
- From network reinforcement postponement: 0,17 EUR

Energy price optimisation and grid service provision could put additional strain on the grid under certain circumstances. These two actions could hence counteract an optimisation of EV charging for network reinforcement postponement. Therefore, although savings from energy price optimisation and grid service provision can be combined, they cannot be combined with savings from network reinforcement postponement.

EV charging can be optimised to facilitate increasing the share of renewables in electricity consumption by supporting increases to renewable capacity build. However, where there is no renewables export or spill (due to grid congestion), EV charging is not required to assist (as is the case in 2023). In 2030 and assuming an incentivised plug-in behaviour, the share of renewable electricity in final consumption on the highest generation day (summer high generation day) is 39,6% at National Energy and Climate Plan (NECP) target scenario renewables level. In this scenario, since all renewable energy is absorbed, EV charging cannot contribute to increasing absorption. Therefore, as per Fig. 2, a simulation was performed with EV charging optimised to absorb renewables, and renewable installed capacity increased to the point where renewable energy export first occurs at the national level (whilst observing regional grid capacity levels). This resulted in an additional 1.198 MW of installed renewables capacity (an 80% increase compared to the NECP target scenario), and 73,5% share of renewables in electricity consumption on the highest generation day (summer high generation day). With unmanaged EV

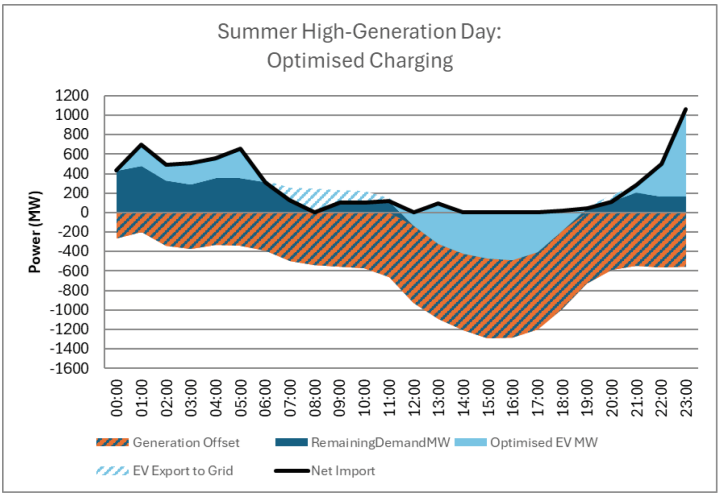


Fig. 2. EV Charging Optimised for Increased Renewables Installation, 2030

charging a renewable electricity consumption share of only 64,5% could be obtained on the same day (assuming the same installed renewables capacity). This means that EV charging can contribute to a 9% additional absorption of renewable electricity on the summer high generation day (1.959 MWh).

4 Conclusion

There are clear benefits to optimised EV charging for the Luxembourg electricity system, including cost optimisation, reducing peak demand and renewables integration. We recommend pursuing optimised EV charging due to the multiple possible benefits for the electricity system.

The incremental benefit of V2G charging above smart charging is such that it could pay for itself within 1 to 4 years. We recommend that V2G charging is pursued as it can contribute a net benefit to the electricity system. Grid services (specifically aFRR and FCR) could be considered within an optimised EV charging solution. However additional hardware, monitoring and integration costs to facilitate grid service provision may challenge economic viability.

Energy cost optimisation alone from EV charging could put additional strain on the grid during the cheapest priced periods. We recommend that such effects are avoided by initiatives such as diversification of price signals to EV charging, differing charging objectives, or explicit capacity costing for users. Optimising EV charging for day ahead wholesale electricity prices will sometimes compete against shaving peaks in electricity demand profiles. Co-optimising both is out of the scope of this project, but peaks from cost optimisation need to be carefully watched in the future.

Future iterations of this report should consider a co-optimisation solution where EV charging optimised for energy price signals and grid service provision is balanced against the future network limitations at local and regional levels. Some examples of considerations to be included in future iterations of this report are:

- Flexibility can be modelled not only theoretically but also including technical and practical limitations to obtain a more realistic flexibility potential.
- New iterations of electricity demand scenarios from future Creos Scenario Reports.
- A deeper analysis of sensitivities impacting not only energy price optimisation and grid services, but also grid reinforcement and absorption of renewables, as a result from different plug-in behaviours and EV or V2G charging uptake rates.
- A more detailed simulation of the Luxembourgish grid including local and regional constraints and considering low, medium and high voltage networks.
- Grid reinforcement modelling including grid safety margins and security criteria such as “N-1”.
- Projections going out to 2040 or 2050 for a better understanding of grid reinforcement requirements.
- Refined charging powers and dwell times for workplace, residential and destination charging if the data is available.
- A fully co-optimised modelling balancing out the often-competing objectives from cost optimisation (from energy pricing and grid services), peak power optimisation (reducing cost from grid reinforcement), and increased absorption of renewables.

Incentivised plug-in behaviour for EV charging could increase savings (from day ahead optimisation and grid services in 2030) from between 6% and 18% each day compared to the current plug in behaviour. We recommend that actions are taken to encourage EV owners to plug-in EVs more frequently where a dedicated charger for the EV exists. This could be done via the customer value proposition to EV/chargepoint users. Examples of this proposition include rewarding users for the time EVs are plugged in and available, cheaper EV charging during certain windows, passing through a portion of grid services revenue (via aggregator) to EV users, or gamification to earn rewards and compete with friends.

As it currently stands it is not yet clear which technology, between alternating and direct current (AC and DC) V2G, will win out, as this is still dependent upon vehicle OEMs and how interoperable different solutions become. There are no clear recommendations currently between AC and DC V2G technology solutions.

All EU states are mandated by the AFIR to conduct this analysis in the short term. We encourage the relevant country authorities to commission these studies and follow a similar methodology to the one proposed in this paper, with scope for further improvements as explained.

References

1. European Parliament Regulation (EU): 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU. Official Journal of the European Union 32 (2023)
2. ILR publications: Institut Luxembourgeois de Régulation. https://www.ilr.lu/wp-content/uploads/consultation/ilr_elec_pub_2025_09_24_EV-Contribution-to-Luxembourg-Grid.pdf. Accessed 30 Sep 2025
3. Creos: Electricity transmission grid scenario report 2040 (version 2022). Luxembourg: Creos (2023)
4. Statistiques.lu, Lustat: Number of used vehicles registrations by type of vehicle. https://lustat.statec.lu/?lc=en&pg=20&fs[0]=Topics%2C1%7CEnterprises%23D%23%7CTransport%23D6%23&fc=Topics&snb=40. Accessed 30 Sept 2025
5. Institut Luxembourgeois de Régulation (ILR): Le secteur de l'électricité. https://www.ilr.lu/espace-statistiques/les-statistiques-par-secteur/le-secteur-electricite/. Accessed 30 Sept 2025
6. Ministère du Développement durable et des Infrastructures: Enquête Luxmobil Portal of mobility and transport in Luxembourg. https://transports.public.lu/en/plus/publications/situation-actuelle/enquete-luxmobil-2017.html (2017). Accessed 30 Sept 2025
7. Payne, G., REVOLVE model webinar: Optimising EVs and storage for consumer & grid. Cenex. https://www.cenex.co.uk/app/uploads/2020/01/REVOLVE-Webinar-V2.pdf (2020). Accessed 30 Sept 2025
8. Cenex: Power requirements for charging electric MHDV across Luxembourg. https://www.cenex.co.uk/resources/power-requirements-for-charging-electric-mhdv-across-luxembourg-report/ Accessed 30 Sept 2025
9. Liebensteiner, M.: High electricity price despite expansion in renewables: how market trends shape Germany's power market in the coming years. Energy Policy. **198**, 114461 (2025)
10. National Energy System Operator (NESO): CrowdFlex availability trial. https://www.neso.energy/document/365936/download. Accessed 30 Sept 2025

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Investigating the Impact of Different Operating Strategies on the Efficiency of Air Conditioning Systems for Electric Vehicles

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Abstract. HVAC operating strategy can significantly reduce the driving range of electric vehicles. This study evaluates PI-based operating strategies for the air-conditioning system of an Iveco eDaily MY22 electric minibus under 40°C ambient conditions. A Dymola/Modelica model validated with measurements was used to compare baseline operation with controlled compressor speed and cabin fan airflow. The improved strategy reached target temperatures faster and reduced energy consumption by 14% after one hour, indicating that simple feedback control can improve HVAC efficiency and support longer EV range.

Keywords: Electric vehicles (EVs) · Air conditioning system · HVAC efficiency · Dymola simulation

1 Introduction

The transition toward sustainable mobility has become one of the European Union's (EU) central policy objectives in the fight against climate change. Road transport is responsible for nearly one quarter of the EU's greenhouse gas emissions, and passenger cars alone account for over 60% of these emissions. To meet its climate neutrality target by 2050, the EU has introduced a series of ambitious regulatory measures aimed at reducing the carbon footprint of vehicles [3].

Nowadays, electric vehicles play an important role in decarbonising of the transportation sector. Advancements in battery, power electronics and manufacturing, has enabled widespread use of EVs. EVs bring important benefits, but they also introduce new design challenges, mainly related to driving range and battery lifetime. The driving range is limited by the size and cost of the battery pack, which can make drivers worry about running out of power on the road - a concern known as range anxiety [13]. Most of the energy from the battery is used to supply the electric motor, while the battery also supplies other auxiliary components. Heating, Ventilation and Air Conditioning (HVAC) is one of the main auxiliary components in EVs that consumes its energy directly from the

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battery pack and therefore significantly reduces the driving range. The driving range of electric vehicles is affected by the climate temperatures. For cold ambient conditions, PTC heater is used to heat up the cabin while uses the energy from the battery and therefore decreases the driving range [16]. In hot climates, both the air conditioning system and the battery management system significantly use energy leading to a noticeable reduction in driving range [6]. Driving range is decreased by up to 50% by the usage of the air conditioning system [1]. In order to address this issue energy efficient HVAC technologies should be used alongside efficient thermal design - insulation and an advanced battery cooling system [5].

Recent studies have explored various strategies to enhance the efficiency of HVAC systems in electric vehicles. For example, the use of recirculated cabin air in EVs HVAC systems reduces the need to constantly condition outside air, which lowers the heating or cooling load. This strategy can cut HVAC energy use by 14–57% and extend driving range by 11–30% compared to using fresh air only [9]. Another promising approach to improve the HVAC system is to use Model Predictive Control (MPC). It represents a smart control method that predicts how the cabin temperature and humidity will change and adjusts the HVAC system in advance. This makes the system more efficient, achieving 15.4% energy savings in cold weather and 39.7% savings in hot weather [11]. Moreover, by combining reversible heat pumps with regenerative heat exchangers, a 17 to 25% reduction in energy consumption is achieved [6]. Recently, some EVs use heat pump systems with CO2 as refrigerant. Together with an optimized control strategy an improved heating capacity by 11.6%, and a reduced energy use by 34.7% compared to R134a at -20°C could be achieved. This leads to an increased driving range by 9.3–16.6% under Worldwide harmonized Light Vehicle Test Procedure (WLTC) [12].

This study focuses on implementing various operational strategies in the air conditioning system to improve its energy efficiency. Objective of this study is to investigate whether simple feedback-based operating strategies could be used to reduce HVAC energy consumption under the hot ambient conditions, while maintaining cabin comfort targets. To evaluate this strategy, key performance indicators such as Coefficient of the Performance (COP), energy consumption and the time needed to reach cabin temperature were analysed. These results will show how improving the HVAC system can reduce the battery usage and increase the driving range of the EVs.

2 Methodology of the MINDED Project

The main goal of the MINDED project [7] is to deliver a battery-electric, zero-emission Iveco eDaily minibus with 20% improved driving range at 0°C. Moreover, the MINDED project aims to reduce the energy consumption by 15% throughout the optimised HVAC system. That is possible using an e-compressor with gas bearing technology and optimisation of the HVAC system during cold and warm environmental conditions using a Proportional Integral (PI) controller.

2.1 Measurements Setup and Control

A PI controller is a feedback controller that regulates the system by comparing the error between the desired and measured output, using proportional and integral actions [10].

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,\mathrm{d}\tau \ , \tag{1}$$

where $e(t)$ is the control error, K_p is the proportional gain, and K_i is the integral gain. It is commonly used in HVAC systems due to its simple structure and reliable performance [15]. The Iveco eDaily MY 22 electric minibus was tested under hot and cold environmental conditions using a chassis dynamometer of TU Wien Automotive Test Center GmbH. To evaluate it's energy consumption and range multiple consecutive driving cycles were performed based on a WLTC driving cycle. The WLTC is a global driving cycle standard for determining the driving range of road vehicles. Moreover, this vehicle falls into the category of WLTC class 2 and the maximum speed of the bus was limited to 85 km/h. Modern vehicles have several control units that monitor and manage the different parts of the vehicle. To do this, many sensors are used. The large amount of data from these sensors is transferred using CAN buses, which have been logged during the measurements to generate the reference measurement data set.

In this study the operational strategy for the HVAC system under warm environmental conditions of 40°C will be evaluated. The cooling system for the EV was simulated in Dymola/Modelica, using the models from the Modelica Standard Library [8] and the TIL Suite [14]. In addition, each component was first parametrised individually with the data from the technical datasheets or from measurement data.

In the first case, the compressor speed was set exactly as in the measurements obtained from the dynamometer over multiple consecutive driving cycles. For the initial 2000 s compressor operated at a constant speed of 3500 rpm. In the next phase, it switched to on-off mode operating at a speed of 1000 rpm during active phases. The ramp was used as the input for the volume flow of the fan. The volume flow was first 100 m^3/h, after the 2000 s it dropped to 80 m^3/h. A thermostatic expansion valve (TXV) regulates the refrigerant flow by responding to the feedback temperature and pressure at the evaporator outlet.

In order to make the air conditioning system more efficient two different scenarios were investigated and compared to each other regarding their performance:

- The baseline cooling system with the original compressor speed from the dynamometer measurements alongside with the measured air-volume flow that is blown into the cabin;
- One PI controller was added to control the compressor speed using the temperature feedback measured at the pipe near the dashboard. The desired temperature is 15°C. The initial compressor speed was 3000 rpm and the

maximum allowable speed was set to 8600 rpm. Proportional gain of the controller was set to 80, while integral gain was set to 30. A second PI controller is used to regulate the cabin fan airflow based on the average cabin temperature. The cabin temperature setpoint was 22°C. The initial value for fan volume flow was 80 m^3/h and a maximum of 250 m^3/h. The proportional gain was set to 0.04 and the integral gain to 0.0005.

2.2 HVAC System

The Hydrofluorocarbon-based refrigerant R134a was used for the refrigerant cycle. The implemented model of the air conditioning system is provided in Fig. 1. The compressor rapidly increases the temperature and pressure of the refrigerant. The refrigerant then flows to the condenser, where heat is transferred from the refrigerant to the outside air, and the refrigerant condenses to a high-pressure liquid. The TXV lowers the pressure and temperature of the refrigerant. Cold refrigerant enters the evaporator, where it absorbs heat from the cabin. The model is developed in Dymola/Modelica using the TIL Suite library. It consists of the refrigerant, shown in green, air cycle, shown in orange along the volume representing the cabin, which is used to measure the average cabin temperature. The refrigerant cycle operates with R134a refrigerant. The refrigerant cycle consists of a compressor, condenser, TXV and evaporator. The cabin model is a simplified one-volume representation of the cabin, added to measure the average temperature in the cabin. All components were first parametrised separately according to the datasheets provided by the manufacturer and then connected. Furthermore, the complete air conditioning model was simulated and then tuned in according to the measurements. The evaporator and condenser were modelled as air-refrigerant fin and tube crossflow heat exchangers with core dimensions of 306.5×181 x 38 mm, a fin pitch of 3 mm and three passes. In the first case, the compressor speed was set exactly like in the measurements obtained from dynamometer over multiple consecutive driving cycles. For the initial 2000 s compressor operated at constant speed of 3500 rpm. In the next phase, it switched to on-off mode operating at a speed of 1000 rpm during active phases. Ramp was used as the input for the volume flow of the fan. The volume flow was first 100 m^3/h, after the 2000 s it dropped to 80 m^3/h. The TXV regulates the refrigerant flow by responding to the feedback temperature and pressure at the evaporator outlet. For high pressure side, 18 bar was taken, and for low pressure side 2.2 bar. Nominal mass flow was 0.046 kg/s.

Different parameters were analysed and compared in order to enhance the performance and efficiency of the HVAC system. The temperature at the dashboard and the average temperature in the cabin were compared with the measured temperature in the cabin. Moreover, the COP of the compressor was evaluated alongside the energy consumption of the compressor in two scenarios.

The COP in the cooling system model was calculated based on the following equation:

$$\mathrm{COP} = \frac{Q_{\mathrm{evaporator}}}{P_{\mathrm{compressor}}} \tag{2}$$

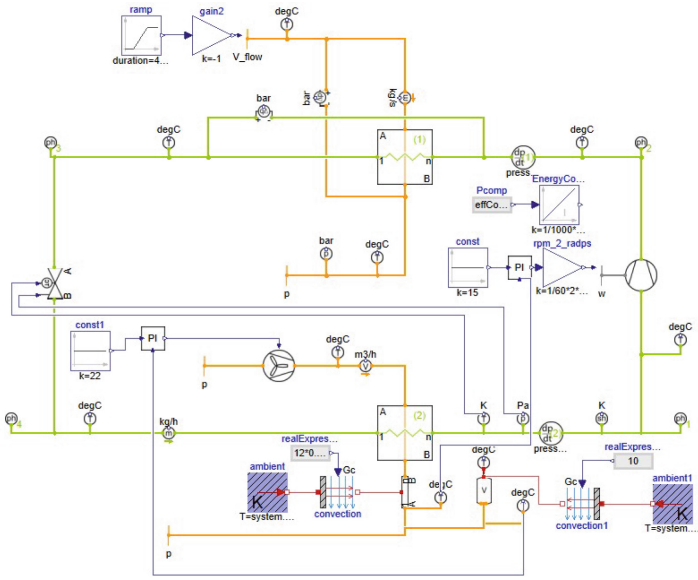


Fig. 1. System model implemented in Dymola/Modelica.

while the energy consumption of the compressor was calculated based on the equation:

$$E = \int P_{\text{compressor}}\, dt \tag{3}$$

where:
$Q_{\text{evaporator}}$ [W] - thermal power output of the evaporator
$P_{\text{compressor}}$ [W] - electrical power consumption of the compressor

The following algorithms were applied to reduce the energy consumption of the HVAC system:

- PI controller for the compressor that controls the compressor's speed in order to reach the target temperature at the dashboard of the cabin to 15°C.
- PI controller for the cabin fan to control the air-volume flow in the cabin in order to reach an average air temperature in the cabin of 22°C.

3 Results and Discussion

This section analyses results obtained from two cases. Figure 2a presents the temperature profiles under baseline operating conditions. The measured cabin temperature is shown in blue alongside the dashboard temperature in orange and the average cabin temperature in red, both obtained from simulation. After approximately 2000 s, temperature oscillations appear as a result of the compressor's on–off cycling. To quantify the difference between the simulation and

measurements, the root mean squared error (RMSE) was calculated between the measured temperature and the simulated dashboard cabin temperature, over the entire time interval. This comparison was chosen because the measurement temperature sensor was located close to the dashboard. The obtained RMSE was 7.66°C. Subsequently, Fig. 2b illustrates the temperatures with the PI controllers on the compressor and fan. Fan was working with maximum power for the first 300 s in order to reach the desired average temperature of 22°C in the cabin, while the compressor speed is 8000 rpm for the first 300 s in order to reach the desired dashboard temperature of 15°C. Once the setpoints are reached, fan speed decreases along with the speed of compressor which stabilises around 1300 rpm. It can be observed that the system with a PI controller faster reaches a temperature of 22°C and 15°C compared to the baseline case.

Figure 2c compares the coefficient of performance (COP) of the compressor for the two cases. The COP decreases when the compressor speed increases. Finally, Fig. 2d shows the comparison of the energy consumption over time. The PI-controlled case achieves lower overall energy consumption compared to the baseline. In the first 1000 s energy consumption of the case with PI controllers is higher than the energy consumption from the initial case, due to the high speed of the compressor and fan in order to reach the target temperature as quickly as possible. Once the setpoints are reached, the control system runs at a lower, stable operating level. After driving the vehicle for 1h energy consumption of the case with PI controller is 14% less than the baseline case. This reduction lowers the battery energy demand and therefore increases the vehicle's driving

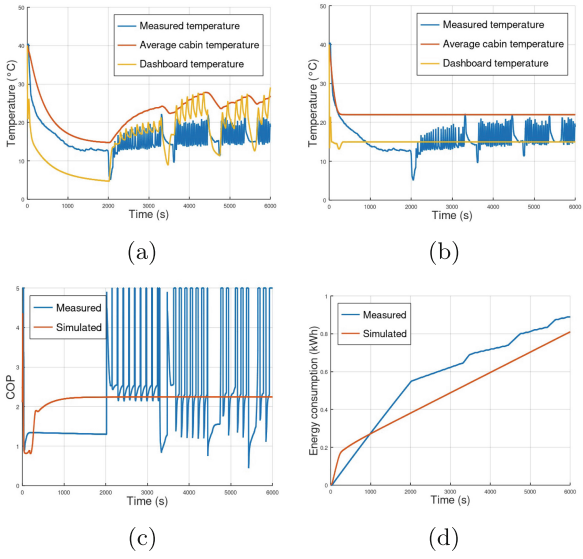


Fig. 2. (a) Baseline scenario; (b) Improved system using PI controller; (c) Comparison of COP for the two cases; (d) Comparison of energy consumption for the two cases.

range. HVAC control involves a trade-off between thermal comfort and energy use. If the setpoint is set to 25°C, it can reduces the energy consumption but may lower occupant comfort. Whereas decreasing the setpoint improves comfort but requires higher energy consumption.

4 Conclusion

This study demonstrates that the performance of the HVAC system in EVs plays a critical role in maximizing driving range and energy efficiency. All models were parametrised based on the measurements and therefore, implemented in the HVAC system. Simulations and experimental validation at 40°C confirmed that baseline operation of the cooling system leads to temperature oscillations due to on–off cycling of the compressor, in contrast the application of PI controllers on both the compressor and fan significantly improved system efficiency and comfort levels. The desired cabin and dashboard temperatures were achieved more quickly, after which both compressor and fan speeds adjusted to maintain setpoints.

Although the PI-controlled strategy initially required higher energy input the overall energy consumption was lower compared to the initial case.
After one hour of driving, the energy consumption is up to 14% lower compared to the baseline case. Overall, the results indicate that integrating PI control with an efficient HVAC design can reduce energy consumption, extend EV driving range, and enhance passenger comfort under high outdoor temperature conditions. These findings support the objectives of the MINDED project and underline the significance of advanced thermal management strategies in the transition toward sustainable electric mobility.

For future work, Model Predictive Control (MPC) will be investigated, as it has the potential to further improve energy efficiency and comfort by predicting for future temperature changes and optimizing control actions in advance, offering higher efficiency than the PI controller.

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References

1. Song, B., Kwon, J., Kim, Y.: Air conditioning system sizing for pure electric vehicle. World Electr. Veh. J. **7**(3), 407–413 (2015). https://doi.org/10.3390/wevj7030407
2. Doyle, A., Muneer, T.: Energy consumption and modelling of the climate control system in the electric vehicle. Energy Explorat. Exploit. **37**(1), 519–543 (2019). https://doi.org/10.1177/0144598718806458

3. European Parliament and Council of the European Union: Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. Official Journal of the European Union L 111, 13-53 (2019). https://eur-lex.europa.eu/eli/reg/2019/631/oj/eng
4. Hamwi, H., Rushby, T., Mahdy, M., Bahaj, A.: Effects of high ambient temperature on electric vehicle efficiency and range: Case study of Kuwait. Energies **15**(9), 3178 (2022). https://doi.org/10.3390/en15093178
5. Jeffers, M. A., Chaney, L., Rugh, J. P.: Climate control load reduction strategies for electric drive vehicles in warm weather. SAE Technical Paper 2015-01-0355 (2015). https://doi.org/10.4271/2015-01-0355
6. Kılıç, M., KorukÖçu, M.Ö.: The effect of energy management in heating-cooling systems of electric vehicles on charging and range. Appl. Sci. **14**(15), 6406 (2024). https://doi.org/10.3390/app14156406
7. MINDED Project Homepage. https://www.minded-project.eu/, Accessed 23 March 2026
8. Modelica Libraries. https://modelica.org/libraries/, Accessed 23 March 2026
9. Pan, L., et al.: Energy-saving effect of utilizing recirculated air in electric vehicle air conditioning system. Int. J. Refrig **102**, 122–129 (2019). https://doi.org/10.1016/j.ijrefrig.2019.03.018
10. Voltage Voyager: Understanding PI, PD, and PID Controllers: A Comprehensive Guide Homepage, https://www.electrical-blog.com/understanding-pi-pd-and-pid-controllers-a-comprehensive-guide/, Accessed 18 Feb 2026
11. Schutzeich, P., Pischinger, S., Hemkemeyer, D., Franke, K., Hamelbeck, P.: A predictive cabin conditioning strategy for battery electric vehicles. World Electric Veh. J. **15**(6), 224 (2024). https://doi.org/10.3390/wevj15060224
12. Teng, H., et al.: Performance research on a CO2 heat pump system with novel control strategy in electric vehicle. Appl. Therm. Eng. **259**, 124877 (2025). https://doi.org/10.1016/j.applthermaleng.2024.124877
13. Thorhauge, M., Rich, J., Mabit, S.E.: Charging behaviour and range anxiety in long-distance EV travel: an adaptive choice design study. Transportation, 1-23 (2024). https://doi.org/10.1007/s11116-024-10561-x
14. TIL Suite Homepage. https://www.tlk-thermo.com/en/software/til-suite/, Accessed 23 March 2026
15. Yi, H., Zhou, J., Zhang, J., Chen, E.: Adaptive thermal comfort control of electric vehicle air conditioning using GWO-optimized fuzzy PID. Thermal Sci. Eng. Progress **66**, 104057 (2025). https://doi.org/10.1016/j.tsep.2025.104057
16. Zhao, C., et al.: Research on electric vehicle range under cold condition. Adv. Mech. Eng. **14**(3), 1–11 (2022). https://journals.sagepub.com/doi/10.1177/16878132221087083

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Wide-bandgap Technologies in Electronic Power Circuits for Electrified Vehicles and Charging Infrastructures

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Abstract. Wide-bandgap (WBG) semiconductors play a pivotal role in advancing the next generation of electric vehicles. Compared to conventional silicon-based semiconductors, WBG materials offer superior performance, enabling a faster transition toward sustainable mobility.

To support this technological shift, several research initiatives have been launched. This paper focuses on a series of interconnected projects: starting with HiPERFORM in 2018, followed by HiEFFICIENT from 2020, and continuing with HiPower 5.0, which begins in 2025.

These projects bring together stakeholders across the entire value chain – from semiconductor manufacturers to leading automotive OEMs. Their shared goal is to enhance the power density, efficiency, and reliability of WBG-based power electronics for applications in electric vehicles, maritime transport, and charging infrastructure.

The paper highlights recent advancements in WBG materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), also considering emerging bidirectional WBG technologies enabling high power density and performance. In addition, these emerging materials offer significant benefits over traditional Silicon, including improved switching performance, higher operating temperatures, and increased power density. As a result, they contribute to reduced energy losses, smaller system sizes, and lighter components.

To illustrate these developments, the paper presents selected technical solutions and benchmarks them against the current state of the art.

Keywords: Electromobility · Design and Optimization · Reliability · Wide-bandgap Semiconductors · Embedding

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1 Introduction

Back in 2017, the HiPERFORM project, a Research and Innovation Action funded by the CHIPS Joint Undertaking, was started to introduce wide-bandgap (WBG) semiconductors in electric vehicles and according charging infrastructures. The focus was on Silicon Carbide (SiC) based semiconductors, demonstrating the potential in inverter and charger applications to reduce drawbacks like price, driving range and charging times of electrified vehicles [1]. At the end of the project, the partners were able to demonstrate prototypes with up to 98% efficiency and 50% spatial volume reduction compared to state-of-the-art solutions.

In late 2019, the European Commission unveiled the "European Green Deal," setting strategic goals such as achieving net-zero greenhouse gas emissions by 2050 and decoupling economic growth from resource consumption. Based on the results achieved in HiPERFORM, a follow-on project was launched: HiEFFICIENT. With HiEFFICIENT the partners continued the developments to directly support the Green Deal objectives by advancing sustainable mobility and resource efficiency through next-generation power electronics. HiEFFICIENT focused on the development and integration of wide-bandgap (WBG) semiconductor technologies, specifically GaN and SiC devices, into power electronic systems for electrified vehicles, testing platforms, and charging infrastructure [2]. The project targeted several ambitious technical milestones, significantly outperforming HiPERFORM targets:

- Efficiency: Achieving system-level energy conversion efficiencies exceeding 98%, with a 50% reduction in power losses compared to conventional solutions.
- Volume Reduction: Realizing up to 40% reduction on chips, subsystems and system volume, e.g. by integrating traction inverters, DC/DC converters, and on-board chargers into compact, shared housings.
- Reliability: Enhancing the operational lifetime of WBG-based power electronic systems by 20%, supported by advanced sensor integration, predictive health monitoring (PHM), and optimized thermal management.

These innovations were successfully validated across ten industrial use cases, including inverters (48 V, 400 V, 800 V), versatile off- and on-board chargers, and multi-purpose DC/DC converters.

This paper highlights two innovations in detail, showing the advantages of the latest power electronics embedding technologies for future traction inverters as well as innovative solutions for highly reliable on-board chargers.

2 Highly Integrated e-Powertrain Inverter

2.1 Introduction & Methodology

As already demonstrated in several applications, wide bandgap semiconductors enable higher power density, reduced heat generation, higher operating voltages, and longer component lifetimes. For these reasons, they play a crucial role in the transportation electrification challenge. Silicon carbide (SiC) is now widely adopted in automotive power conversion, while gallium nitride (GaN) is gaining more momentum. To fully

exploit GaN's potential in power electronics, advances in system integration are required. Embedding GaN bare dies directly into printed circuit boards (PCBs) reduces stray inductance, improves switching performance, and minimizes losses [7, 8]. To demonstrate these potential advancements, a novel inverter concept optimized for high-voltage traction motors has been developed, utilizing GaN transistors and embedding technology.

Embedding technology is widely recognized as a key enabler for reducing electrical losses and enhancing the performance of power modules incorporating embedded wide bandgap (WBG) devices. The patented AT&S PlAnaR Surface Embedded Components (Parsec) Technology enables direct interconnection to the top side of components through galvanic copper micro-via deposition. The backside of the components can be fully connected via galvanic copper plating, resulting in lower thermal resistance (R_{th}) and facilitating advanced cooling strategies and high current handling capabilities. Compared to conventional interconnection methods such as wire bonding, ribbon bonding, and lead frame packaging, this alternative approach achieves significantly lower parasitic inductance. Furthermore, embedding technology allows for substantial miniaturization of package and module dimensions. Embedded constructions are considerably thinner compared to traditional multilayer and surface-mount technology (SMT) packaged components, resulting in a drastic reduction in loop inductance.

For greater modularity and scalability, the inverter has been organized into three separate boards, each with a dedicated role: the power stage, the gate driver and the control board. The Power Stage is designed to be fully compatible, in terms of physical dimensions, with Infineon's HPD power modules. It consists of three primary components: the half-bridge stage, the support frame, and the heat sink. The half-bridge stage is a single-phase power module built using Parsec technology, where the GaN dies are integrated within the inner layers of the PCB. The heat sink is an aluminum structure with fins to maximize the dissipation surface toward the liquid coolant, and it is directly sintered to the PCB for optimal thermal contact.

2.2 Results

A complete three-phase power stage requires three of these modules. Each module contains four GS-065-060-2-D2 GaN devices (Vds = 650 V, Imax = 60 A), with two devices in parallel for the low side and two for the high side. The embedding approach also allows for a distributed DC-link capacitor directly on the module, substantially reducing inductance compared to conventional designs. Furthermore, the overall size of the converter is significantly reduced: this leads to shorter current paths, which in turn lowers interconnection resistance and parasitic inductance [13]. As a result, system-level efficiency is improved by minimizing both conduction and switching losses. Furthermore, thick copper substrates enable efficient heat-transfer due to their low thermal resistance [11].

Thermal reliability remains a key concern of packaging. In conventional power stages, interconnection structures are still often based on common materials and processes (e.g., solder, epoxy, bond wires) that are susceptible to thermo-mechanical fatigue. Power cycling tests are widely used to evaluate the robustness of such devices under realistic operating stress conditions, and the thermal resistance (R_{th}) extracted during these tests is one of the most reliable indicators of degradation progress [4, 12].

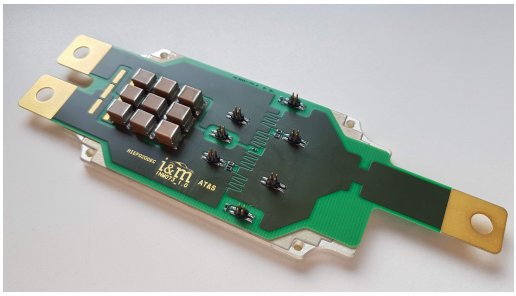


Fig. 1. Power module with embedded GaN half-bridge

Power cycling experiments have been performed on GaN embedded modules (Fig. 1) operated in MOSFET mode. A heating current of 3 A was used during measurement to ensure sufficiently high sensitivity of the thermal sensing parameter (TSEP). The TSEP chosen was V_{GS_cold} of 0.174 V at a current of 15 A with the measurement taken immediately after the heating pulse to capture the junction temperature rise. The reported thermal resistance values are normalized to their initial baseline values to mitigate nonlinearities associated with high-current heating and to focus on relative degradation trends [9].

Table 1. Power cycling test conditions

Technical Parameter	Test Conditions
$T_{j,min}$ [°C]	10
$T_{j,max}$ [°C]	150
$\Delta T_{j,APC}$ [K]	140
t_{on} / t_{off} [s]	3 / 6

Throughout the test (Table 1), the supply voltage and drain-source voltage drop were continuously monitored and found to remain stable within the measurement uncertainty, excluding electrical drift as a cause for the observed R_{th} variations. Analyzing the evolution of the normalized R_{th} over approximately 500,000 power cycles, several distinct behaviors have been observed:

1. **Initial stability**: During the first tens of thousands of cycles, the R_{th} fluctuated within ±5% of the baseline, consistent with measurement reproducibility and TSEP sensitivity.
2. **Step-like variations:** Between ~100 k and 300 k cycles, the R_{th} exhibited discrete downward and upward shifts. Such discontinuous changes are consistent with partial delamination or micro-cracking at the die-attach or die top side interface, which can abruptly modify the dominant thermal conduction path [12].
3. **Progressive increase:** Beyond ~350 k cycles, R_{th} demonstrated a clear upward trend, culminating in a sharp rise at ~500 k cycles. This catastrophic increase is characteristic of delamination, leading to significant loss of thermal contact [4, 10].

4. **Voltage drop** for both devices under test also had an increment to 3% but didn't reach the failure criteria of 5%.

The observed degradation behavior is in line with previously reported power cycling studies on both GaN and SiC devices. Thermo-mechanical fatigue due to coefficient of thermal expansion (CTE) mismatch in the various materials is widely recognized as the dominant mechanism for R_{th} increase during cycling [10, 12]. The stepwise changes observed in this work indicate localized, discrete damage events (e.g., interconnect failure), whereas the long-term gradual rise reflects progressive damage accumulation until catastrophic failure.

The use of a 3 A heating current, although higher than typical TSEP measurement conditions, ensured sufficient resolution for detecting small thermal changes. It is acknowledged that higher measurement currents can induce additional self-heating, potentially elevating absolute R_{th} values. For this reason, all results are presented in normalized form relative to the initial baseline, as also recommended in recent methodological studies [9]. Importantly, since the monitored voltage drop across the device remained under 5% level the changes in R_{th} are attributed solely to thermal-path degradation and not to electrical drift or trapping phenomena. This confirms that thermal resistance remains a robust indicator of package-level reliability for GaN modules under long-term cycling.

Consequently, this extremely robust design clearly demonstrates the potential of embedding technology in connection with inverter applications in the automotive sector.

3 Smart Bidirectional GaN on-Board Charger

3.1 Introduction & Methodology

On-board chargers are typically restricted to slow charging due to limitations in cost, weight and size. Generally, power electronic devices using WBG materials, such as GaN devices, are rapidly advancing and are expected to significantly enhance power converters. GaN technology brings significant advantages for charging systems, being particularly competitive and mature for applications in the lower voltage range and ideal for high-frequency operations. Compared to Si devices, GaN technology results in lower energy losses at higher frequencies. This advantage enables the development of more compact devices with increased power density, thereby affecting the size and weight of the on-board charger. The bidirectional on-board-charger (OBC) is based on the phase modular structure [3]. This structure enables operation from both single-phase AC supplies (typically 230 V in Europe, Asia, and many international regions; 240 V in North America) as well as from three-phase AC grids, commonly 400 V line-to-line in IEC-compliant regions. The phase-modular structure enables the use of 650 V GaN semiconductors, as DC-link voltages as low as 350 V can be supported under ideal operating conditions for the AC-DC conversion stage. Since single-stage OBC topologies make it challenging to achieve reliable soft-switching across varying operating conditions – such as input voltage rms value, output power, battery voltage, and circuit parameter deviations – as well as to realize effective low-frequency (LF) power decoupling under single-phase operation, the well-known dual-stage architecture

[6] has been adopted in this study. This approach provides greater flexibility in meeting soft-switching requirements, improves control of LF power ripple, and ensures robust performance under varying operating conditions [3].

3.2 Results

The OBC is intended to be used in EVs equipped with 400 V battery voltage, and the design is based on 650 V GaN Half-Bridge (HB) System on Chip (SoC) semiconductors. Commercially available bidirectional OBC products, when designed for universal AC input and with an integrated low-voltage auxiliary battery charger, typically achieve power densities below 1 kW/l. An example reaching 0.75 kW/l can be found in [5], with efficiencies $<96\%$ in both charging and discharging modes. A conversion efficiency of $>97\%$, volumetric power density of >2 kW/l and gravimetric power density of 1.5 kW/kg is targeted in this study. A downsized 6 kW prototype, as shown in Fig. 2, has been developed for 11 kW three-phase OBC system, and the optimized circuit parameters are summarized in Table 2.

Table 2. Design Parameters for dual-stage OBC

Technical Parameter	Value
PFC Switching frequency	135 kHz
DC Link filter capacitance	600 uF (4x150uF)
PFC Inductance	250 uH
X2 capacitors	2.2 uF
DM EMI filter inductance	15 + 15 uH
DAB switching freqency	250 kHz
DAB auxliary inductance	6 uH (each side)

The OBC's overall dimensions are 254 mm x 279 mm x 60 mm, resulting in a volume of 4.25 L. However, this includes extra spacing left for experimental purposes, as shown in Fig. 2. Once this additional spacing is removed, the board fits into a more compact area of 210 mm x 240 mm. This brings the total volume down to 3.024 Liters, achieving a power density of 1.98 kW/l, which is very close to the project target of 2 kW/l with negligible deviation. Furthermore, the cold plate design is based on the final nominal power rating of 11 kW, ensuring that when scaled to this level, the cold plate thickness will remain nearly unchanged. By leveraging GaN-based technology, the OBC not only surpasses the target power density of 2 kW/l but also achieves superior performance within a more compact form factor. Similarly, when scaled up to 11 kW, the current design achieves a weight-specific power density of 1.66 kW/kg, thereby exceeding the target of 1.5 kW/kg.

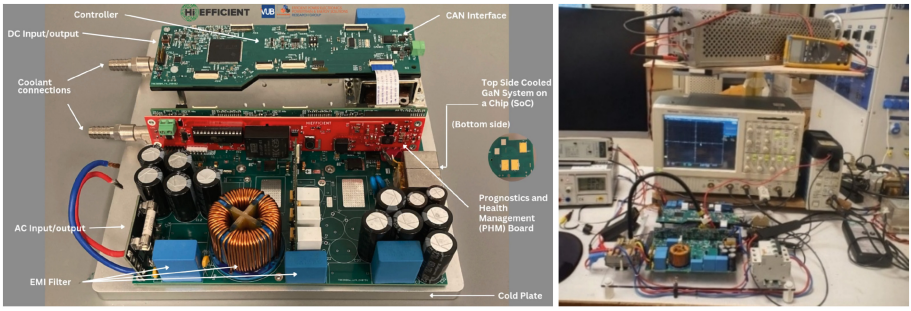


Fig. 2. a) GaN-based three-phase 6 kW OBC demonstrator populated with controller boards and components necessary for 1-ph operation and b) experimental setup

4 Conclusions and Outlook

This paper presents the evolution and impact of wide-bandgap (WBG) semiconductor technologies – specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) – on power electronics for electrified vehicles and charging infrastructures. Through a series of European research projects (HiPERFORM, HiEFFICIENT, and HiPower 5.0), significant advancements have been achieved in efficiency, reliability, and system integration for future electric mobility applications.

Two latest results of the HiEFFICIENT project are shown in detail. First example is a highly integrated GaN-based traction inverter concept using embedded die technology, which drastically reduces parasitic inductance, improves thermal management, and consequently enhances power density. Reliability assessments through power cycling tests confirm the robustness of embedded GaN modules, with thermal resistance (R_{th}) serving as a reliable degradation indicator. These technologies demonstrate clear potential for scalable, compact, and efficient solutions in future electric mobility systems. Secondly, a smart bidirectional GaN on-board charger with modular phase architecture, achieving nearly 2 kW/l volumetric power density and $> 97\%$ efficiency, surpassing current commercial benchmarks, is presented.

Looking ahead, the continued integration of WBG devices, advanced packaging, and digital twin methodologies will be critical to meeting the demands of next-generation transportation and energy systems. The HiPower 5.0 initiative will further build on these foundations, targeting even higher performance and sustainability goals to enable a more efficient and sustainable mobility of tomorrow.

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References

1. Abart, C., Berberich, K., Hegazy, O., Abdel-Monem, M., Vanegas, O., Lis, A.: Wide bandgap semiconductors enabling highly efficient electrified vehicles. Transp. Res. Procedia. **72**, 17–23 (2023). https://doi.org/10.1016/j.trpro.2023.11.317
2. Abart, C. et al.: Latest reliable power electronics Technologies for Zero-Emission. In: McNally, C., et al. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility, Proceedings of the 10th TRA Conference, 2024 Dublin, Ireland Eco-Efficient Mobility Systems, vol. 3, pp. 185–190. Springer, Cham (2025). https://doi.org/10.1007/978-3-031-89444-2_26
3. Bay, O., et al.: A comprehensive review of GaN-based bi-directional on-board charger topologies and modulation methods. Energies. **16**(8), 3433 (2023)
4. Celaya, J.R., Saxena, A., Saha, S., Goebel, K.: Prognostics of power MOSFETs under thermal stress accelerated aging using data-driven and model-based methodologies. Annu. Conf. PHM Soc. **3**(1), 1995 (2011). https://doi.org/10.36001/phmconf.2011.v3i1.1995
5. Delta Electronics (Thailand) PCL: Bi-directional On-Board Charger. Delta Electronics (Thailand) Public Company Limited https://www.deltathailand.com/en/products/mobility/EV-Powertrain-System/EV-Power-Electronics/Bi-directional-On-Board-Charger (2024). Accessed 12 Mar 2026
6. Liu, G., et al.: Implementation of a 3.3-kW DC–DC converter for EV on-board charger employing the series-resonant converter with reduced-frequency-range control. IEEE Trans. Power Electron. **32**(6), 4168–4184 (2016)
7. Knoll, J.S., Son, G., DiMarino, C., Li, Q., Stahr, H., Morianz, M: A PCB-embedded 1.2 kV SiC MOSFET half-bridge package for a 22 kW AC–DC converter. IEEE Trans. Power Electron. **37**(10), 11847–11859 (2022)
8. Korkmaz, O. et al.: Using embedding die technology in GaN half bridge module for 48V inverter application. In: Proceedings of PCIM Conference, Nuremberg (2025)
9. Pirosca, A.V., Vecchio, M., Rizzo, S.A., Iannuzzo, F.: Evaluation of the thermal resistance in GaN HEMTs using Thermo-sensitive electrical parameters. Energies. **16**(6), 2779 (2023). https://doi.org/10.3390/en16062779
10. Pozo, A. et al.: GaN Reliability and Lifetime Projections, Phase 14. Efficient Power Conversion https://epc-co.com/epc/portals/0/epc/documents/product-training/Reliability%20Report%20Phase%2014.pdf (2022). Accessed 12 Mar 2026
11. Pradhan, A., Grosso, G., Bharath Kurukuru, V.S., Romano, C., Petrella, R.: Coupled electrothermal analysis with reduced order models for optimizing GaN HEMTs performance in traction inverters. In: IEEE 10th Electronics System-Integration Technology Conference (ESTC) (2024). https://doi.org/10.1109/ESTC60143.2024.10712122
12. Shi, Y., et al.: The Chip-level and package-level degradation of Cascode GaN device under repetitive power cycling stress. IEEE J. Electron Devices Soc. **11**, 426–431 (2023). https://doi.org/10.1109/JEDS.2023.3297329
13. Tranchero, M., Bongiovanni, L., Vinci, A., Romano, C., Santero, P.: Characterization of the power stage for a GaN-Embedded-Based traction inverter. In: PCIM Europe Conference 2025 (2025)

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Performance Evaluation of Solid-State Li-Ion Batteries with a Novel Solid Composite Electrolyte Under Automotive Driving Conditions

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Abstract. Solid-state batteries are expected to represent the next major advancement in battery technology for Electric vehicles; however, further research and development are still required. In this study, a novel polymer solid electrolyte based on a polymerized ionic liquid and an ionic liquid plasticizer was used paired with an NMC 622 cathode. The cells performances were investigated to assess their suitability for automotive applications through driving cycle simulating real-driving conditions and based on the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Specifically, the cells were evaluated under standard aging conditions at low C-rates (e.g. C/20), rate capability tests ranging from C/20 to C/3, and WLTP cycling protocols. On two cells WLTP cycles were repeated until 85% of state of health (SoH) was reached. As a result of the WLTP application, the cells reached driving ranges of 209 km and 244 km on a single charge. These findings are encouraging and suggest a promising outlook for further developments and optimizations in the field.

Keywords: Solid state battery (SSB) · Worldwide Harmonized Light Vehicles Test Procedure (WLTP) · Solid composite electrolyte (SCE) · Polymer solid electrolyte · Polymerized ionic liquid

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1 Introduction

Solid-state batteries (SSBs) are widely regarded as a promising next-generation rechargeable energy storage technology. By replacing flammable liquid electrolytes with solid electrolytes, the SSbs can overcome safety concerns such as poor thermal stability and flammability that limit conventional lithium-ion batteries [1]. In addition, solid electrolytes open the possibility of employing lithium metal as anode electrode that offers an exceptionally high specific capacity (3860 mAh/g) and the lowest electrochemical potential (−3.04 V) among all known electrodes [2], which theoretically enables cell-level energy densities of 500 Wh/kg and 1000 Wh/L when combined with high-capacity cathodes [3]. One of the major obstacles to achieving safe and reliable Li-metal electrodes is the development of a stable and homogeneous solid electrolyte interphase (SEI) [4]. Variations in SEI composition across the electrode can promote the growth of high-surface-area lithium dendrites, which accelerate electrolyte degradation and lead to the formation of electrically isolated "dead" lithium that can cause also short circuits [5]. This, in turn, increases cell impedance and results in progressive capacity fading. Moreover, the practical use of Li metal in commercial battery has not been realized because of the consumption of Li metal by side reaction with the electrolyte. With the employment of solid electrolytes high values of energy density can be reached, however most solid electrolytes suffer from a limited electrochemical stability window, which hinders their compatibility with lithium metal and high-voltage cathodes (>4 V) required to achieve such high energy densities [2]. Lastly to reach high energy density it is of paramount importance to minimize the lithium metal anode thickness, that is indeed important also for safety and cost [6]. There are three main kinds of solid electrolytes: organic (polymeric), inorganic and solid composite electrolyte (SCE) [7]. Compared with inorganic solid electrolytes, polymer-based solid electrolytes generally offer superior mechanical flexibility, which facilitates the electrode–electrolyte contact during cycling and mitigates formation of voids at the lithium interface. However, their low ionic conductivity at room temperature and relatively narrow electrochemical stability window remains key limitations for practical applications [8]. The solid composite electrolyte integrates both the inorganic and organic component trying to take the advantages of both categories. Incorporating ionic liquid plasticizers into polymer electrolytes has emerged as a promising strategy to enhance ionic conductivity at ambient conditions while maintaining mechanical flexibility [9]. To test the electrochemical performances of lithium-ion batteries the majority of existing studies are focused on understanding the degradation mechanisms under controlled cycle aging conditions, typically involving standardized charge/discharge protocols [10]. In contrast, fewer works address aging processes that arise under real-usage scenarios, such as automotive applications. The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) was chosen to standardize the driving profile, avoiding the application of profiles that are dependent by the selected vehicle. This driving cycle is commonly employed to estimate the range of electric light-duty vehicles. Its use offers the possibility to evaluate small cell capacity by scaling the driving-cycle input parameters according to the actual capacity of the cell compared to the battery pack at which the driving cycle was referred.

2 Methodology

2.1 Cell Assembly

A NMC 622 based cathode with a capacity of 2 mAh/cm^2 was employed, which the composition was: 92% of active material, 4% of binder and 4% of electrical additive. The anode consisting of a 20 μm lithium film was evaporated on a copper current collector foil in an industrial roll-to-roll evaporation system under vacuum, later the lithium film is treated with N_2 (Sidrabe Vacuum LTD). The polymer based electrolyte precursor was prepared by mixing poly[(N,N-diallyl-N,N-imethylammonium) bis(fluorosulfonyl)imide] (PDDAFSI) with an ionic liquid based electrolyte (LiFSI (lithium bis(fluorosulfonyl)imide) dissolved in EMImFSI (1-ethyl-3-methylimidazolium bis(fluorosulfonyl)imide)) in acetonitrile for the catholyte and in a mixture of propylene carbonate (PC) and ethyl methyl carbonate (EMC) for the anolyte (Solvionic). The electrolyte precursor was solidified to form a solid composite electrolyte (SCE) onto the electrode foils in particular the precursor solution was used as a catholyte, and as an anolyte. Cathode impregnation is achieved by blade coating the catholyte onto the cathode and evaporating the solvent. The anolyte solution is casted directly on the N_2-treated lithium, subsequently a polypropylene separator (Celgard 2500) was placed on the fresh electrolyte film letting evaporate the solvent.

A calculation on the gravimetric energy density was made which led to 253 Wh/kg at cell level using a simplification for which the weight of the external case was neglected in order to have the possibility to increase the dimensions of the active material used. The computed energy density is far from what is the actual goal of the SSB, however inside the Solidify project other partner tested high mass loading NMC811 cathode with an areal capacity of 2.8 mAh/cm^2 which give instead an energy density $>$ 360 Wh/kg [6]; moreover, some other calculations were made considering instead a 4.5 mAh/cm^2 achieving an energy density of 430 Wh/kg which is an ambitious goal but definable achievable [6].

2.2 Experimental Setup

The pouch cells were tested using a BasyTec© XCTS cycler controlled by BasyTec© Software. To guarantee an isothermal and uniform temperature during cycling tests a FALC climatic chamber was used setting the temperature to 40 °C for all the tests. Moreover, the pouch cells were tested under pressure using a tailored setup to ensure a constant stack pressure on the active material of 4.1 MPa in order to avoid contact losses between the electrodes and the solid electrolyte [11] however when moving from cell level to module level the energy density will be lower because it is required to take into account also the volume and/or the weight of the solution used to achieve the desired stack pressure [12]. Six cells were tested, each one undergoes the formation protocol and later a different typology of test was performed: in Table 1 are reported the different test that were applied, the detailed protocols are reported below. To avoid aging effects observed when reusing cells during early electrolyte development cells, all tests were performed on fresh cells to ensure reliable results.

Table 1. Summary of the test performed for each cell

N° cell	Test performed		Purposes
1–2	Formation [3.2 V–3.85 V]	Aging [3.2 V–4.3 V]	To check cyclability
3–4	Formation [3.2 V–3.85 V]	Rate Capability [3.2 V–4.3 V]	To check the performances at different C-Rates
5–6	Formation [3.2 V–3.85 V]	WLTP protocol [3.2 V–4.3 V]	To check the performances using a driving range profile

2.3 Testing Protocol

Formation. After the cell assembly (Fraunhofer), the formation protocol is applied: a cycle of charge/discharge at constant current (CC) at C/20. A voltage range between 3.85 V and 3.2 V was used. In this specific test a conservative upper cutoff voltage was selected, to avoid cells misbehaviours, while in the following test a higher value was chosen (4.3 V). The selection of this high value of voltage was possible thanks to other partner works in which it was seen that the SCE is stable between 0.1 V and 5 V [2].

Aging. This test consists of 10 cycles at C/20 both in charge and in discharge, with the aim to obtain the preliminary cells performances and to check the assembly goodness.

Rate Capability. Cell performances were evaluated at different C-rates: 3 different cycles at CC applying the following C-rates both in charge and discharge: C/20, C/10, C/5, C/4, C/3.

WLTP. To evaluate the batteries performances in real driving conditions of an electric vehicle the Worldwide harmonized Light vehicles Test Cycle (WLTC) was applied. This protocol has been developed for the determination and homologation of emissions and fuel consumption of light-duty vehicles. The applied protocol is defined from the duty profile of an 80-kW electric powertrain of a segment A vehicle, to which is applied the WLTC on a chassis dyno facility. The duty power profile is related to the energy variation of the battery pack during test and need to be scaled down considering both the capacity of the pack and of the tested cell. The vehicle speed varies from 0 to 131 km/h dividing the protocol in 4 different phases such as low, medium, high and extra high vehicle speed. Furthermore, to simulate better an urban and sub-urban utilization of the battery the first two phases are repeated: in Table 2 are reported the details of the WLTC phases. For the sake of simplicity, the classical WLTC and the repetition of the initial profile is considered as a single WLTC in this work. The WLTP is the overall schedule in which the WLTC profile is repeatedly applied until the cell reaches the lower cut-off voltage. Before to apply each WLTP the cell is fully charged at C/20, then the WLTP is performed and the procedure is repeated until a reasonable SoH, the cell capacity is regularly checked after a certain amount of WLTP repetition. The WLTC profile includes also some charge phases due to regenerative braking the aim of this regenerative braking is to simulate the actual behaviour of a real car in which thanks to this system the cell

is charged while decelerating. To allow this charging step instead to apply the WLTP protocol on cell 100% charged it was decided to apply it at cell charged to 95%.

Table 2. Details of the different speed phases of the WLTC applied

	Low speed	Medium Speed	High Speed	Extra High Speed	Repetition of the initial profile	Total
Duration [s]	589	433	455	323	1255	3055
Stop Duration [s]	139.9	47.1	29.1	1.1	191.2	408.4
Distance [m]	3094.2	4754.6	7161.0	8254.1	11630.6	34894.6
Maximum speed [km/h]	56.52	76.72	97.43	131.32	97.43	131.32
Average speed without stops [km/h]	24.80	44.36	60.53	92.31	39.35	47.46
Average speed with stops [km/h]	18.91	39.53	56.66	92.00	33.36	41.12
Minimum Acceleration [m/s^2]	−2.64	−2.63	−2.49	−1.96	−2.64	−2.64
Maximum Acceleration [m/s^2]	2.11	2.53	2.08	1.61	2.53	2.53

3 Discussion and Results

3.1 Testing Protocol

Aging. The aging protocol was applied on cell 1 and 2. As reported in Table 3 the specific discharge capacity of Cell 2 was almost constant along all the 10 cycles. While, for Cell 1 the capacity increased from 1.61 mAh/cm2 to an almost constant value of 1.86 mAh/cm2 from the 8° to 10° cycles, this probably means that only one formation cycle was not enough to properly activate the cell.

Table 3. Specific Discharge capacity of Cell 1 and Cell 2 along the aging protocol

N° Cycle	Cell 1 - Specific Discharge Capacity [mAh/cm^2]	Cell 2 - Specific Discharge Capacity [mAh/cm^2]
1	1.61	2.04
2	1.71	2.07
3	1.76	2.08
4	1.79	2.09
5	1.81	2.09
6	1.83	2.10
7	1.84	2.10
8	1.85	2.11
9	1.86	2.11
10	1.87	2.11

Rate Capability. From Fig. 1 is evident that the performances are similar between the two cells thus only the average results are discussed. The specific discharge capacity at C/4 and C/3 is respectively 53% and 31% respect the capacity achieved at C/10. Between the first and the second repetition of the protocol at C/20 and C/10 the discharge capacities were almost constant, while at C/5, C/4, C/3 there was a decrease of 22%, 31% and 31% of capacity. Instead, the Coulombic Efficiency is always around 100% only when moving from one C-Rate to the following ones it has a drop to 90%.

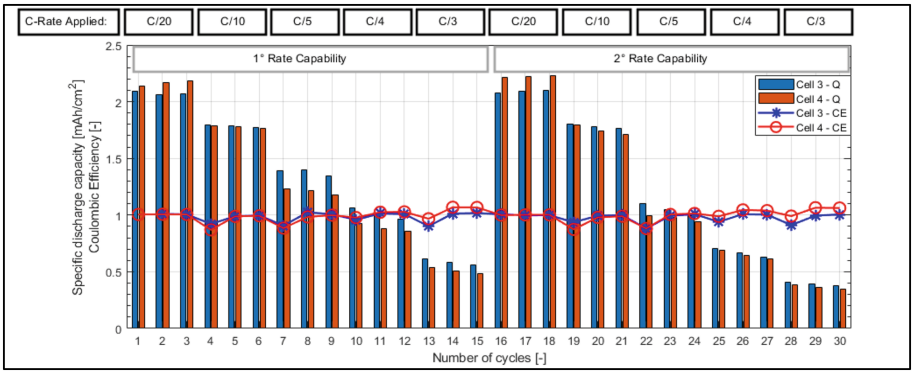


Fig. 1. Rate capability applied at Cell 3 and Cell 4: Specific discharge capacity (mAh/cm2) and Coulombic Efficiency (CE) respect the applied C-Rate

WLTP. In Fig. 2a it is showed the power profile of one single WLTC normalized to the capacity of the tested cell, while in Fig. 2b it is showed the C-rate profile applied while performing one WLTC. This single WLTC power profile in then repeated for how much was possible (6 and 7 repetitions for Cell 5 and Cell 6 reaching 209 km and 244 km respectively) before reaching the lower cutoff voltage boundary with a single charge resulting in the final WLTP that is represented in Fig. 2c and d. Moreover, to determine the State of Charge (SoC) reached after the WLTC, a discharge step was applied: the SoC vs. time plot is reported in Fig. 2e and f in which it should be noted that the residual charge of cell 5 was still the 38% of SoC, while cell 6 was 25% of SoC. In conclusion, Cell 5 was able to simulate 209 km with a SoC depleting of 57%, while Cell 6 was able to simulate 244 km with a SoC depleting of 70%. The SoH evolution during the WLTC test is reported in Fig. 2g: Cell 5 was able to perform 540 WLTC cycles reaching 79.5% of SoH. Cell 6 instead showed a different behaviour, after the first 80 WLTC the specific discharge capacity increased, this probably means that only one cycle of formation was not sufficient to fully activate the cell. The SoH values for Cell 6 were computed taking into account the greater capacity as reference. After 490 WLTC cycles Cell 6 had an SoH of 98%, however a drop of the state of health occurred in the following cycles, in the end the cell was able to perform 870 WLTC cycles reaching the 85% SoH, way above the 80% limit of the end of life.

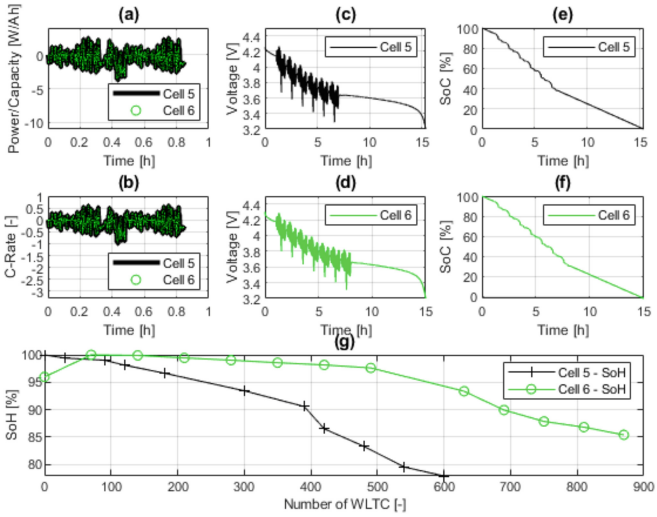


Fig. 2. a) Single WLTC power profile normalized for the capacity of cell 5 and 6; b) C-rate applied performing one WLTC. c) and d) Voltage trends performing the WLTP (repetition of maximum WLTC) for cell 5 and 6; e) and f) SoC trends over time performing WLTP; g) Trend of the specific discharge capacity and the SoH vs. the n° of WLTC applied for Cell 5 and Cell 6

4 Conclusion

This study has successfully demonstrated the strong potential of SSBs based on a solid composite electrolyte (SCE) and a thin lithium anode. The use of reduced lithium thickness will give 235 Wh/kg when scaling up the proposed cell setup but could go to >400 Wh/kg when using cathode with higher superficial capacity [6]. The results obtained from the WLTP, corresponding to driving ranges of 209 km and 244 km per charge are lower respect commercial vehicle which the average value is around 400 km with some technology going to >500 km [13]; however, the results are comparable and thus stimulate to continue the improvement of the proposed technology. Equally notable is the cycling stability, with the cells sustaining almost 500 and 900 WLTC cycles, without dropping below the 80% SoH threshold. These results pose the SSB proposed in this work as a promising candidate for next-generation energy storage in electric mobility, but improvements are required in particular the performance at high C-rate: the achieved results showcase ionic transport limitation and thus more studies on the SCE are required in which more testing on the conductivity and on the charge transfer resistance will be done to furthermore continue the development of this SSB in order to reach a final prototype at high level of industrialization.

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References

1. Tian, Y., et al.: Promises and challenges of next-generation "beyond Li-ion" batteries for electric vehicles and grid decarbonization. Chem. Rev. **121**, 1623–1669 (2021). https://doi.org/10.1021/acs.chemrev.0c00767
2. Fu, C., et al.: A polymerized-ionic-liquid-based polymer electrolyte with high oxidative stability for 4 and 5 V Class solid-state lithium metal batteries. Adv. Energy Mater. **12**, 2200412 (2022). https://doi.org/10.1002/aenm.202200412
3. Mao, J., et al.: Graphene aerogels for efficient energy storage and conversion. Energy Environ. Sci. **11**, 772–799 (2018). https://doi.org/10.1039/C7EE03031B
4. Li, Z., et al.: A review of lithium deposition in lithium-ion and lithium metal secondary batteries. J. Power Sources. **254**, 168–182 (2014). https://doi.org/10.1016/j.jpowsour.2013.12.099
5. Koshikawa, H., et al.: Dynamic changes in charge-transfer resistance at Li metal/Li7La3Zr2O12 interfaces during electrochemical Li dissolution/deposition cycles. J. Power Sources. **376**, 147–151 (2018). https://doi.org/10.1016/j.jpowsour.2017.11.082
6. Homann, G., et al.: A quasi-solid-state polymer lithium–metal battery with minimal excess lithium, ultrathin separator, and high-mass loading NMC811 cathode. ACS Appl. Energy Mater. **7**, 10037–10043 (2024). https://doi.org/10.1021/acsaem.4c02099
7. Xiao, Z., Long, T., Song, L., Zheng, Y., Wang, C.: Research progress of polymer-inorganic filler solid composite electrolyte for lithium-ion batteries. Ionics. **28**, 15–26 (2022). https://doi.org/10.1007/s11581-021-04340-2

8. Barbosa, J.C., Gonçalves, R., Costa, C.M., Lanceros-Méndez, S.: Toward sustainable solid polymer electrolytes for lithium-ion batteries. ACS Omega. **7**, 14457–14464 (2022). https://doi.org/10.1021/acsomega.2c01926
9. De Sloovere, D., Van Bael, M.K., Hardy, A.: Organic-inorganic hybrid solid composite electrolytes for high energy density lithium batteries: combining manufacturability, conductivity, and stability. Adv. Sci. **11**, 2406774 (2024). https://doi.org/10.1002/advs.202406774
10. Micari, S., et al.: Effect of WLTP CLASS 3B driving cycle on lithium-ion battery for electric vehicles. Energies. **15**, 6703 (2022). https://doi.org/10.3390/en15186703
11. Doux, J.-M., et al.: Pressure effects on sulfide electrolytes for all solid-state batteries. J. Mater. Chem. A. **8**, 5049–5055 (2020). https://doi.org/10.1039/C9TA12889A
12. Pan, H., et al.: A solid-state lithium-ion battery with micron-sized silicon anode operating free from external pressure. Nat. Commun. **15**, 2263 (2024). https://doi.org/10.1038/s41467-024-46472-9
13. Electric Vehicle Database.: https://ev-database.org/cheatsheet/range-electric-car. Accessed 31 Mar 2026

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A Bottom-Up Framework for Early-Stage Battery Concept Development

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Abstract. The shift toward electrified vehicle powertrains and rising performance expectations are driving innovation in battery systems. Meeting targets for energy density, power output, safety, and service life requires rapid exploration of new cell chemistries, integration strategies and thermal concepts. Early-stage design is particularly challenging due to limited availability of data and the inefficiency of traditional CAE simulations and prototyping. To address this, a MATLAB-based method has been developed that enables efficient bottom-up design of battery systems from cell to module to system level. This approach automates key tasks such as electrical configuration, material selection, and geometric arrangement, allowing fast evaluation of feasible design variants.

It also incorporates subsystems such as housing, thermal management, BMS hardware, and E/E components, generates simplified 3D models and calculates key performance indicators (KPIs) including energy density, power capability, and system weight. These are benchmarked against predefined targets to identify the best possible concepts. This method supports further assessments such as LCA, cost, and safety analysis, and guides the selection of optimal configurations. Use cases demonstrate the value of this method through enabling systematic comparison and supporting early decision-making for both academic and industrial stakeholders.

Keywords: Battery concept · Pack design · Cell-to-pack · NMC · LFP

1 Electrification Challenge: Accelerating Battery Development

The accelerating decarbonization of road transport places stringent demands on battery electric vehicles, which must deliver high energy and power density, long service life, and uncompromising safety under tight cost and time constraints [1, 2]. At the same time, heterogeneous applications – from passenger cars to heavy-duty and off-road vehicles – require a broad design space of cell chemistries, formats, and integration strategies, making early architecture decisions both highly influential and difficult to revise later in the development process [3].

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Conventional development processes, which rely heavily on detailed CAE simulations and physical prototyping, are often too slow and data-intensive to support rapid iteration in the concept phase [4, 5]. In early-stage design, only sparse cell data and few boundary conditions are typically available, yet engineers must already decide on key aspects such as cell format, module architecture, and thermal management strategy. This creates a need for agile, data-efficient methods that can quickly generate and compare consistent battery system concepts from cell to pack level [6].

In this context, we present a MATLAB-based battery concept method for the bottom-up design and evaluation of battery system concepts. The method is tailored to support the early-phase development by enabling fast assessment of multiple configurations. This paper outlines the structure and functionality of the proposed methodology and demonstrates its application through representative use cases.

2 Methodology: Object-Oriented Framework for Rapid Battery Concept Evaluation

The battery concept method is an object-oriented MATLAB framework that allows for the design and evaluation of battery concepts from cell to pack in a bottom-up approach. It is employed in concept studies to assess the impact of cell chemistry and format, packaging configuration and design parameters on system KPIs such as energy density, voltage level and pack dimensions.

The battery concept method takes different levels of data maturity into account. With only a few general cell properties such as voltage and capacity the method populates missing descriptors through physical correlations or extrapolation from a proprietary database of more than 1600 commercial cells. If instead a complete supplier data sheet is available, the same object simply stores the verified values and bypasses all correlations. A projection method further allows proportional resizing of a fully defined reference cell, preserving electro-chemical consistency while enabling the exploration of virtual formats such as the LFP quasi-blade cell described in Sect. 3.

At the module and pack level, geometric properties such as cell-to-cell spacing, end plate thickness, vent-channel width, wall thickness and crash frame dimensions are direct input parameter, supported by standard default values derived from experience of extensive concept studies and battery development projects [7]. The method derives pack-level electrical properties from cell data, accounting for viable series and parallel connections. Figure 1. illustrates the configuration of the battery concept method using different cell and module types as examples.

The battery concept method includes scalable plate-based cooling layouts and a simplified E/E design representation. Conventional bottom cooling plates or lateral cooling channels adapt dynamically to the geometric properties of the pack. Pack-level voltage and peak current determine the sizing of E/E components such as contactors, fuses and pre-charge components.

Since all computations rely on algebraic correlations, numerous pack variants are generated within minutes on a standard workstation. Each variant returns a consistent KPI set including energy, power (continuous/peak), external dimensions, mass, cell-to-pack fill factor, and more.

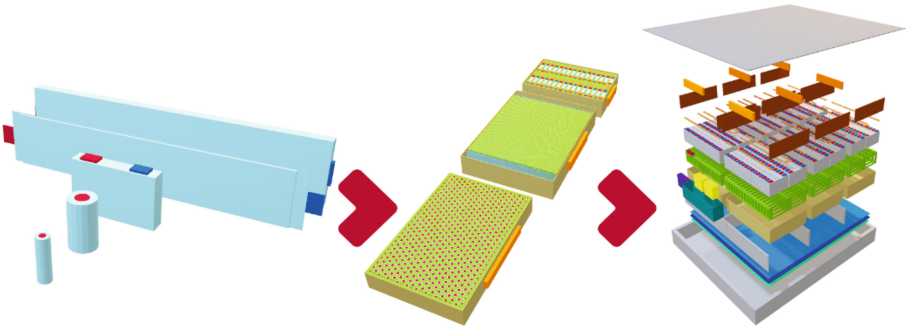


Fig. 1. Bottom-up concept approach illustrated with various cell and module types

In summary, the battery concept method provides a versatile, data-adaptive environment for rapid battery-system design. Access to an extensive teardown library and a proprietary cell database provides the basis for standard parameters and correlations, while the object-oriented architecture ensures that geometric, electrical and thermal interactions are captured with sufficient fidelity for the integration-level trade-offs explored in the subsequent chapter.

3 Layout Study: Evaluation of Integration Level of LFP and NMC Based Packs

Beyond conventional layout developments, the battery concept method described above can also be applied to various parameter studies. As an example of how the concept design method can be applied, a study is conducted that compares different integration levels for battery systems based on NMC and LFP cells. Starting with a conventional modular approach, moving on to a state-of-the-art lean-module design, and concluding with highly integrated cell-to-pack solutions, various integration concepts and corresponding prismatic cell formats are considered and their effects on the system level are evaluated. The focus is on geometric aspects, rather than gravimetric considerations.

The underlying cell technology is derived from commercially available battery electric vehicles. Specifically, it includes the prismatic Audi SQ6 cell (NMC, 151 Ah) and the prismatic Zeekr 001 cell (LFP, 143 Ah), both supplied by CATL. Since the cell formats in this study change dynamically from concept to concept, virtual cells, with unchanged composition and electrical properties, are constructed for each concept based on the reference cells mentioned above. Cell design parameters such as cell casing thickness, jelly roll winding and resulting dead volume in the cell can corners are considered, and the pure effective electrode stack volume is used as a proportionality factor for scaling.

The two selected cells were recently launched by CATL, the world's largest battery manufacturer [8], and represent state-of-the-art technology. With energy densities of 405 and 602 Wh/l for the LFP and NMC cell respectively, these cells lie in the typical range for high-energy prismatic cells in BEV applications [7].

For this study, a higher thermal safety level is assumed for LFP cells compared to NMC cells, which affects the dimensioning of thermal propagation (TP) prevention

measures and enables a higher integration density. This assumption is based on the findings of various studies and applies to a large number of specific battery cells [9, 10]. However, it should be noted that this is not a general assumption that can be applied to any pairing of LFP and NMC cells. In addition to the selection of active materials, other passive components such as separator thickness and composition also affect thermal safety.

To demonstrate the full potential of highly integrated design solutions, the first approach is to construct a modular system design with compact subunits as a reference concept. It is based on prismatic cells in the PHEV2 standard format from the VDA with top terminals, which was widespread until a few years ago and offered by various manufacturers [11]. The concept 1 small modules comprises a total of 24 modules, each with 16 cells. The interconnection of 4P 96S cells results in an energy content of 57 and 79 kWh for LFP and NMC cells respectively at a 400 V pack voltage.

In addition to the cells as energy-carrying core elements, various design parameters for passive components that are essential for safe and reliable operation are considered. These include a cell-to-cell distance of 2 mm, which is required for a mica sheet as a thermal barrier and foam for swelling compensation. The cell stacks in a module are mechanically pre-tensioned by 5 mm thick end plates, which are fastened to each other via the module housing. Above the cells, a gap of 8 mm provides space for the cell contacting system and the required distance for HV-safety. Since these cells release gas upwards in the event of thermal runaway (TR), 12 mm high venting channels are located above the modules. The battery housing ensures mechanical integrity and features a body frame with 30 mm sidewall thickness supported by an L-shaped crash frame, as well as a structurally rigid longitudinal member with attachment points for the vehicle. Based on the housing design of the Audi SQ6 battery [7], transverse load paths are also implemented via the compression end plates within the battery modules instead of conventional cross beams. For thermal management, an 8 mm high cooling plate is included throughout the battery floor, including thermal interface material as a link to the cells.

The front section also provides space for the E/E components required for operation and is designed to meet the electrical specification of the battery system. The resulting external dimensions of the pack, measuring 1860 mm in length, 1555 mm in width, and 140 mm in height, correspond to typical traction batteries in the mid- to upper-class vehicle segment. The width size already includes 120 mm from the side crash frames, so that it matches typical vehicle track gauges. In all subsequent virtual concepts, the cell dimensions are tailored to achieve identical external dimensions, thereby enabling proper comparability.

In the corresponding concept with battery cells based on LFP, the underlying assumption of a higher thermal safety level allows the TP protection mechanisms to be reduced. This applies to the thermal insulation provided by mica sheets, which reduces the cell-to-cell spacing from 2 to 1.3 mm, and to the venting channels, which are only 8 mm high instead of 12 mm. The cell dimensions are increased accordingly and the filling ration of the cells in the pack increases from 41.6% for the NMC variant to 44.7% for the LFP variant.

Starting from this very conservative design, which no longer represents the state of the art, the integration density is progressively increased in subsequent layouts, moving toward a cell-to-pack design. Each concept is designed to comply with the same safety and reliability requirements as concept 1 small modules to allow a meaningful comparison. Functions on the module-level like mechanical structural rigidity, passive thermal safety insulation and thermal management are implemented on pack-level for the concepts with higher integration density (concepts 2–5). The outer housing with body frame, crash frame, base plate, and cover, as well as the distances to the outer walls, remains identical in each layout considered.

The first step towards a higher integration level is to employ fewer but larger modules. This reflects the trend among automotive OEMs to use larger, wider cells that require less parallel wiring and less passive materials. In addition to this change in dimensions, the position of the cell terminals is moved from the top to the two side surfaces. Implementing cell contacting on the significantly shorter side edges also provides benefits in terms of integration density.

Concept 2 large modules thus has a total of 12 modules with 2P 96S interconnection. Analog to the cell terminals, the venting valve of the cells featuring this concept is moved to the short side. To avoid thermal propagation (TP) in the case of a thermal event in a single cell, a 12 mm wide lateral venting with a 5 mm steel strip on the opposite side is employed. For the LFP cell, the channel width is reduced to 8 mm and the wall thickness to 2 mm owing to the lower volume and lower temperature of the venting gases.

The next integration level, concept 3 lean modules, still represents a module subunit, but the 2 mm thick module housing is omitted. The cells are now only tensioned between the end plates, which are fastened against each other with 1 mm thick steel belts. The omission of the module bottom improves the thermal connection of the cells to the cooling plate.

In the concept 4 cell-to-pack, the individual cell stacks are now shifted together lengthwise so that the end plates lie back-to-back. This configuration allows for a reduction in thickness to 3.5 mm for the end plates that lie between the cell-stacks.

Thermal-runaway behavior places a practical upper limit on the physical dimensions of battery cells, because beyond a certain size thermal-propagation barriers and vent-gas management on pack-level become unfeasible. This constraint is particularly apparent for NMC cells, which exhibit a higher heat release and vent gas temperature compared to LFP cells. Accordingly, concept 4 employs an NMC prismatic cell of 287 x 117 x 27.8 mm^3 and 152 Ah – close to the largest NMC formats currently available in series production [7].

By contrast, LFP cells exhibit lower heat-release during thermal runaway, permitting the use of significantly larger cell formats. Several manufacturers have already exploited this characteristic, most prominently BYD with its blade cell [12]. Based on this, a concept 5 quasi-blade, was implemented exclusively for the LFP variant, in which the cell width is approximately doubled, resulting in a 1P 96S connection. The cell, measuring 623 x 117 x 28.5 mm^3, has a capacity of 268 Ah. All concepts are visualized in Fig. 2.

Across the integration stages, the energy content increases to 108 kWh for NMC and 82.2 kWh for LFP in their highest development stages. The external dimensions of the

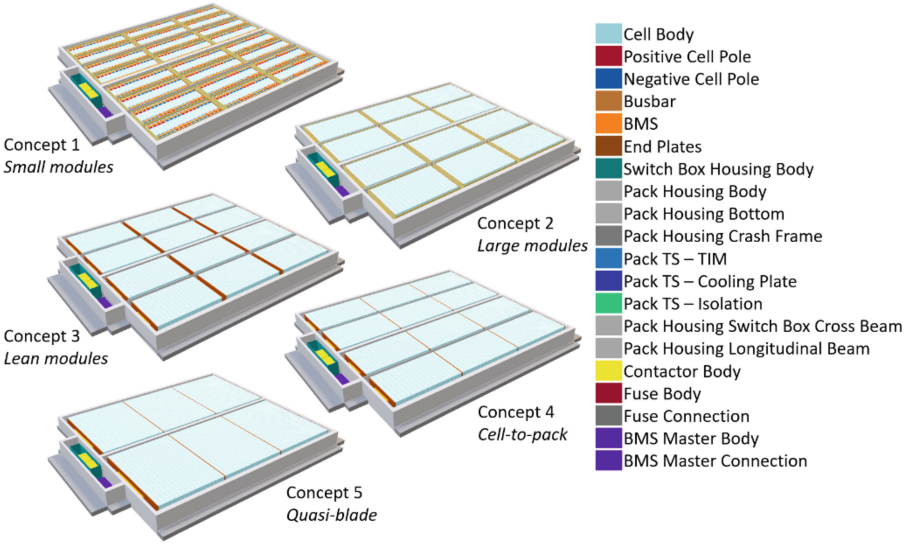


Fig. 2. The five progressively higher integration levels for a pack based on the LFP cell

battery housing were fixed over all integration stages while the cell dimensions – and therefore their capacity – were dynamically adjusted.

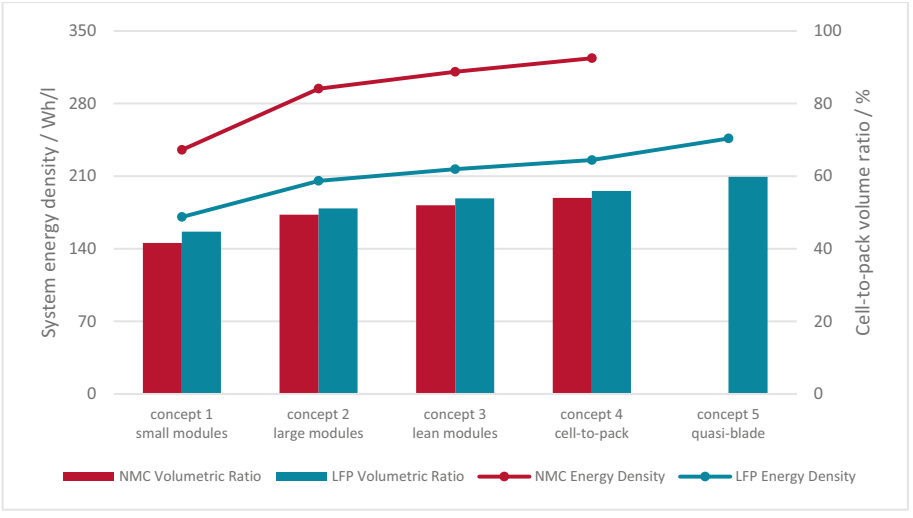


Fig. 3. Results of the layout study: energy density on system level (lines) and cell-to-pack volume ratio (bars)

At the cell level in the VDA PHEV2 reference format, the NMC cell has 565.4 Wh/l, which is 48.2% more in volumetric energy density than the LFP cell with 381.6 Wh/l. At

the system level in the highest integration density for each cell, this difference is reduced to only 31.4% between concept 4 cell-to-pack NMC with 323.7 Wh/l and concept 5 quasi-blade LFP with 246.3 Wh/l. Figure 3. shows the energy density on system level and the cell-to-pack volume ratio for all evaluated concepts. The achievable integration densities of up to 54.0% for NMC and up to 59.8% for LFP are realistic compared to current benchmarks. The BYD Han battery pack mentioned above, which served as a reference, even has a fill factor of 62%, but also has significantly wider blade cells [13].

4 Conclusions

The results demonstrate that with sufficiently high thermal safety of the cell, an LFP pack can achieve the energy-density values of an NMC pack better than the values at the cell-level would suggest. This improvement is attributable to system integration effects: large format cells reduce the total number of cell-to-cell gaps, decrease the relative mass of the housing frame, and simplify the busbar arrangement due to the smaller number of parallel cells, increasing the cell-to-pack volume ratio and thus the energy density at the pack-level. These benefits, however, are dependent on two conditions. First, cells must be available in the required large, customized formats and secured through long-term supply contracts, an option realistically available only to high-volume OEMs. Second, the thermal-propagation risk caused by a single-cell runaway must be mitigated to a level that justifies the tight packing.

Conversely, packs based on smaller, standardized cells offer greater modularity, broader re-use across vehicle lines and reduced dependence on any single supplier. Packs with smaller cells also have a higher fault tolerance, since TP of a small cell is less likely to cause TR compared to a large cell. Hence, while large cells unlock superior integration density under favorable supply and safety conditions, standardized small cells provide robustness and flexibility that remain attractive, particularly for programs with moderate volumes or uncertain long-term demand.

In general, the demonstrated battery concept method delivers realistic designs consistent with the KPIs of comparable battery packs on the market. Concepts generated with this method can be further evaluated in CAD design studies leading up to A-sample development. It should be noted that the battery concept method is no replacement for conventional design activities rather than a dedicated tool for decision making in the concept phase of battery development.

References

1. IEA: Global EV Outlook 2024, IEA, Paris Licence: CC BY 4.0 (2024). https://www.iea.org/reports/global-ev-outlook-2024
2. Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H.: Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. **17**(1), 53–64 (2013)
3. Pesaran, A.A., Markel, T., Tataria, H.S., Howell, D.: Battery requirements for plug-in hybrid electric vehicles - analysis and rationale. In: 23rd International Electric Vehicle Symposium, Anaheim, California (2007)
4. Neubauer, J., Pesaran, A.: A techno-economic analysis of BEV Service providers offering battery swapping services. In: SAE World Congress and Exhibition (2013)

5. Kim, G., Smith, K., Lee, K., Santhanagopalan, S., Pesaran, A.: Multi-domain Modeling of lithium-ion batteries encompassing multi-physics in varied length scales. J. Electrochem. Soc. **158**(8), A955 (2011)
6. Ellingsen, L.A., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Strømman, A.H.: Life cycle assessment of a lithium-ion battery vehicle pack. J. Ind. Ecol. **18**(1), 113–124 (2014)
7. FEV Consulting: Battery Benchmarking Program. https://www.fev-consulting.com/benchmarking/. Accessed 15 Aug 2025
8. CompaniesMarketCap: CATL. https://companiesmarketcap.com/eur/batteries/largest-battery-companies-by-market-cap/. Accessed 15 Aug 2025
9. Schöberl, J. et al.: Thermal runaway characterization of cylindrical lithium-ion and sodium-ion batteries with various sizes and energy contents. J. Power Sources. **648**, 237240 (2025)
10. Golubkov, A.W. et al.: Thermal runaway of commercial 18650 li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge. RSC Adv. **70**(5), 57171–57186 (2015)
11. DIN 91252:2016-11: Elektrisch angetriebene Straßenfahrzeuge – Batteriesysteme – Anforderungen an die Gestaltung von Lithium-Ionen-Batteriezellen (2016)
12. Gorsch, J. et al.: Contrasting a BYD blade prismatic cell and tesla 4680 cylindrical cell with a teardown analysis of design and performance. Cell Rep. Phys. Sci. **6**(3), 102453 (2025)
13. Hummes, D.N., Hunt, J.D., Hervé, B.B., Smith Schneider, P., Montanari, P.M.: A comparative study of different battery geometries used in electric vehicles. Lat. Am. J. Energy Res. **10**(2), 94–114 (2023)

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A Power-Sharing System for Electrically Coupled Urban Bus Convoys: Initial Design and Simulation Results

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Abstract. This paper investigates a bidirectional power-sharing system for two mechanically coupled automated electric buses forming a convoy. The system enables dynamic energy exchange between vehicles, and between the convoy and the grid via a tramway overhead line and a ground conductor. The proposed architecture is designed to optimize onboard energy distribution, reduce peak power demands, and enhance operational resilience in urban environments. The paper presents the general functional design of the energy management system, validated through practical experiments. A dedicated simulation environment developed in MATLAB/Simulink is used to model the energy exchanges between the two buses and with the grid while the convoy travels along a realistic urban route. The simulation results illustrate the effectiveness of the power-sharing strategy under varying operating conditions. The proposed solution offers a versatile basis for cooperative electric mobility and infrastructure-integrated energy management. Using the developed simulator it was possible to assess that the initial power levels considered for the system (20 kW from the infrastructure and 5 kW for vehicle-to-vehicle sharing) are not sufficient to sustain continuous operation along the observed route, and that specifications should be set according to different route requirements (32 kW and 7 kW respectively for our case study).

Keywords: Innovative Public Transportation Systems · Convoys · Shared Charging · Dynamic Charging

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1 Introduction

Urban mobility faces increasing challenges related to congestion, environmental impact, and the need for flexible and sustainable solutions. Modular electric convoys based on automated driving [1] and V2V communication offer adaptable capacity, cooperative energy management, and improved operational efficiency [2]. Integrating power-sharing systems enables dynamic energy exchanges between vehicles and infrastructure, enhancing flexibility and reducing peak power demand [3].

Most studies focus on vehicle-to-grid (V2G) interactions, while vehicle-to-vehicle (V2V) energy transfer has mainly been explored in stationary or wireless power transfer (WPS) solutions. Coordinated V2V power sharing through direct physical connection during motion remains largely unexplored, representing the research gap addressed in this work.

This study develops and validates a simulation environment for modular bus convoys with bidirectional power sharing. While the hardware energy management system was experimentally validated [4], realistic performance assessment requires simulation of energy flows, vehicle interactions, and route constraints. The MATLAB/Simulink simulator models convoy dynamics, batteries', converters', and motors' behavior, and infrastructure interaction.

The simulator allows for a detailed analysis of operational scenarios, including energy redistribution, infrastructure interaction, and realistic driving conditions. It also provides a tool for evaluating potential improvements in convoy performance and infrastructure design, supporting decision-making for future urban mobility solutions. The following sections describe the design and testing of the power management system, the motivation for the development of the simulator, its implementation and simulation results, and planned future improvements.

2 Project Context

The project aims to research new models of adaptable and sustainable urban mobility. To do this this authors are drawing inspiration from the growing interest in automated driving [5] and V2V communications to develop modular convoys. These consist of minibuses, agile vehicles suitable for urban traffic, and the convoy capacity can be adapted by adding or removing minibuses according to demand [6] and route requirements. The leading vehicle is driven by a human operator, while following vehicles operate autonomously. This work focuses on mechanically coupled vehicles, which allow installation of power exchange links between adjacent units [7].

Tecnobus Gulliver minibuses were selected for their suitability in urban environments and equipped with a custom energy management system and lithium-ion battery. Bidirectional current interfaces enable V2V power transfer, supporting strategies such as SOC balancing, prioritization of certain vehicles over others based on route planning, and minimization of battery degradation.

Some vehicles are equipped with pantographs and ground-contact shoes [8] to draw power from tramway infrastructure, allowing energy capture and redistribution within the convoy.

The UniFi-ENEA research aims to validate a modular and adaptable transport model based on cooperative energy management and integration with existing infrastructure. From an operational perspective modular convoys enhance service flexibility: multiple units can operate together during peak hours and split during off-peak periods. Convoys on partially overlapping routes can also dynamically couple and decouple, improving network efficiency.

3 Energy Management System Architecture

The energy management system enables both current collection from the catenary and power exchange between buses [9]. It includes a 400 V lithium-ion battery and DC-DC converters maintaining a 72 V DC-BUS supplying auxiliaries and powertrain.

In a two-vehicle convoy one acts as Leader and the other as Follower. The Leader interfaces with the pantograph, while both vehicles exchange power via the DC-BUS. This choice increases current losses compared to high-voltage linking but offers greater operational flexibility.

The choice of a 72 V DC-BUS is dictated by the characteristics of the experimental vehicles, which are designed to operate at this voltage level, allowing for straightforward integration.

By adjusting converter output voltages, both direction and amount of current flow can be controlled allowing to implement different strategies, such as SOC balancing, prioritization of specific vehicles, and minimization of battery degradation.



Fig. 1. Connection between the Follower (left) and Leader (right, on roller bench)

4 Experimental Validation

The experimental campaign represents the first step of the study, providing data for system validation and simulator calibration. The energy management system was installed on two minibuses and tested [4] under simulated driving conditions. For this, the Leader

was placed on a roller bench and connected both to a 20 kW programmable power source simulating the catenary, connected to the 400 V branch directly linked to the battery, and to the Follower via the 72 V DC-BUS (Fig. 1).

The tests, summarized in Table 1, included stationary and traction conditions with varying loads simulating road slopes, and the programmable power source could be switched on and off during the experiment. The system also allowed bidirectional energy sharing between vehicles, both in reception and donation. The system proved adaptable: even during high traction demand, power shared with the Follower remained stable around 5 kW. This stability was maintained under even the more demanding conditions, confirming the robustness and adaptability of the system. These results support the validation of the power management system design.

Following hardware validation, system performance must be evaluated under realistic operating conditions. A test infrastructure near the University of Florence was identified to conduct controlled experiments. A 150 m long catenary and ground contact rail will be installed, allowing to test the system under actual driving conditions. This setup cannot however represent a full trip along a traditional bus route.

A simulation environment is therefore developed to assess performance in realistic scenarios, modeling power exchanges between vehicles, infrastructure interaction, and current flows internal to each vehicle. It includes battery SOC estimation, converter behavior, and motor contribution to convoy motion, as well as control laws allowing the convoy to follow a speed profile based on actual autobus routes.

The following sections describe the simulator design, results, and planned improvements.

Table 1. Summarization of experimental tests

Type of Test	Power from Infrastructure	Power Exchanged	Observed Outcomes
Stationary	Yes, 20 kW	Yes, 5 kW	Starting point for the test campaign, meant to check if everuthing is properly connected and working as intended
Traction	No	Yes, 5 kW	Traction test with low electrical stress on the battery. The system followed the 5 kW power sharing target with precision
Traction	Yes, 20 kW	Yes, 5 kW	Highest stress conditions. Despite some oscillations the system reliably followed the target power values

5 Simulator Design

The simulator, developed in MATLAB/Simulink, reproduces both convoy longitudinal dynamics and vehicle electrical behavior. Mechanically the convoy is modeled as a single system, while electrically the Leader and Follower are considered separate subsystems. The general structure is presented in Fig. 2.

Since all vehicles share the same speed the convoy is represented as a single body, with combined mass and length. The convoy subsystem receives as input the motor torques of the Leader and Follower and calculates the current position and speed.

Each vehicle includes three main components: battery, bidirectional DC-DC converters, and motor. The battery is described using the Rint model, consisting of an ideal voltage source in series with an internal resistance. While not as complete as other battery models [10] the Rint model was selected for its simplicity and ease of implementation, while still providing sufficient accuracy for the variables of interest. It does not, however, capture transient behavior which can influence thermal and mechanical stress and degradation phenomena such as lithium plating.

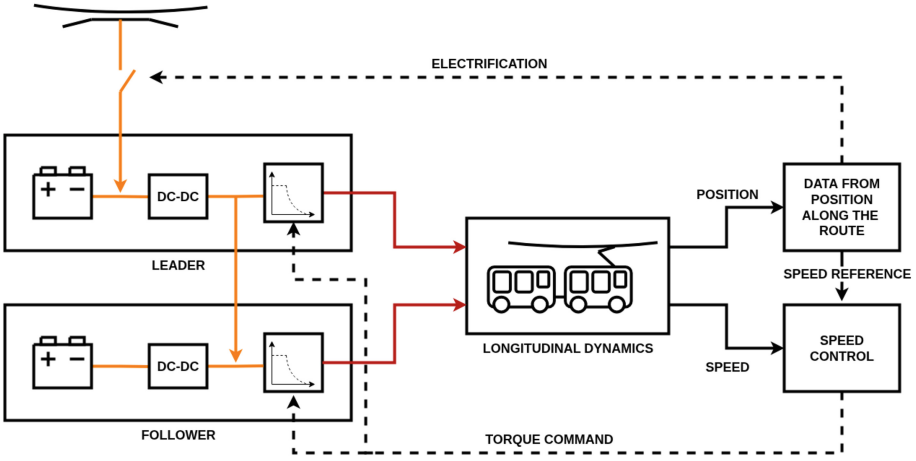


Fig. 2. Schematized architecture of the simulator

The motor is modeled through lookup tables derived from its characteristic curve. The converters supply the motor, the auxiliary services, and power exchange between vehicles. For the Leader an additional input represents the power collected from the catenary. The subsystems output the supplied torque values, which feed into the convoy subsystem to compute vehicle dynamics. Position information is used to determine the convoy's location along the route.

Each segment of the selected route based on Line 23 in Florence defines a reference speed, calculated considering both the speed limits and the route timetable to ensure timely arrival at designated stops, and information on infrastructure availability. The convoy follows the speed profile, decelerates near stops, remains stationary for passenger boarding, and then accelerates back to cruising speed.

6 Simulation Results

The simulator was used to model the convoy's operation along the predefined route, analyzing power flows among the various vehicle components and their interaction with the electrical infrastructure. It should be noted that the presented simulations are intended primarily as a validation of the developed simulation environment rather than a final assessment of system performance. We adopted a constant power-sharing strategy meant to replicate the experimental test conditions therefore representing just a baseline scenario. In the tests we assumed the vehicles starting their trip with a fully charged battery (SOC at 100%).

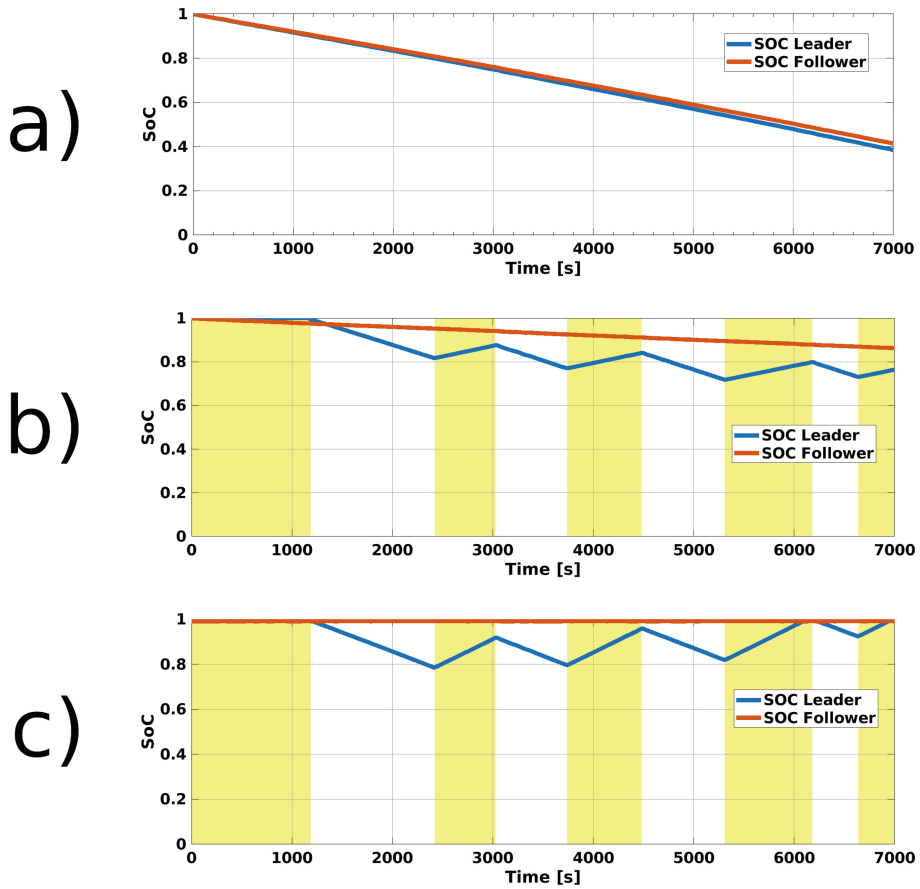


Fig. 3. Comparison of SOC evolution in different scenarios. (a) No infrastructure, no power exchange; (b) 20 kW from infrastructure, 5 kW exchange; (c) 32 kW from infrastructure, 7 kW exchange. The yellow areas in (b) and (c) represent the segments where electrical infrastructure is present

Initially, a control case without power exchange or external charging was simulated. (Figure 3-**a**). As expected, a progressive decrease in the state of charge was observed, with the battery of both the Leader and Follower reaching 40% SOC by the end of the route.

The second scenario replicated the experimental configuration, with the Leader collecting 20 kW from the catenary where present and continuously providing 5 kW to the Follower (Fig. 3-**b**). The Follower ends at approximately 85% SOC, while the Leader reaches 76% (with a minimum of 72%). In this scenario the system is still not capable of sustaining more than three consecutive trips. This suggests that the target power values initially set during the design phase may not be sufficient for all routes and should be adjusted according to the specific segment to be served.

We observed that continuous operation requires 32 kW of power collection by the Leader and a constant 7 kW sharing to the Follower (Fig. 3-**c**). With these values the Follower is able to meet all its electrical consumption needs, and the Leader maintains a sufficiently high SOC, recharging along the route and terminating at full charge. These results indicate that the selected power levels have a strong impact on system feasibility and must be adapted to the specific route and infrastructure.

7 Conclusions and Future Works

This work presented the development of a MATLAB/Simulink simulator for modular electric bus convoys, enabling realistic analysis of energy flows and system performance. The experimentally validated energy management system supports direct energy sharing between vehicles and interaction with electrified infrastructure. The simulator allows for a detailed evaluation of its performance on realistic urban routes.

Future developments will include more detailed battery models [11, 12] and advanced energy management strategies, such as SOC balancing, reduced cycling, and minimization of battery aging through optimized current control [13].

The simulator can also support infrastructure planning by identifying whether existing electrified sections are sufficient or require extension.

Overall, it provides a robust platform for analyzing modular urban mobility systems and optimizing sustainable transport solutions.

From an economic perspective, the proposed system shows promising potential. The additional cost of the system can be offset by improved vehicle utilization, reduced fleet oversizing, and lower infrastructure investments through the use of existing tramway electrification. Dynamic capacity adaptation can further improve efficiency and reduce operating costs.

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References

1. Zhang, Z., Tafreshian, A., Masoud, N.: Modular transit: using autonomy and modularity to improve performance in public transportation. Transp. Res. Part E Logist. Transp. Rev. **141**, 102033 (2020). https://doi.org/10.1016/j.tre.2020.102033

2. Cao, H., Zhao, J.: Optimizing modular vehicle public transportation services with short-turning strategy and decoupling/coupling operations. Sustainability. **17**(3), 870 (2025). https://doi.org/10.3390/su17030870
3. Shafiqurrahman, A., Khadkikar, V., Rathore, A.K.: Electric vehicle-to-vehicle (v2v) power transfer: electrical and communication developments. IEEE Trans. Transport. Electrific. **10**(3), 6258–6284 (2023). https://doi.org/10.1109/TTE.2023.3345738
4. Alessandrini, A., et al.: Vehicle to vehicle recharge and power sharing for modular public transportation systems: design and testing of the unifi fleet at enea casaccia research center. In: SETC2025: 29th Small Powertrains and Energy Systems Technology Conference, SAE Technical Paper (2025). https://doi.org/10.4271/2025-32-0095
5. Golbabaei, F., Yigitcanlar, T., Bunker, J.: The role of shared autonomous vehicle systems in delivering smart urban mobility: a systematic review of the literature. Int. J. Sustain. Transp. **15**(10), 731–748 (2021). https://doi.org/10.1080/15568318.2020.1798571
6. Lin, J., Nie, Y.M., Kawamura, K.: An autonomous modular mobility paradigm. IEEE Intell. Transp. Syst. Mag. **15**(1), 378–386 (2022). https://doi.org/10.1109/MITS.2022.3159484
7. Alessandrini, A., Ortenzi, F., Berzi, L., Gulino, M.-S., Cignini, F., Pugi, L.: An innovative convoying and power management system for public transportation. In: 2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring), pp. 1–5. IEEE (2023). https://doi.org/10.1109/VTC2023-Spring57618.2023.10200691
8. Alessandrini, A., et al.: Preliminary design and simulation of a return current collector for an innovative trambus system. In: International Symposium on Industrial Engineering and Automation, pp. 85–92. Springer (2024). https://doi.org/10.1007/978-3-031-70465-9_10
9. Alessandrini, A., et al.: Design, simulation and testing of a fast recharge system for public transportation system. In: 2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON), pp. 318–323. IEEE (2022). https://doi.org/10.1109/MELECON53508.2022.9843089
10. Cittanti, D., Ferraris, A., Airale, A., Fiorot, S., Scavuzzo, S., Carello, M.: Modeling li-ion batteries for automotive application: a trade-off between accuracy and complexity. In: 2017 International Conference of Electrical and Electronic Technologies for Automotive, pp. 1–8. IEEE (2017). https://doi.org/10.23919/EETA.2017.7993213
11. Locorotondo, E., Pugi, L., Berzi, L., Pierini, M., Lutzemberger, G.: Online identification of thevenin equivalent circuit model parameters and estimation state of charge of lithium-ion batteries. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), pp. 1–6. IEEE (2018). https://doi.org/10.1109/EEEIC.2018.8493924
12. Saw, L., Ye, Y., Tay, A.: Electro-thermal characterization of lithium iron phosphate cell with equivalent circuit modeling. Energy Convers. Manag. **87**, 367–377 (2014). https://doi.org/10.1016/j.enconman.2014.07.011
13. Omar, N., et al.: Lithium iron phosphate based battery – assessment of the aging parameters and development of cycle life model. Appl. Energy. **113**, 1575–1585 (2014). https://doi.org/10.1016/j.apenergy.2013.09.003

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Evaluating the Potential of Hybrid Ship Retrofitting Combining Tubercle-Assisted Propellers, Fuel Cells, and Liquid Inorganic H2 Storage

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Abstract. As the maritime industry is facing increasing pressure to reduce its environmental impact, ship owners and operators are exploring innovative propulsion technologies. The EU-funded RESHIP research project investigates the use of Tubercle Assisted Propellers (TAP), Proton Exchange Membrane (PEM) Fuel Cells (FCs) using liquid inorganic hydrogen storage (Hydrosil), and battery packs as potential solutions for retrofitting an existing vessel: OS Energy's Fortuna Crane. This study focused on the evaluation of the most optimal configuration using a combination of fuel cells and batteries. To find the most optimal configuration, BV M&O's tool Ship Energy Efficiency Calculation and Analysis Tool (SEECAT) was used to assess various fuel cell power capacities and batteries configurations on 3 profiles describing the operations of the vessel. Although the entire power demand could be provided by fuel cells, batteries were necessary to ensure low power demand. Naval architecture analysis confirmed that the system could be integrated while respecting the volume and weight constraints of the vessel. However, the most optimal in terms of volume, weight and total cost appeared to be the configuration using fuel cells with average sizing. This result demonstrates the potential of the integration of tubercle-assisted propellers, fuel cells using Hydrosil, and batteries to enhance the environmental performance of maritime transportation.

Keywords: Retrofit · Hybrid Propulsion · Fuel Cells · Tubercle Assisted Propellers · Hydrosil (liquid inorganic hydrogen carrier)

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1 Introduction

The maritime industry is facing increasing pressure to address its environmental impact, driven by stringent regulations and the global push towards sustainability. Achieving compliance with these requirements often requires the integration of multiple technologies, as a single solution may not be sufficient to meet the diverse operational and environmental demands of modern vessels. In this context, the RESHIP project has explored the combination on board of ESD i.e. Tubercle Assisted Propeller (TAP,) with hydrogen fuel cell power generation as a promising approach to address the environmental challenges faced by the maritime sector.

Hydrogen fuel cells offer promising emission reductions for maritime applications by converting hydrogen into electricity through electrochemical reactions. While emission reduction is essential, enhancing overall ship energy efficiency is equally critical. In this case, Newcastle University addressed this by developing TAP, a whale fin-inspired propeller that substantially decreases energy consumption while maintaining vessel speeds. Full-scale integration simulation through the RESHIP project represents a crucial milestone to validate the feasibility and performance of these technologies in a virtual maritime environment that reproduces real-world conditions, accounting for the complex and dynamic factors such as load profiles and operational patterns that significantly influence new technology performance and integration.

Furthermore, an optimization analysis is proposed within the scope of this paper, with the assistance of SEECAT, it will provide important insights into the trade-offs and considerations involved in the integration of hydrogen power systems and ESDs for full electric retrofit [1]. By evaluating factors such as weight, volume, capital expenditure (CAPEX), and operational expenditure (OPEX) across various fuel cell capacities, the most optimal configurations that balance performance, cost, and environmental impact for full electric ship were identified.

2 Methodology

2.1 Sizing

RESHIP used iterative approaches to investigate the potential of hybrid ship retrofitting combining TAP, FCs, and liquid inorganic H2 storage. Input data were collected from the partner, such as ship dimension and specifications as well as operational profiles i.e. 1-, 2- and 14-days. Fortuna Crane was optimized based on various combinations of FC-battery capacities, Table 1 illustrates the considered sizings.

As a result, a total of 18 scenarios were considered. FC and batteries were selected upon the highest power demand and required energy for three operational profiles. Comparing several makers, the chosen battery and FC are detailed in Table 2.

Electric propulsion motor was also selected in this project, which based on the ship resistance, speed, propeller rotation and a margin of 30%. The selected motor was Marelli Motori B5C400LC4 with 710 kW of power, 4543 Nm of motor and 1490 rpm.

HSL Technologies estimated the required Hydrosil quantity and storage based on chosen electrical components, while Glafcos assessed integration feasibility regarding weight and volume. A full electric retrofit with maximum fuel cell sizing served as

Table 1. Applied sizings of FC-battery combination

Sizing	Explanation
Full Battery	All power demand is provided by battery (no fuel cell)
Average	Installed FC maximum power equals to average power demand
50%	Installed FC maximum power equals to 50% of maximum power demand
75%	Installed FC maximum power equals to 75% of maximum power demand
90%	Installed FC maximum power equals to 90% of maximum power demand
100%	Installed FC maximum power equals to 100% of maximum power demand

Table 2. Technical specification of the selected fuel cell unit

	Fuel Cell	Battery
Brand	**EH Trace**	**Corvus**
Model	**250** [2]	**Dolphin Energy** [3]
Volume [m3]	1.3464	0.033
Weight (max.) [kg]	1100	45,5
Power [kW]	250	N/A
Volumetric energy density [Wh/l]	N/A	212.5
Gravimetric energy density [Wh/kg]	N/A	168
Electric storage [kWh]	N/A	8.2
C-rate for charge	N/A	0.5
C-rate for discharge	N/A	0.5
Nominal voltage [V]	850	1046
Min voltage [V]	700	130
Max voltage [V]	1150	1205.00
Min Current [A]	0	N/A
Max Current [A]	375	N/A
Efficiency	0.49	–

a benchmark since this was the heaviest and most voluminous and also one of the main objectives of the project was to demonstrate maximum Hydrosil and Hydrogen Reactor Unit (HRU) integration. Other configurations would be feasible if this integration succeeds, except 100% battery sizing, which exceeded available volume. Optimization was rigorously evaluated across weight, volume, and cost parameters.

2.2 Modelling

Several systems were not available in SEECAT such as FC and dedicated Energy Management System (EMS). Following an iterative approach, Bureau Veritas M&O developed these by combining empirical formulas and data provided by the project partners.

Fuel cell type used in this project is the Proton Exchange Membrane fuel cell (PEMFC). The development of fuel cell in SEECAT was done through literature works and collecting available data from partners. PEMFC performance can be modelled with electromechanical approach by estimating the maximum voltage of a cell subtracted by several losses' terms [4]. However, due to data availability in the market and in the project, fuel cell performance, H_2 consumption and H_2O production were estimated by curves provided by the manufacturer.

Since FC must operate consistently at their designated duty rate, they require an embedded control system; the proposed Voltage-Power Droop Control approach uses an Automatic Voltage Regulator (AVR) that dynamically adjusts voltage set-points based on actual power delivered to the electrical network, enabling the fuel cell to respond quickly to load variations while maintaining stability and operating at maximum efficiency for reliable, responsive energy delivery, as written in Eq. 1.

$$V = V_{nom}\left[1 - \delta\left(\lambda_e - \lambda_{duty}\right)\right] \tag{1}$$

Where V is voltage set point of the AVR at time t [V], V_{nom} is fuel cell nominal voltage [V], δ is droop value, usually between 1% to 3%, λ_e is actual delivered electrical load by fuel cell [0–1] and λ_{duty} is fuel cell duty rate [0–1].

3 Results

3.1 Integration

This study explored retrofitting an existing vessel for zero-emission shipping by replacing conventional internal combustion engines and electro-mechanical systems with a hydrogen-powered system comprising a Hydrogen Reactor Unit (HRU), FCs, and battery-based Energy Storage Systems (ESSs). The retrofit involved removing two of 20 t of marine diesel engines, three of 5,5 t of electric generators, and oil and fuel storage tanks exceeding 30,8 m^3, which significantly reducing the vessel's low-placed concentrated mass while creating space for an innovative hydrogen-based energy architecture.

The new hydrogen-based system introduced two HRU units on the open deck, eleven PEMFCs distributed around the former engine room, approximately 12,1 t, with Hydrosil tanks were placed in previous fuel tank locations, and four lithium-ion battery packs in fire-protected A60 enclosures, weighted of 7–8 t. To maintain propulsion integrity, two high-efficiency electric motors, total weighted of 6,2 t, and two new gearboxes, weighted 650 kg each, were precisely aligned with the original shaft layout, effectively transforming the vessel into a zero-emission maritime solution.

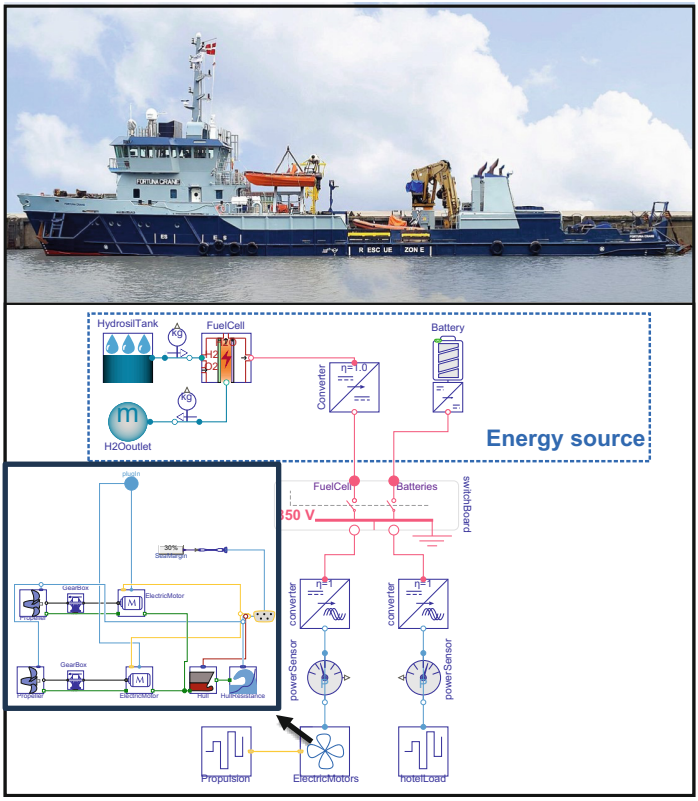


Fig. 1. Fortuna Crane (above), SEECAT's Fortuna Crane model and propulsive part (below)

3.2 Simulation of Full Electric Retrofit

The ship used in RESHIP is MV. Fortuna Crane, see Fig. 1, owned and operated by OS Energy. This ship is a multipurpose service vessel which uses mechanical propulsion and diesel gensets to answer the electrical power demand, with 15 knots of maximum speed and 30+ days of offshore endurance.

The simulation focused on a ship with average FC sizing, where the maximum operational power demand was 1886 kW and average power requirement was 618 kW. Applying a 70% duty rate margin to preserve fuel cell lifespan resulted in a minimum power of 882 kW, which led to selecting 4 fuel cell modules, with total power of 1000 kW from 250 kW per module. Battery configuration was then iteratively sized with 20 series-connected modules to answer 850 V of bus voltage, and parallel cells were adjusted across simulations to maintain a State of Charge (SoC) around 0,5 to optimize battery lifespan [5].

Using the configuration above, the three operational profiles were simulated, and various variables were monitored such as power demand, power generation and distribution

and battery SoC. Although the comprehensive study evaluated multiple potential configurations, there is only one configuration demonstrated viability across three distinct operational profiles.

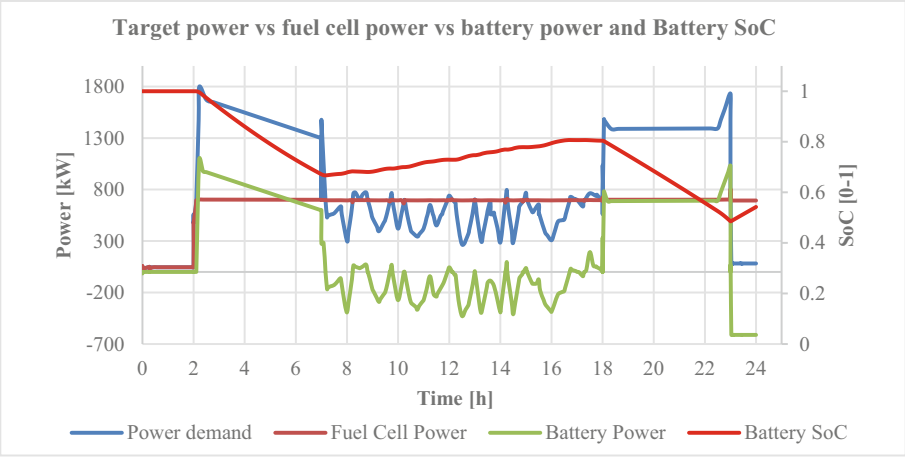


Fig. 2. Power comparison and battery SoC level for 1 day operation of full electric Fortuna Crane

Figure 2 compares target power demand with simulated fuel cell and battery power output, plus battery SoC. The battery primarily supplied power during start and end of operation, while the FC charged it during cruise phases when power demand remained below the fuel cell's 1050 kW duty rate. The red line shows battery SoC for 65 parallel-connected modules over one day: the battery discharged for departure maneuver, recharged from hour 7 onward, and maintained SoC above 0.5 for the arrival maneuver. Table 3 shows the results of battery sizing for average application of three operational profiles.

Table 3. Battery sizing for average application of full electric Fortuna Crane

Profile	Parallel Modules	Battery total capacity [kWh]
1 day	65	10660
5 days	40	6560
14 days	45	7380

The one-day operational profile required the highest battery capacity among all profiles tested. Since all profiles 4 modules, the optimal system design retained 4 fuel cell modules and 65 parallel battery modules. This configuration was applied across all operational profiles and fuel cell sizing scenarios.

4 Optimisation

Optimizing ship weight is critical for stability, seaworthiness, fuel efficiency, and cargo capacity, requiring balance between lightweight construction and essential systems [6]. Similarly, minimizing total cost (CAPEX and OPEX) through optimal selection of propulsion, auxiliary power, and mechanical equipment is crucial for project viability and lifetime operation. This study therefore aimed to identify the lightest and lowest-cost configuration, prioritizing weight and cost optimization over volume minimization, which was constrained by available onboard space.

The comparison included fuel cell, battery, HRU system, Hydrosil tank, gearbox [7], and electric motor components [8] and full battery sizing was excluded due to space constraints. Cumulative weights and costs were derived from systematic aggregation with key assumptions: 20-year lifespan, no maintenance or installation costs, ¾ year operational availability (20 operations per year at 14 days each), constant energy costs, and no end-of-life costs. Energy price references were: green H_2 at 6610 €/mt and green NH_3 at 1000 €/mt [9, 10]. At the time of writing, Hydrosil pricing had not yet a precise the price, hence green H_2 and green NH_3 prices were used as high and low price benchmarks. CAPEX price references obtained from partners and manufacturers.

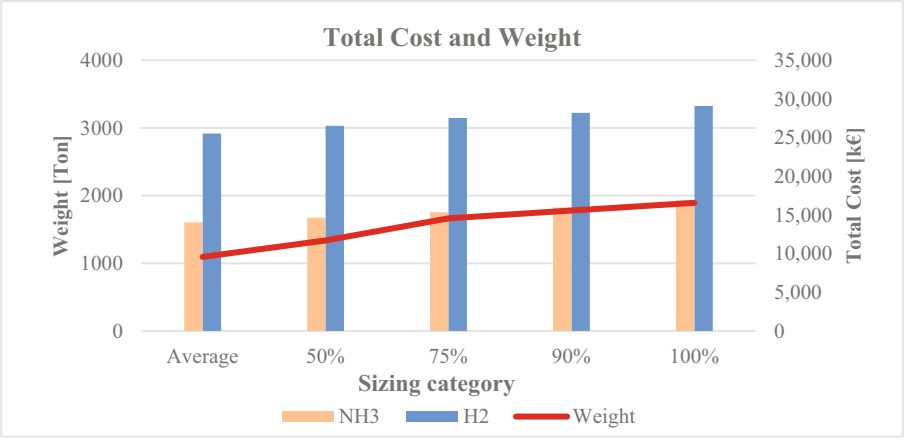


Fig. 3. Total cost and weight of various sizings and fuel types for full electric Fortuna Crane

According to Fig. 3, it can be concluded that a system using FC with average sizing appears as the best compromise. This system weighs 1095 tons, which is almost half of the one with the maximum FC sizing. When considering NH_3 as the fuel price reference, the system using fuel cells with average sizing would offer 14 038 k€ as total cost, which is around half cost of the same system considering green H_2 as the fuel price reference. Green H_2 fuel reference appears as the fuel with the highest price due to the utilization of renewable energy in its production process. It is worth noting that the obtained retrofit price appears very high as this is a prototype.

5 Conclusion and Future Works

The integration and optimization strategies presented in this study demonstrate the feasibility of incorporating TAPs, PEMFCs, HRU and Hydrosil storage onboard, while maintaining cost-effectiveness. The integration proved that zero-emission hydrogen-powered system fitted on existing onboard available space by replacing all conventional internal combustion engines and electro-mechanical systems. To enhance the performance, through comprehensive simulation and analysis using SEECAT, the study systematically evaluated multiple FC-battery configurations across three distinct operational profiles, optimization was conducted with respect to volume, weight, CAPEX, and OPEX. Among the various proposed fuel cell–battery configurations, average sizing with fuel reference of green NH_3 emerged as the most promising configuration.

Acknowledgments. RESHIP was the joint effort between 14 companies across Europe to develop and evaluate the integration of TAP, FC, and liquid inorganic H2 storage onboard of a ship. The project has received funding from the European's Horizon 2020 research and innovation program, under contract number 101056815.

The integration and the choice of components and systems were made by considering Bureau Veritas Marine & Offshore rules as a reference. However, none of the design elements presented in this article was reviewed by a classification society.

References

1. Gunawan, R. et al.: Ship performance and energy consumption evaluation based on modular design approach. In: Transport Research Arena Conference, Dublin (2025)
2. EH Group: Product Homepage. https://www.ehgroup.ch/product/fuel-cell-systems. Accessed 29 Apr 2026
3. Corvus Energy: Dolphin NxtGen ESS - Energy Product Homepage. https://corvusenergy.com/products/energy-storage-solutions/corvus-dolphin-power/. Accessed 29 Apr 2026
4. Saeed, W., Warkozek, G.: Modeling and analysis of renewable PEM fuel cell system. In: International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15, Damascus (2015)
5. Papanikolaou, A. et al.: Holistic ship design for green shipping. Transp. Res. Procedia, 1224–1231 (2023)
6. Jokinen, M. et al.: Design of double ended ferry. In: A Holistic Approach to Ship Design, pp. 373–426. Springer Nature, London (2021)
7. ZF: ZF Gearbox 3101_643 Drawing, Friedrichshafen. ZF Friedrichshafen, Friedrichshafen (2024)
8. Marelli: Three Phase Squirrel Cage Induction Motor. Marelli, Arzignano (2012)
9. CleanHydrogenPartnership: The European Hyrdogen Market Landscape November 2024. European Hydrogen, Brussels (2024)
10. Haveresch, B., Gallardo, T.: The Future of Ammonia Supply in Europe. KBR, Houston (2024)

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Data Study into Onshore Power Demand of Container Ships: Strategic Implications for Shore Power Rollout and Emission Reduction in Ports

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Abstract. AFIR and Fuel EU Maritime legislation requires increased use of onshore power supply (OPS) in European ports to meet the sustainability goals of maritime transport. OPS is considered an effective way to reduce greenhouse gas (GHG) and pollutant emissions, such as NO_x, in port areas. A challenge for ports is the appropriate dimensioning of OPS infrastructure. The available infrastructure should be sufficient to facilitate the ships that are obligated to use it, but since energy contract tariffs are based on the maximum available power, overdimensioning the power supply infrastructure results in an increase in CAPEX and OPEX costs. However, data on energy use of maritime ships at berth is scarce, and only publicly available as averages over ship segments during an entire port stay. This paper presents a comprehensive analysis of operational profiles in the container ship segment. Data was acquired through direct collaboration with ship owners, enabling the collection of high-resolution operational profiles. The analysis reveals significant variability in power demand based on operational behaviour. By aligning OPS capacity with actual demand patterns, ports can optimise investments and installed power. The potential for reductions of NO_x and CO_2 emissions by using OPS is therefore quantified.

Keywords: Maritime · Power demand · Data insights · Shore power · Emissions

1 Introduction

Onshore power supply (OPS) is considered an effective way to reduce greenhouse gas (GHG) and pollutant emissions in port areas. By supplying ships with electric power from shore, generator sets do not have to be used to power the on-board systems during the port visit. Maritime shipping has a strong impact on local pollutant emissions, particularly in port areas [1–3]. This primarily concerns emissions from ships that are manoeuvring or stationary in port areas. For example, in the Port of Rotterdam, the emissions of stationary and manoeuvring seagoing ships account for more than 78% of the total transport related emissions in the port area [4]. NO_x emission reductions can be achieved through aftertreatment technologies, the use of alternative energy carriers, and the implementation of OPS [5]. The implementation of OPS is the focus of this research.

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In order to reduce emissions and improve air quality in Europe, Article 6 of the FuelEU Maritime regulation [6] prescribes that container ships and passenger ships larger than 5000 GT (as set out in article 9 of AFIR [7] must connect to OPS while moored on the quayside from 2030 onwards, or use another zero-emission technology. In addition, the supply side of OPS is regulated. Article 9 of AFIR makes port authorities responsible for facilitating OPS infrastructure if they have a certain number of calls for the relevant ships - first in the busiest TEN-T ports by 2030 and requires them to cover 90% of relevant port calls [7].

Currently, there is a lack of accurate knowledge on the fuel- or power demand of ships in ports. In ports only averages are reported for different ship types, cargo capacities, or weight sizes [8, 9]. For instance, under the EU MRV Regulation (Monitoring, Reporting, Verification), operators are required to report, among other metrics, their total fuel consumption at berth [9]. However, these reports only provide absolute fuel (in tonnes) and do not include fuel consumption rates. For the roll-out of OPS, it is therefore important to have a validated bandwidth of this power demand in order to prevent over- or under-dimensioning for OPS infrastructure. Over-dimensioning infrastructure can lead to significantly increased costs, which rise disproportionately with higher installed peak power, and puts unnecessary strain on the electricity grid. Under-dimensioning risks operational inefficiencies and potentially slows down adoption of the technology and compliance with FuelEU Maritime and AFIR obligations. Accurate forecasts of power demand are important to ensure that berthing ships can effectively utilise OPS. This work focusses on the power demand of container ships, which is the most fuel consuming ship segment of the types that are mandated to use OPS (or an alternative zero-emission technology) by AFIR regulations by 2030. This paper investigates the temporal characteristics of energy and power demand of berthed container ships. To address this, the study examines how ship size affects the average power demand during port visits. The analysis explores several interrelated factors that influence demand variability and operational behaviour during port stays. It also investigates the impact of refrigerated container (reefer) counts on total power demand, aiming to quantify their contribution to onboard energy needs. Furthermore, the impact of power distributions on CO_2 and NO_x emissions is discussed, providing insights into the environmental implications of OPS infrastructure planning. The results of this paper are part of a larger study conducted by TNO on the validation of shore power by investigating the onshore power demand data of different sea-going ship segments [10].

2 Methodology

2.1 Data Acquisition

Data was acquired through direct collaboration with ship owners and operators, enabling the collection of operational profiles and onboard usage patterns. To assess the onshore power demand of maritime ships in detail, a comprehensive dataset was requested from ship operators encompassing both general ship characteristics and detailed power-related metrics. Additionally, both the active power and reefer power demand was requested at

high temporal resolution (preferable 5 min intervals), in combination with GPS coordinates and logged operational activities. Specific subsystems such as hotel load, heating/cooling, number of reefers at arrival and departure were also included to enable granular analysis of energy demand profiles. Furthermore, auxiliary generator specifications were gathered to understand the onboard power generation. This includes generator type, regulatory NO_x classification (IMO Tier), maximum power rating, brand/model, fuel type, and operational hours. This data is used to estimate emissions from onboard generation, which could potentially be avoided by using OPS. Not all requested data was available from every collaborating party at the desired level of detail. As digitalization is still a work in progress for many owners and operators, accessing the requested information is often challenging, and in many cases, the data is not yet monitored systematically. Aside from MRV, which requires reporting the total fuel consumed, there is no standardized practice in the maritime sector for collecting more detailed power demand data. Consequently, the availability of data varies significantly between operators and ships.

2.2 Emission Estimates

The collected power profiles, together with generator specifications, can be used to estimate emissions. Since emissions strongly depend on power output, the load fraction (lf) - the ratio of actual to maximum generator load- must first be determined. An estimate of the load fractions of the generators can be made using the empirical relation for Specific Fuel Consumption (SFC) as a function of the load fraction for main engines [9]. At low loads, the SFC is at its highest level, it decreases until it reaches a minimum (e.g. 75% MCR, lf = 0.75), then begins to rise again:

$$SFC = SFC_{base}{}^{*}\left(0.455^{*}\, lf^{2} - 0.710^{*}\, lf + 1.280\right) \tag{1}$$

Although this relation was developed for main engines, the principle of higher fuel consumption at low and very high loads also applies to auxiliary engines. An optimisation algorithm is used to predict the load fractions of the available generators, optimising for total fuel rate in kilograms per hour. This approach provides an approximation of how power generation is managed on board. Based on the fuel rate, the CO_2 emissions can be calculated directly using the Well-to-Wake emission factors [11].

$$CO_2\left[g/h\right] = EF_{WTW}{}^{*}\, SFC^{*}\, MCR^{*}\, lf \tag{2}$$

In Eq. 2, the EF_{WTW} for CO_2 is assumed to be 3173 g/kg MGO [12]. The NO_x emission rate in kg/h can be computed by using the following equation:

$$NO_x\left[g/h\right] = EF_{base}{}^{*}\, CEF^{*}\, MCR^{*}\, lf \tag{3}$$

In Eq. 3, EF_{base} represents a baseline NO_x emission factor. CEF is a load-dependent factor that also depends on the IMO Tier and rated RPM of the generator. MARIN [12] also published fuel consumption factors for ships at berth which depend on their gross-tonnage. These factors are based on aggregated data and give a less detailed view on the emissions on individual ship level. For container ships, an MGO fuel rate of 6 kg/1000 GT per hour is reported, of which 90% would be used for electric power and

10% for the on-board boilers. Based on the build year, NO_x emission in g/kg fuel (MGO) is also reported. For example, for Tier III ships a NO_x emission of 12.81 g/kg fuel is reported [12]. These high-level fuel consumption and emission factors will be compared to generator load-dependent emission factors of Eqs. 2 and 3.

3 Results

3.1 Power Demand Profiles

This section presents an analysis of power demand during port stays for container ships. First a comparison of average power demand at berth between different twenty-foot equivalent unit (TEU) container capacity categories is shown, and then operational power profiles of the largest capacity categories is used to focus on the influence of reefer loads. Figure 1 shows how the average power demand per visit varies for container ships of different size classes, defined by their TEU capacity, in a specific port between 2024 and 2025. The average power demand of the smallest size class (<4000 TEU) is significantly lower than the other two size classes. The variance in the power demand of the smallest and largest size class (>10000 TEU) is significantly higher than in the middle size class (4000–10000 TEU).

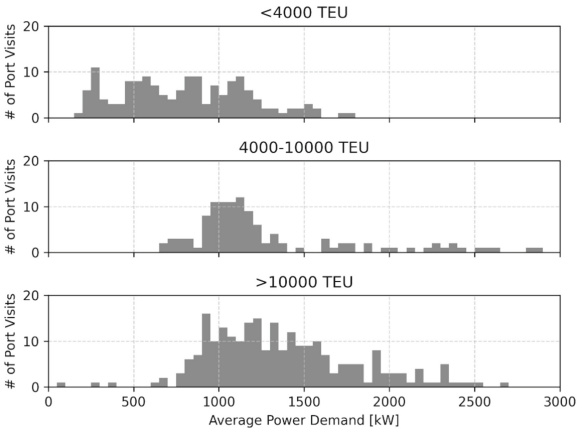


Fig. 1. Distribution of the average power demand per visit in a specific port between 2024 and 2025 for container ships of different size classes, based on their TEU capacity

To take a closer look at power demand on an individual ship level, three container ships with comparable TEU capacities (about 20000 TEU) are investigated. Figure 2 presents the total active power and total reefer power profiles during the port visits of three comparable container ships in TEU capacity. Container Ship X reported 576 reefers at departure, while the number at arrival was not documented. In contrast, Container Ship Y reported 189 reefers upon arrival and 91 at departure. Container Ship Z reported similar reefers upon arrival and departure, 154 and 113, respectively. Despite their similarity in

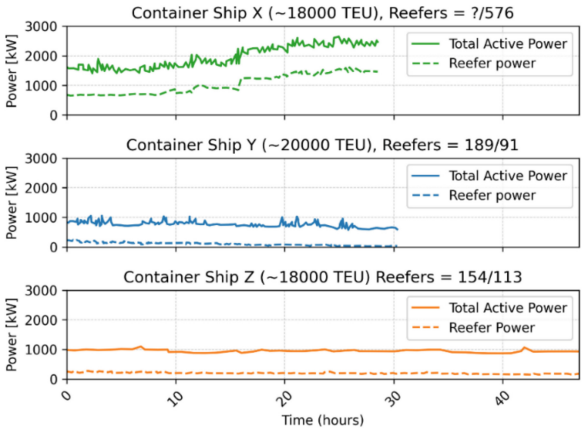


Fig. 2. Total active power and total reefer power during specific port visits for three large container ships (18000–20000 TEU)

ship type and TEU capacity, the temporal evolution of onshore power demand during the port visits differs markedly between the three ships.

In the top graph in Fig. 3, the total active power of Fig. 2 for Container Ships X, Y and Z have been converted into power distributions. This way the different operating points of the three ships can be more easily compared. The differences in these distribution underscores the variation in power demand. The distributions are compared with the average power value for container ships with a similar TEU capacity (14500–19999 TEU), as reported by the IMO [9]. In the bottom graph, the total reefer power of the three container ships has been subtracted from the total active power. This adjustment reveals a much narrower spread in total active power across these ships, indicating that the reefer load is a primary driver of variability in onshore power demand. The reduced variation after removing reefer contributions emphasises the importance of accounting for refrigerated cargo when assessing power needs for shore power roll-out strategies and during port operations.

3.2 CO_2 and NO_x Calculations

Using the specifications of the generators that provide power onboard, the expected fuel rate and emissions can be estimated as described in Sect. 2.2. For all three ships (Container Ship X, Y and Z), it holds that the smallest generator on board has a rated power output of 2800 kW. As shown in Fig. 3, the total active power of Container Ships Y and Z does not exceed 1100 kW during the monitored port stays. That means that on average, the generators on ships Y and Z run on a load fraction of less than 0.5, while the generator on ship X runs with a load fraction of 0.7. From Eq. 1, it is clear that the generators run most efficiently at a load fraction of about 0.75. Using Eqs. 2 and 3, the CO_2 rate and NO_x rate can be calculated for the monitored port visit. The range of emissions are presented in Table 1.

Table 1 indicates that the relationship between power demand and emissions is not strictly linear. While Container Ship X operates at approximately 2.5 times the power

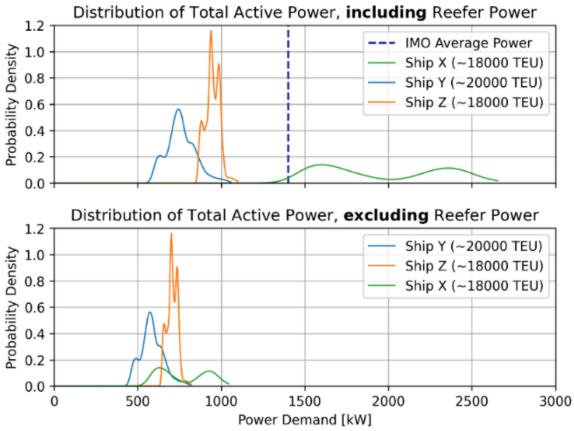


Fig. 3. Distribution of power demand at berth for a single port visit of Container Ships X, Y, and Z. Top: Total active power including reefer power. Bottom: Total active power excluding reefer power

Table 1. Range of total active power, CO_2 emission rates and NO_x emission rates of Container Ships X, Y, and Z during monitored port stays

Ship	Total active power [kW]	CO_2 rate [kg/h]	NO_x rate [kg/h]
X	1400–2500	800–1400	16–21
Y	600–1000	500–600	7–12
Z	800–1100	400–600	10–13

demand of Ship Y, its CO_2 and NO_x emissions are somewhat lower than 2.5 times those of Ship Y. This deviation shows that emission rates increase with power, but not in exact proportion. In other words, a rise in power demand does not necessarily translate into a directly equivalent rise in emissions. The CO_2 and NO_x emission rates can also be calculated based on the GT-based fuel consumption as reported by MARIN [12]. That leads to CO_2 emission rate of approximately 2700 kg/h, and a NO_x emission rate of about 35 kg/h, both significantly higher than the emission rates shown in Table 1.

4 Conclusion

This paper highlights substantial variability in power demand among large container ships during port visits. First, we have investigated the average power demand per port visit, which varies for container ships of different size classes. Additionally, by looking at the power demand over time for large container ships (>10000 TEU), we have investigated that the onshore power demand is primarily driven by the number of reefers on board. The dynamic nature of reefer loads between arrival and departure significantly influences operational behaviour and results in distinct power demand patterns, even

among ships of similar type and TEU capacity. Furthermore, by combining empirical insights on power demand variability with ship-specific generator specifications, this study enables a more detailed modelling of NO_x emissions. While power data collection remains essential for meaningful analysis, the data acquisition for this study was limited due to the absence of standardised measurement systems. Apart from the EU MRV Regulation, which only requires reporting total fuel consumption, there is currently no industry-wide standard for monitoring power demand over time. This makes data collection and detailed emissions modelling cumbersome, as information must be gathered separately from each individual operator.

Our findings suggest that the power demand of reefers contributes most significantly to the observed variability. As such, it represents one of the primary challenges in developing an effective deployment strategy. These findings underscore the importance of moving beyond generalised assumptions when planning for shore power infrastructure. Variability in power demand demonstrates that even container ships of similar type and TEU capacity can exhibit markedly different energy profiles during port stays. This has direct implications for the design and sizing of OPS systems, which must be flexible and responsive to actual operational conditions rather than based solely on ship classification or gross tonnage. Three key benefits emerge from further investigation into detailed power demand across ship types. First, aligning OPS capacity with actual demand patterns enables ports to optimise infrastructure investments, ensuring cost-effective and targeted deployment. Second, access to day-ahead information on reefer capacity at arrival allows shipowners and port authorities to better anticipate electricity demand, facilitating more accurate and efficient participation in day-ahead electricity markets. Third, improved quantification of CO_2 and NO_x emission reductions strengthens the environmental case for OPS, supporting policy and regulatory initiatives aimed at decarbonising port operations. Although compliance with EU shore power regulations appears feasible for container and passenger ships, the extension of these regulations to other ship categories remains uncertain and warrants further investigation. Additionally, the growing relevance of hybrid and fully electric ships presents new research avenues beyond the scope of this study.

References

1. Bullock, S., Hoolohan, C., Larkin, A.: Accelerating shipping decarbonisation: a case study on UK shore power. Heliyon. **9**(7), e17475 (2023)
2. Herrero, A., Ortega Piris, A., Diaz-Ruiz-Navamuel, E., Gutierrez, M.A., Lopez-Diaz, A.-I.: Influence of the implantation of the onshore power supply (OPS) system in Spanish medium-sized ports on the reduction in CO_2 emissions: the case of the port of Santander (Spain). J. Mar. Sci. Eng. **10**(10), 1446 (2022). https://doi.org/10.3390/jmse10101446
3. Daniel, H., Trovão, J.P.F., Williams, D.: Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier. eTransportation. **11**, 100150 (2022). https://doi.org/10.1016/j.etran.2021.100150
4. Port Xchange: Emission insider: Pave the way to a zero-emissions port. https://port-xchange.com. Accessed 29 Sep 2025
5. Daniel, H., Trovão, J.P.F., Boulon, L., Williams, D.: Shore power deployment strategies and policies including alternative fuels. Transp. Res. Part D: Transp. Environ. **148**, 104999 (2025). https://doi.org/10.1016/j.trd.2025.104999

6. European Commission: Decarbonising maritime transport: FuelEU Maritime. https://transport.ec.europa.eu. Accessed 15 Oct 2025
7. European Commission: Alternative fuels infrastructure, and repealing directive 2014/94/EU (AFIR). https://transport.ec.europa.eu. Accessed 15 Oct 2025
8. Royal Haskoning DHV: Walstroom inventarisatie 2024. Technical Report. Royal Haskoning DHV (2024)
9. International Maritime Organization: Fourth IMO GHG Study 2020: Full Report and Annexes. Technical Report. IMO, London (2020)
10. van Beurden, T.J.H., van de Water, O.P., Harmsen, J.: Data Study into Onshore Power Demand Highlights Strategic Implications for Shore Power Rollout and Emission Reduction in Ports . Technical Report. TNO (2025)
11. European Maritime Safety Agency: Reducing GHG emissions: MRV regulation. https://www.emsa.europa.eu. Accessed 26 Mar 2026
12. European Parliament and Council of the European Union: Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, and amending directive 2009/16/EC. Official Journal of the European Union, L 234 (2023)

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The Key Technological Challenges and Choices to Be Made for Hyperloop

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Abstract. Thermal management in Hyperloop vehicles presents a major challenge due to operation in low-pressure environments (1–15 mbar), where conventional cooling is ineffective. Various Hyperloop drivetrain concepts and tube pressures are under consideration. Especially vehicle-based drivetrain systems and high tube pressures result in high thermal loads to the cooling system. Two primary cooling approaches have emerged: latent Thermal Energy Storage (TES) and evaporative cooling coupled with stationary vapor removal systems. TES systems (using ice or water) are simple but have a relatively low energy density, meaning they are only feasible for moderate thermal loads, given the stringent mass budget of the vehicle. Alternatively, evaporative cooling dissipates heat by releasing water vapor into the tube, which is extracted by infrastructure-based condensers. While efficient at higher pressures (above 10 mbar, COP $>$ 3), this method introduces challenges in vapor management and system integration. After quantifying the thermal load of each drivetrain concept for 1 and 10 mbar it was concluded that the TES cooling concept is feasible for offboard and combined type drivetrains. Fully onboard drivetrains require evaporative cooling. Above 10 mbar, an efficient vaporizer/mixing condenser can be used while below, at 1 mbar, a batched sublimator/ice condenser system is required.

Keywords: Hyperloop · Drivetrain · Cooling · Thermal storage · Vaporizer

1 Introduction

Hyperloop is a high-speed transport system with so-called pods travelling through low-pressure tubes, achieving airplane-like speeds with a train's environmental footprint. Electromagnetic motors provide propulsion, and pumps maintain near-vacuum conditions to reduce air resistance. The concept has recently attracted increasing interest from the European Commission as part of its sustainable transport agenda because of its promising fast travel and low environmental impact [1].

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Effective thermal management is essential for Hyperloop vehicles to ensure safe, reliable operation and prevent overheating of critical components. The drivetrain, batteries, power electronics, and linear motors produce substantial heat that must be removed from the vehicle. In the low-pressure environment (1–15 mbar), conventional convection-based cooling is largely ineffective [2].

The tube pressure strongly affects both drivetrain performance and thermal management. Lower pressures reduce aerodynamic drag, altering propulsion power needs, while also influencing cooling effectiveness. To capture these effects, two representative pressures are considered: 1 and 10 mbar. Their impact on drivetrain power and thermal loads are addressed in Chapter 2, the effects on cooling system performance are addressed in Chapter 3 and the overall feasibility is addressed in Chapter 4.

2 Drivetrain and Vehicle Mass

2.1 Drivetrain Concepts

Hyperloop drivetrain concepts (Fig. 1) can be divided into vehicle-based, infrastructure-based, or a combination. Vehicle-based propulsion uses on-board, short-stator linear motors and power electronics, powered by a battery and optionally a wireless range-extender. Infrastructure-based propulsion relies on off-board, long-stator linear motors fed from the grid, sized differently for acceleration and cruise sections. The booster concept combines both: infrastructure motors provide acceleration, then reduced on-board motors maintain cruise speed.

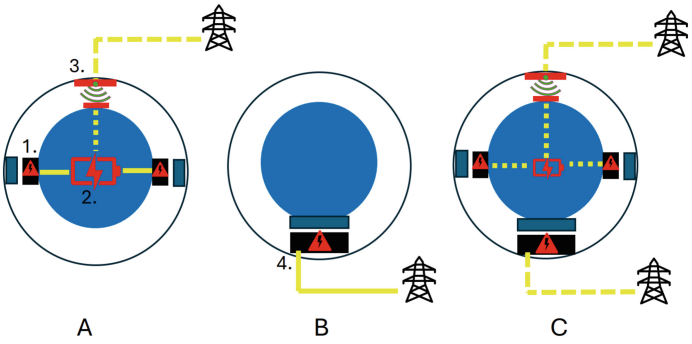


Fig. 1. Overview of different drivetrain concepts: A) on-board propulsion, B) off-board propulsion, and C) booster. Numbered components are 1) on-board motor, 2) on-board battery, 3) wireless power transfer and 4) off-board motor

2.2 Representative Cruise Scenario

For a consistent analysis, a fixed operational scenario is defined. A 1-h (500 km) trip, with an average of 500 km/h and a maximum cruise speed of 700 km/h. Vehicle dynamics assume 1 m/s^2 longitudinal acceleration, with 30% of the route allocated to acceleration and braking phases, accounting for start-up, deceleration, curves, and other operational speed constraints.

2.3 Thermal Load Calculation

Thermal loads and losses during acceleration, cruising, and braking are evaluated. The pod mass is calculated iteratively based on the required motor and battery mass. All relevant system input parameters are listed in Table 1.

Table 1. System input parameters

	Description	Value	Unit	Rationale
η	Drivetrain efficiency full load/cruise	0.80/0.90	–	Assumption for full drivetrain efficiency (incl. battery and inverter losses)
F_(d,air)	Air drag at 1 mbar/10 mbar	1000/10000	N	Estimated order of magnitude for air drag for Hyperloop at cruise speed
L/D	Lift over drag ratio magnetic suspension	500	–	Assumption based on EMS system and laminated steel levitation tracks
$\dot{Q}$_cabin	Cabin heat production	25	kW	Assumption based on 50 passengers and 500 W/pax (body heat + cabin systems)
$\dot{Q}$_susp/m_vehicle	Suspension power per unit mass	2	kW/ton	Estimation based on Transrapid EMS system power consumption

The following equations are used to calculate the heat losses listed in Table 2. During acceleration, the average heat generated on-board by the propulsion system can be calculated using:

$$\dot{Q}_(prop, acc) = ((1 - \eta))/\eta \cdot m_vehicle \cdot \overline{a} \cdot \overline{v} \tag{1}$$

During braking, the average heat generated on-board by the propulsion system can be calculated using:

$$\dot{Q}_(prop, dec) = (1 - \eta) \cdot m_vehicle \cdot \overline{a} \cdot \overline{v} \tag{2}$$

During cruise phase, the total vehicle drag consists of air drag and magnetic drag, and the average heat generated on-board by the propulsion system can be calculated using:

$$\dot{Q}_(prop, cruise) = ((1 - \eta))/\eta \cdot (F_(d, air)\ (p) + F_(d, magn)\ ) \cdot \overline{v} \tag{3}$$

In which:

$$F_(d, magn) = (m_vehicle \bullet g)/(L/D) \tag{4}$$

Next, the average heat generated by the on-board propulsion system can be calculated using:

$$\dot{Q}_(prop, avg) = t_acc/t_trip \bullet \dot{Q}_(prop, acc) + t_dec/t_trip \bullet \dot{Q}_(prop, dec) + t_cruise/t_trip \bullet \dot{Q}_(prop, cruise) \tag{5}$$

Ultimately, the total heat generated by the vehicle including cabin heat and suspension heat is:

$$\dot{Q}_avg = \dot{Q}_(prop, avg) + \dot{Q}_cabin + \dot{Q}_susp \tag{6}$$

Additionally, the peak heat generated is defined as:

$$\dot{Q}_peak = \max\left(\dot{Q}_(prop, acc), \dot{Q}_(prop, dec), \dot{Q}_(prop, cruise)\right) + \dot{Q}_cabin + \dot{Q}_susp \tag{7}$$

Table 2. Average and peak heat for various drivetrain concepts at 1 and 10 mbar

Pressure		1 mbar	1 mbar	1 mbar	10 mbar	10 mbar	10 mbar
Drivetrain		*onboard*	*offboard*	*booster*	*onboard*	*offboard*	*booster*
$m_vehicle$	kg	20000	14000	16000	42000	14000	35000
$F_(d, magn)$	N	392	275	314	824	275	687
$F_(d, air)$	N	1000	1000	1000	10000	10000	10000
$\dot{Q}_(prop, acc)$	kW	556	0	0	1167	0	0
$\dot{Q}_(prop, dec)$	kW	444	0	0	933	0	0
$\dot{Q}_(prop, cruise)$	kW	34	0	32	267	0	264
$\dot{Q}_(prop, avg)$	kW	174	0	23	502	0	185
$\dot{Q}_susp$	kW	40	28	32	84	28	70
$\dot{Q}_cabin$	kW	25	25	25	25	25	25
$\dot{Q}_avg$	kW	239	53	80	611	53	280
$\dot{Q}_peak$	kW	621	53	89	1276	53	359

Apart from the heat load, the required cooling temperatures are relevant to assess the cooling concept feasibility. In this case the passenger cabin and the batteries, if available, are the limiting components, which both have a target cooling temperature of 20 °C.

2.4 Vehicle Mass Budget

Adding mass to a vehicle increases its needed propulsion power, which in turn raises heat dissipation, creating a positive feedback loop limiting the mass available for the cooling

system. Closed-loop systems tend to have lower gravimetric energy densities and thus require more cooling material as heat loads increase [3]. Beyond a certain threshold, the mass needed for heat storage exceeds the vehicle's practical mass budget, reducing payload capacity and making it unfeasible. As an example, aviation air conditioning typically accounts for about 3% of vehicle mass [4]. Given that Hyperloop vehicles operate under even stricter constraints, the authors suggest allowing up to 10% of the total vehicle mass for its cooling system.

Open-loop systems, in contrast, are less affected by this feedback. They release mass during operation, particularly during acceleration when power and heat generation are highest. As the journey progresses, the cooling system's mass continues to decline, reducing energy requirements. Additionally, they usually benefit from higher energy densities, as the enthalpy of vaporization is an order of magnitude higher than the enthalpy of fusion, allowing the same cooling effect with significantly less mass.

3 Cooling Concepts

The unique operating environment imposes strict thermal management constraints. Several cooling strategies with different advantages and disadvantages are possible; Table 3 presents the feasible concepts selected by the authors.

Convective heat release as the most common approach for terrestrial vehicles has been proven by different authors [2, 5] to be ineffective in partial vacuum environments. Heat transfer coefficients are small and finned heat exchangers increase the air drag of the vehicle, imposing more propulsion power needs. Consequently, convection is not considered as a viable cooling option below 100 mbar tube pressure.

Radiative heat transfer seems to be ideal in vacuum but has a strict limitation in its transfer power by the high temperature of the radiation partner (tube) of ~30 °C. Different authors [2, 6, 7] have shown that an onboard heat pump elevating the waste heat temperature would make this approach theoretically feasible under certain assumptions but is not practical from an engineering or integration standpoint.

Thermal energy storage (TES) allows heat to be temporarily stored via sensible, latent or adsorption heat, and its regeneration during station stops. Thermo-chemical heat storage (TCS) offers the highest energy densities among known heat storage technologies. The cooling effect is caused by the release of steam desorpted from a porous salt hydrate material. Depending on the design, its engineered energy density, including pressure tanks or heat exchangers, becomes similar to a latent storage or a direct steam release system.

3.1 Latent Thermal Energy Storage

The first considered concept, the onboard latent TES is a closed system by design, avoiding implications with the tube environment, and has a high TRL. Its low gravimetric energy density limits feasibility as capacity requirements increases with heat load and trip duration.

Ice storage is a simple, nearly passive latent TES implementation featuring a direct contact heat exchanger. It exploits the phase change of water near 0 °C, providing

predictable thermal behavior without complex control, making it safe and largely self-regulating. Like all closed-loop TES, mass is the limiting factor. Scalability of the heat exchanger surface is a strength of ice storage, as the phase-change material also serves as the transport medium. Direct contact between the coolant and the ice allows efficient heat exchange. The water's density anomaly near 4 °C promotes stratification and thus the efficient use of both sensible and latent heat. With subcooling the ice, energy density can be increased and allows an operating range between −5 and + 15 °C. This aligns well with given sensitive vehicle components such as the passenger cabin (~21 °C) and the electrical batteries (~25 °C).

3.2 Liquid or Gas Release

The second concept considered is evaporating a liquid or sublimating a solid and releasing the resulting gas into the tube environment. This open system reduces onboard mass needs but requires infrastructure-based condensers to remove and recycle the released vapor, adding system-level complexity.

The vaporizer is a mature and straightforward implementation of this principle, functioning like a water boiler. It works only at environmental pressures above the triple point of water. Its effectiveness depends on tube pressure, and scaling or upgrading the system is limited by the condensers at the infrastructure.

The sublimator applies the same principle, but using ice instead of water, converting the solid directly to vapor. While it shares the same mass-response-capacity trade-offs as the vaporizer, sublimators are low TRL, more complex due to frost management, and require batched condenser systems [8, 9]. At 1 mbar, sublimation occurs at around − 30 °C, far below component cooling needs, causing poor thermodynamic efficiency and significant exergy losses, despite rapid response.

The type of needed infrastructure-based condensing systems varies depending on the pressure and phase change process. Cheap and simple mixing condensers can be used above 15 mbar, where vapor is efficiently mixed with cool water to condense it. At pressures below 15 mbar, heat exchangers are required, utilizing metal surfaces for vapor condensation. At pressures below the triple point of water (~ 6 mbar), parallel, batched condenser systems are required, which alternate between condensation and de-icing cycles. These batched processes introduce challenges in controlling, scalability and cost.

Table 3. Collection of the three feasible cooling concepts for Hyperloop vehicles

Aspects	Ice storage TES (sensible & latent)	Vaporizer ($p \geq 10$ mbar)	Sublimator ($p < 6$ mbar)
Technology readiness level	TRL: 6–7 Mature for heating and HVAC of buildings	TRL: 8–9 Mature and widely used	TRL: 2–3 Experimental, in space applications only [9]
Implications	Storage mass to transport	Steam in tube	Steam in tube

(*continued*)

Table 3. (*continued*)

Aspects	Ice storage TES (sensible & latent)	Vaporizer ($p \geq 10$ mbar)	Sublimator ($p < 6$ mbar)
Operability	Simple cooling loop	Single-stage, passive control	Cycled operation under vacuum due to icing
Scalability (limiting technology)	Ice machine and storage swapping	Infra based condensing system	Infra based, batched condensing system
Energy density	407 kJ/kg	2264 kJ/kg	2598 kJ/kg
Cooling temperature	−5 °C to 15 °C (melting point of ice)	+7 °C (boiling temperature at 10 mbar)	−30 °C (sublimation temperature at 1 mbar)
Performance (COP)	~2.3 (chiller)	~3.1 (mixing or plate condenser)	~0.8 (multiple parallel ice condensers)
Cost estimate	700 EUR/kW (recharging)	1200 EUR/kW (condensing)	2700 EUR/kW (freezing)
Upgradability	Easy upgrade together with vehicle fleet	Infra-based system limits upgradability	Infra-based system limits upgradability

4 Feasibility Assessment Results

In this section for each drivetrain concept listed in Table 2, a suitable cooling concept is evaluated and summarized in Table 4. This is done based on the following strategy:

1. The Ice Storage TES is used whenever the mass does not exceed 10% (Sect. 2.4).
2. If the Ice Storage TES is not possible, the Vaporizer is used, but only for operation pressures above or equal to 10 mbar.
3. In case none of the other cooling concepts are possible, the Sublimator is used.

The mass of a TES solution for each drivetrain concept is calculated:

$$m_cool = m_pcm \bullet \left(\dot{Q}_avg, t\right) + m_equip\ \left(\dot{Q}_peak\right) \tag{8}$$

Where m_pcm is the mass of the PCM material, ice in this case and m_equip is the mass for all the equipment like pipes, pumps, valves etc. needed for the cooling loop. The mass of the PCM material is calculated using the total heat energy to be stored and the effective heat capacity of the material. In this case $c_(p, eff) \approx 406.7$ kJ/kg for ice with initial temperature of −5 °C which is then heated to +15 °C.

$$m_pcm = \mathrm{E}_heat / c_(p, eff) = \left(\dot{Q}_avg \cdot t\right) / c_(p, eff) \tag{9}$$

Assuming similar Reynolds and Prandtl numbers, the ice surface area needed in the TES storage is calculated using a lab-scale prototype developed by Hochschule Luzern (HSLU) and the EuroTube Foundation. The prototype is described in their publication [10].

$$\dot{Q}_{prot} = 10\ kW, \mathrm{A}_{prot} = \frac{m_{ice}}{m_{cube}} \cdot \mathrm{A}_{cube} \approx 19.6 m^2 \tag{10}$$

$$m_{ice} = 30\ kg;\ m_{cube} = 0.92\ g;\ \mathrm{A}_{cube} = 6\ cm^2 \tag{11}$$

The mass for the equipment is linearly extrapolated based on the minimal mass required for a TES system with cooling circuit and a linear factor which scales the mass depending on the peak heat power. $m_0 \approx 200$ kg and $k_equip \approx 0.1$ kg/W

$$m_equip = m_0 + k_equip \bullet \dot{Q}_peak \tag{12}$$

Table 4. Feasibility of the Ice Storage TES and Vaporizer cooling concept

Pressure [mbar]	Drivetrain	*m _ vehicle* [kg]	*m _ cool* [kg]	% of total vehicle mass	TES feasible	Vaporizer feasible
1	onboard	20000	2428	12.1	NO	NO
1	offboard	14000	724	5.2	YES	NO
1	booster	16000	967	6.04	YES	NO
10	onboard	42000	5786	13.8	NO	YES
10	offboard	14000	724	5.2	YES	YES
10	booster	35000	2764	7.9	YES	YES

5 Conclusion

The results show the feasibility of Ice Thermal Energy Storage (TES) and vaporizer cooling concepts for different drivetrain configurations. For offboard and booster propulsion, Ice Storage TES is feasible if the cooling system is allowed to occupy up to 10% of vehicle mass.

For onboard propulsion, the low gravimetric power and energy density of TES limits feasibility. In these cases, a Vaporizer or Sublimator, with infrastructure-based condensers, must supplement or replace the TES. The TES is calculated with ice cubes of 1 cm side length, providing 6 cm^2 surface area per cube. This high surface-to-volume ratio favors fast system response but limits storage capacity. Given the mostly static thermal loads with moderate peaks, capacity dominates sizing, making system mass and energy density the driving requirement.

Only the onboard propelled vehicle operating in a 1 mbar environment must rely on sublimation as the primary cooling method. All other drivetrain concepts can be effectively cooled using high TRL 6/7 solutions such as the Ice Storage TES or Vaporizer, both of which offer relatively simple and efficient implementation.

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References

1. Ramboll, TIS, CERTH, SINTEF: Fact-finding study on options for the possible further support of the European Hyperloop sector (2025)
2. Wit, F.L.D., Terpstra, T.: Conceptual feasibility study of hyperloop vehicle thermal management systems. In: Proceedings of the European Hyperloop Week, Edinburgh (2023)
3. Pareschi, G., Ehwald, J., Leng, N., Beckert, P., Guo, B.: Potential Analysis for Vacuum Transport Technologies in Public Transport in Switzerland, Bern (2023)
4. Horvath, B.L., Wells, D.P.: Comparison of aircraft conceptual design weight estimation methods to the flight optimization system. In: Proceedings of the 2018 AIAA Aerospace Sciences Meeting, Florida (2018)
5. Häusler, M.: Cooling Concept for Hyperloop Pod Prototypes, Horw (2019)
6. Aebersold, T.: Phase Change Cooling for Low-Pressure Applications, Zurich (2023)
7. Kälin, M.: Assessment of Heat Management Strategies for Hyperloop Pods, Zurich (2024)
8. Kooger, B.J., Spek, G.: Cooling system for a transportation system arranged to be transported in a low-pressure environment. WO 2022/119439 A1 (2022)
9. Chang, K., Wang, Y., Li, Y.: A review of water sublimation cooling and water evaporation cooling in complex space environments. Prog. Aerosp. Sci. **140**, 100930 (2023)
10. Estermann, P., et al.: Experimental characterization of a direct contact latent cold storage with ice. Energies. **18**, 4290 (2025)

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From Diesel to Fuel-Cell Powertrains, A Virtual Retrofit Use Case for Buses and Airport Ground Service Vehicles

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Abstract. Vehicle fleet decarbonization through electrification and alternative fuels such as hydrogen (H_2) is a key strategy for CO_2 emissions reduction from road transport. H_2-powered vehicles are expected to have a significant impact when integrated into a complete H_2 ecosystem like hydrogen valleys. This study evaluates the transition of the vehicle fleet (buses and airport's ground service vehicles) in the vicinity of Malpensa Airport from conventional to H_2-fuelled powertrains using a combined experimental and computational approach. Fuel consumption of the vehicles is obtained via real world data recording, while the respective simulation models are developed to represent the vehicles' powertrain configuration. To achieve this, all the sub-models are parametrized using the technical specifications of each vehicle. The simulation models are evaluated by comparing calculation results with experimental data. These models are used as a basis for virtual retrofitting with fuel-cell systems. Results demonstrate the potential from switching to H_2-fuelled powertrains, highlighting the reduction of tailpipe pollutants and CO_2 emissions that ranges between 35% and 93% depending on the emissions from H_2 production process.

Keywords: fuel cell vehicles · retrofit · hydrogen valley · environmental impact · vehicle simulation

1 Introduction

Decarbonization is a key objective of the European Union, which aims to achieve carbon neutrality by 2050 [1]. The EU has set ambitious targets for reducing CO_2 emissions from road transport. Electrification and the use of alternative fuels like hydrogen (H_2) are key strategies for achieving emission targets. Green hydrogen [2] offers the greatest potential for reducing CO_2 emissions, as its production does not generate CO_2, unlike other hydrogen pathways [3]. Although passenger cars and commercial vehicles with hydrogen-fuelled powertrains still represent a small share of the European market, they

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have strong potential to contribute to transport sector decarbonization [4–7]. A major factor driving the adoption of H_2-powered vehicles is the expansion of infrastructure and the addition of refueling stations [8]. According to the European Alternative Fuels Observatory [9], in 2024 there is an increase in the number of the refueling points in Spain, France, Germany, Sweden, Poland and the Netherlands, compared to 2023. To promote H_2 adoption, the European Union has funded projects establishing hydrogen valleys in strategic regions. The TH2ICINO project, a European initiative, aims to establish a Hydrogen Valley and H_2 ecosystem near Malpensa Airport. With transportation identified as a primary H_2 consumer, this paper focuses on evaluating the benefits and impacts of transitioning vehicle fleets from conventional fuels to hydrogen. It details the approach used to estimate H_2 demand for various vehicle types operating in the area, with special attention to retrofitting [10–13] of buses and airport ground service vehicles. While many studies focus on retrofitting combustion engines, this work centers on fuel cell systems with the potential for zero tailpipe emissions. The analysis uses simulation to demonstrate and quantify the emissions reduction benefits of replacing conventional vehicles with H_2-powered models.

2 Methodology

The methodology applied in the current paper is based on a combined experimental and computational approach. As a first step, an initial mapping of the available vehicles from the buses and the airport ground service vehicles is performed. The goal of this mapping is to identify the best candidate vehicles that will be part of the evaluation. Following the screening of the vehicles, all technical specifications and necessary data are gathered from vehicles' operators, owners and OEMs' publicly available sources (i.e. websites, brochures, etc.). These data are used for the development and parametrization of the respective vehicle simulation models. The simulation models' accuracy is evaluated using experimental data, obtained during the normal operation of the vehicles. Based on the experimental data, representative mission profiles (velocity and road grade) as well as typical operating conditions were also derived.

2.1 Vehicles Used in the Study and Experimental Data

The study focused on two vehicles: a bus operating a round trip between Malpensa Airport and Milan, and an Ambulift used to transport passengers between the terminal and aircraft. The bus, selected as the most representative from its fleet, is a conventional coach equipped with a 12.4 l diesel engine producing up to 450 hp, and can carry up to 61 passengers. The Ambulift is a specialized vehicle designed for the assistance and transport of passengers with reduced mobility [14]. It features a passenger cabin and cockpit mounted on a hydraulic lifting system, all built on a four-wheel chassis. A diesel engine powers both the vehicle, the hydraulic mechanism, and the HVAC system for cabin comfort.

The initial part of the analysis focuses on evaluating vehicle performance based on data collected during regular operations. All the vehicles considered in this study are

equipped with a monitoring system integrated with the telematics system of the respective fleet operator or owner, enabling real-time tracking of vehicle location, velocity and fuel consumption. Data were collected over a sample period, focusing on measurements that best represent typical vehicle usage and operating conditions. As regards the bus, a complete round trip between the origin and destination was considered, to extract the mission profile and the fuel consumption over the complete trip. The trip included driving in motorways, rural and urban areas, with increased traffic. Based on historical data, 30 passengers are transported per direction on average, a value selected as representative of this use case. Daily operational data for the Ambulift were collected via a telematics system monitoring ground service equipment. Representative conditions were established from samples over an extended period, encompassing different times of the year to capture both ICE and HVAC operation. The Ambulift typically operates at low velocities (below 30 km/h) with frequent, prolonged idle times, where the ICE often remains running to power auxiliaries and the air conditioning system while waiting for passengers. During the lifting process, the ICE operates at a specific point to meet the hydraulic system's power demand for raising the cabin. The Ambulift also frequently waits at standstill without the ICE running. The telematics dataset collected covered several weeks, including the vehicle's position, velocity, and indications of these operating states.

2.2 Simulation Model Development

The study's second stage uses simulation models built in GT-SUITE to compare the diesel bus and Ambulift with their H_2-fuelled versions, starting with a standard layout for conventional vehicles. The template was then adjusted to match the layout of each vehicle. An example of the simulation model with its typical layout is presented in Fig. 1. The template model was parametrized using the technical specifications of the vehicles, including mass, frontal area, aerodynamic drag coefficient, tyre size and rolling resistance, engine specifications, gear ratios. The fuel consumption map and drivetrain efficiency maps were calibrated to ensure that the simulated results matched the measured fuel consumption. The following step was the definition of the equivalent H_2-fuelled simulation models of the vehicles considered in the study. For this study, the H_2-fuelled equivalent vehicles considered as fuel cell electric vehicles (FCEVs). The literature identifies plug-in hybrid and simple hybrid fuel cell vehicles as the most common FCEV powertrain layouts. Both configurations share the same architecture, with a fuel cell stack being the main component used as a power source [5, 15]. The fuel cell stack supplies electric power to the traction motor and wheels, while a parallel high-voltage battery serves as an energy buffer, supporting propulsion, regenerative braking, and excess fuel cell output. The energy management system optimizes efficiency. Plug-in hybrids are distinguished by greater battery capacity, enabling extended electric operation from grid charging. For this study, H_2-fuelled vehicles were modeled as simple fuel cell hybrids, using a fuel cell system and electric machine sized to meet the vehicles' energy and power requirements. The H_2-fueled bus was simulated with a 100 kW nominal power fuel cell stack, an electric machine with 200 kW maximum power and a high voltage battery of 40kWh [16–18]. The Ambulift was modeled with a 25 kW fuel cell stack, a60 kW electric motor, and a 15kWh high-voltage battery, using the same simulation

platform and a corresponding model layout (Fig. 1). The main components of the models are highlighted and number in Fig. 1. Component (1) models the simulated vehicle, using input specifications like dimensions, frontal area, aerodynamic drag, mass, and load. The driver (2) component simulates the driver's behavior, consistently striving to match the target velocity as closely as possible. The engine and its control unit (3) are modeled as a map-based component, using engine characteristic curves (full load and motoring), engine specifications (displacement and fuel type), and a fuel consumption map (FC) as main inputs. The actual FC maps were not available, hence the generic methodology presented in [19] was applied to derive them. The drivetrain system (4) models the vehicle's wheels, brakes, final drive, gearbox, and clutch. Key inputs include tire rolling resistance, wheel size, and gearbox/final drive ratios and efficiency (as a constant or map). The mission profile (5), including target speed and road gradient, is directly derived from measured data. The electric machine (6) simulates the motor/generator with integrated inverter, using the efficiency map and full load curve as inputs. The fuel cell stack (7) models the fuel cell system and its auxiliary components, such as the compressor and controls. The high-voltage battery (8) is represented by an equivalent circuit, with inputs including nominal capacity, internal resistance, and open-circuit voltage as a function of state of charge. The energy management system (EMS) (9) employs a rule-based algorithm to coordinate fuel cell and battery operation, adapted from established ICE hybrid and FCEV EMS methodologies [7, 20–23].

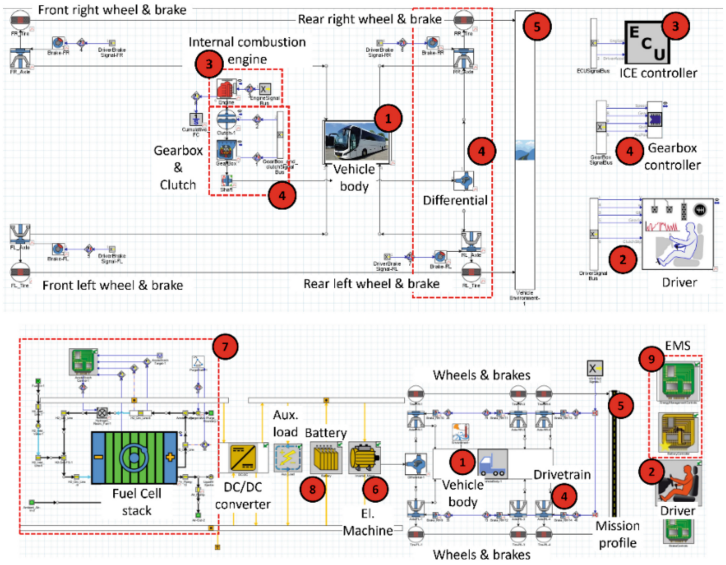


Fig. 1. Simulation model layout for the conventional, diesel fueled vehicles (upper part of the picture) and the fuel cell hybrid H_2-fuelled vehicles (lower part of the picture) (arrows coloring, black: mechanical connections, yellow: electrical connection, bold black: air/fluid pathways/pipes, blue: control/data exchange pathways/signals)

3 Results and Discussion

3.1 Experimental Data Analysis Results

Bus monitoring data included velocity time series for both directions of the round trip and recorded fuel consumption. The total distance was 105 km (53 km and 52 km each way), with an average speed of 45–48 km/h. The round trip took about 3 h (1 h driving and 30 min waiting time per direction) and fuel consumption ranged from 13 to 16 l (about 142 l of diesel for 5 roundtrips per day). The bus typically operates for roughly 16 h daily. For the Ambulift, four main operating states were identified, described as follows; (1) Vehicle at standstill with engine off, (2) Vehicle at standstill with engine on, (3) Vehicle at standstill with engine on and loaded during lifting/lowering process, (4) Vehicle moving. On a typical day, the Ambulift operates for about 21 h and uses roughly 28 l of fuel. The vehicle spends 51% of the time stationary with the engine off, 38% at standstill with the engine running (including idle and lifting operations), and 11% in motion, averaging 27 km per day at 12 km/h. An example of the bus mission profile and the share between the different operating states for the Ambulift for an average day, are presented in Fig. 2.

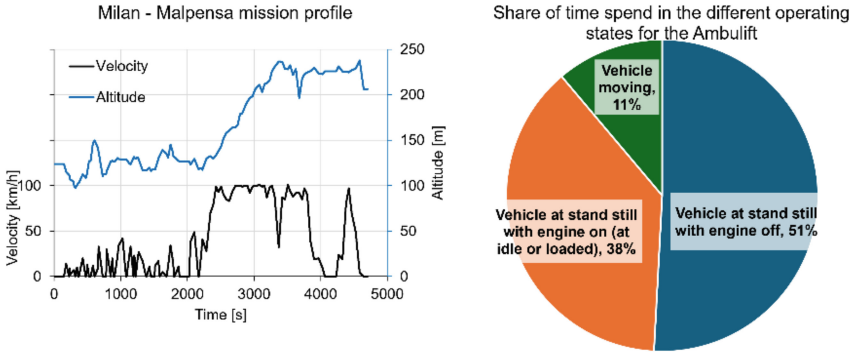


Fig. 2. Mission profile for the Milan–Malpensa trip and share of the time spent under the different operating states for the Ambulift during an average day

3.2 Simulation Results – Model Verification and Application

To assess the accuracy of the simulation models, calculated fuel consumption was compared to actual measurements from vehicle monitoring. Table 1 summarizes the results for both the Milan–Malpensa round trip and typical Ambulift daily operation. The difference between measured and simulated values is within ±10%, showing that the models reliably replicate vehicle performance and energy demand under real-world conditions. This demonstrates that the fuel cell models, developed from conventional simulation models, can accurately forecast energy and H_2 requirements for these scenarios. The calculated H_2 daily demand for the bus is 22.6 kgH_2/day and the Ambulift is 4.1 kgH_2/day. Figure 3 illustrates the comparison of the WtW CO_2 emissions for the diesel (3.23

$\left[kg_{CO_2}/l_{diesel}\right]$) and H_2-fuelled vehicles, considering a best (11.9 $\left[g_{CO_2}/MJ_{fuel}\right]$ Compressed Hydrogen via methane cracking) and worst (109.4 $\left[g_{CO_2}/MJ_{fuel}\right]$ Compressed Hydrogen produced with EU-mix piped natural gas supply) case scenario for the CO_2 emissions from H_2 production [24]. Estimated CO_2 emissions show that switching from diesel to H_2 fuel cell powertrains can reduce emissions by 35% to 93%, depending on the hydrogen production method. Additionally, total energy demand decreases by 14% to 20%, based on application and operating conditions.

Table 1. Comparison between simulated and measured fuel consumption

	Measured fuel [l]	Simulated fuel [l]	Difference [%]
	(per trip for the bus & per day for the Ambulift)		
Bus Milan–Malpensa	16	14.7	−7.9%
Bus Malpensa–Milan	13	13.7	5.7%
Ambulift avg. day	27.8	26.8	−3.7%

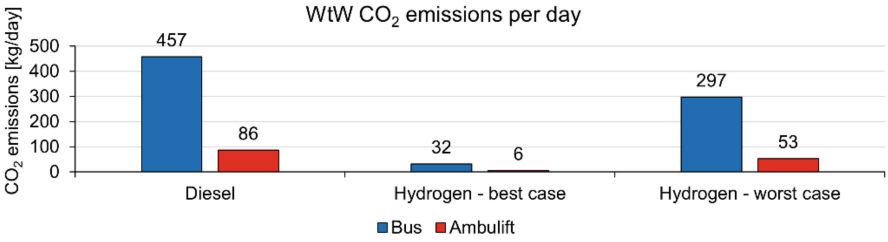


Fig. 3. Comparison of the WtW CO_2 emissions between diesel and H_2 fueled vehicles

4 Summary and Conclusions

This paper outlines the process of estimating hydrogen demand and the expected benefits of converting conventional diesel-powered vehicles to fuel-cell hydrogen powertrains. Simulation models for a bus and an Ambulift were developed using available experimental data, and their prediction accuracy was checked by comparing calculated and measured fuel consumption under typical operating conditions. The uncertainty in diesel and hydrogen consumption estimates is about ±10% but could be reduced to less than ±5% if models are parametrized with actual component specifications rather than generic data. Using these models, hydrogen-powered versions were created to predict daily hydrogen demand. The comparison of Well-to-Wheel (WtW) CO_2 emissions shows a substantial reduction up to 93% with fuel cell applications, and CO_2 emissions could reach zero if hydrogen is produced from fully renewable sources. Retrofitting a significant portion of

the fleet with hydrogen powertrains would achieve considerable decarbonization, though refueling, especially for ground service equipment operating only on the air side, remains a key challenge. This underscores the need for an airport hydrogen refueling station. The methodology can be extended to other vehicle types and used to assess entire fleets. Furthermore, these findings support a broader technoeconomic analysis for transitioning to hydrogen-fueled vehicles.

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References

1. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en. Accessed 25 Sep 2025
2. Hydrogen Europe.: https://hydrogeneurope.eu/. Accessed 25 Sep 2025
3. Wei, Q.S., Zhang, X., Oh, B.S.: The effect of driving cycles and H2 production pathways on the lifecycle analysis of hydrogen fuel cell vehicle: a case study in South Korea. Int. J. Hydrog. Energy. **46**, 7622–7633 (2021). https://doi.org/10.1016/j.ijhydene.2020.09.024
4. Brancaleoni, P.P., Damiani Ferretti, A.N., Corti, E., Ravaglioli, V., Moro, D.: Lifecycle CO2 analysis for urban emission reduction of hydrogen-fuelled and battery electric buses in the European Union current and future energetic scenarios. Int. J. Hydrog. Energy. **123**, 335–353 (2025). https://doi.org/10.1016/j.ijhydene.2025.03.397
5. Halder, P. et al.: Performance, emissions and economic analyses of hydrogen fuel cell vehicles. Renew. Sust. Energ. Rev. **199**, 114543 (2024). https://doi.org/10.1016/j.rser.2024.114543
6. Peiretti Paradisi, B. et al.: A techno-economic life cycle assessment of H2 fuelled and electrified urban buses. Appl. Energy. **401**, 126738 (2025). https://doi.org/10.1016/j.apenergy.2025.126738
7. Taghizad-Tavana, K., Ghanbari-Ghalehjoughi, M., Safari, A., Hagh, M.T., Nezhad, A.E.: From green hydrogen production to artificial intelligence–driven energy management in hydrogen fuel cell electric vehicles: a comprehensive review of technologies, optimization techniques, international standards, and investment programs. Appl. Energy. **399**, 126534 (2025). https://doi.org/10.1016/j.apenergy.2025.126534
8. Lee, H., Kim, A., Lee, A., Lee, B., Lim, H.: Optimized H2 fueling station arrangement model based on total cost of ownership (TCO) of fuel cell electric vehicle (FCEV). Int. J. Hydrog. Energy. **46**, 34116–34127 (2021). https://doi.org/10.1016/j.ijhydene.2021.08.012
9. European Alternative Fuels Observatory.: https://alternative-fuels-observatory.ec.europa.eu. Accessed 25 Sep 2025
10. Bibiloni-Ipata, S., Vielmo-Cogo, V., Frizzo-Prante, G., Martinez-Boggio, S.: Design and study of the effects of retrofitting diesel engines in hydrogen trucks through simulation. Int. J. Hydrog. Energy. **163**, 150806 (2025). https://doi.org/10.1016/j.ijhydene.2025.150806
11. Oktar, H.E., Tonyali, I.H., Apaydin, A.H.: A cost-effective and sustainable path to a green future: retrofitting internal combustion engines for hydrogen fuel utilization. Int. J. Hydrog. Energy. **143**, 969–977 (2025). https://doi.org/10.1016/j.ijhydene.2024.12.240

12. Hausmann, J., Kampker, A., Kemperdick, T., Letmathe, P.: An economic and environmental analysis of retrofitted fuel cell electric heavy-duty trucks. Appl. Energy. **399**, 126455 (2025). https://doi.org/10.1016/j.apenergy.2025.126455
13. Napoli, G., Scardino, A.S., Costanzo, L., Micari, S.: An evaluation of opportunities arising from hydrogen retrofitting of commercial vehicles in urban areas: a case study. World Electr. Veh. J. **17**, 91 (2026). https://doi.org/10.3390/wevj17020091
14. Arcidiacono, G., Giorgetti, A., Pugliese, M.: Axiomatic design to improve PRM airport assistance. Procedia CIRP. **34**, 106–111 (2015). https://doi.org/10.1016/j.procir.2015.08.012
15. Ajanovic, A., Glatt, A., Haas, R.: Prospects and impediments for hydrogen fuel cell buses. Energy. **235**, 121340 (2021). https://doi.org/10.1016/j.energy.2021.121340
16. Li, H., Guo, H., Yousefi, N.: A hybrid fuel cell/battery vehicle by considering economy considerations optimized by converged barnacles mating optimizer (CBMO) algorithm. Energy Rep. **6**, 2441–2449 (2020). https://doi.org/10.1016/j.egyr.2020.09.005
17. Collin, A., Kumar, V.B., Karthikeyan, S., Sankar, M.G.: The performance of a 100 kW proton exchange membrane fuel cell designed for truck applications. Next Energy. **5**, 100167 (2024). https://doi.org/10.1016/j.nxener.2024.100167
18. Zembi, J., Cinti, G., Battistoni, M.: Simulation of a City bus vehicle: powertrain and driving cycle sensitivity analysis based on fuel consumption evaluation. Vehicles. **7**, 93 (2025). https://doi.org/10.3390/vehicles7030093
19. Zacharof, N., Tansini, A., Prado Rujas, I., Grigoratos, T., Fontaras, G.: A Generalized Component Efficiency and Input-Data Generation Model for Creating Fleet-Representative Vehicle Simulation Cases in VECTO (2019). https://doi.org/10.4271/2019-01-1280
20. Yu, P., Li, M., Wang, Y., Chen, Z.: Fuel cell hybrid electric vehicles: a review of topologies and energy management strategies. World Electr. Veh. J. **13**, 172 (2022). https://doi.org/10.3390/wevj13090172
21. Zacharof, N. et al.: A simulation model of the real-world fuel and energy consumption of light-duty vehicles. Front. Future Transp. **5**, 1–21 (2024). https://doi.org/10.3389/ffutr.2024.1334651
22. Zheng, W., Ma, M., Xu, E., Huang, Q.: An energy management strategy for fuel-cell hybrid electric vehicles based on model predictive control with a variable time domain. Energy. **312**, 133544 (2024). https://doi.org/10.1016/j.energy.2024.133544
23. Pla, B. et al.: Optimal control of the power split for a fuel cell vehicle considering air path dynamics. IFAC-PapersOnLine. **59**, 91–96 (2025). https://doi.org/10.1016/j.ifacol.2025.07.087
24. Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R.: JEC Well-to-Wheels Report v5, EUR 30284 EN. Publications Office of the European Union, Luxembourg (2020), ISBN 978-92-76-20109-0). https://doi.org/10.2760/100379JRC121213

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Standard Identification and Drive Cycle Definition for Battery Systems of Non-Common Applications: Off-road, Marine and Stationary

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Abstract. Lithium-ion batteries are being used everywhere in a great variety of applications. There are some mayor applications such as the ones related to road transportation which have consolidated and well-known standards and regulations to guide battery designers. Nonetheless, the design standards and regulations of battery systems for non-common applications such as off-road vehicles, maritime type vessels or stationary applications are either generic from road transportation applications or simply unknown. Consequently, a study of standards for non-common three use cases has been performed. The performed study collects and classifies the most interesting standards that will guide battery system and sub-system designers on the development of battery systems for off-road use cases, marine use cases and stationary use cases. In addition to this, representative electric power profiles for each of these three non-common use cases are presented as alternatives to he well-stablished standardized driving cycles. As result, a list of standards that will guide battery system and sub-system designers have been provided along with a driving cycle that captures properly the characteristics electrical stresses of each of these non-common applications.

Keywords: Standards · Battery system design · Off-road · Marine · Stationary

1 Introduction

The battery systems based on lithium-ion batteries (LIB) are expanding. Day by day, the number of applications that integrate LIB increases. The most common applications have been used to define generic regulations that assist in defining the design specifications of the battery systems of these common application such as the UN Manual of Tests

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and Criteria Sect. 38.3 that focuses of the shipment safety of battery systems [1], the UN regulation No. 10 that focuses on electromagnetic compatibility of the electronic components of the battery systems [2], and the UN regulation No. 100 Rev.3 that focuses on the specific requirements (safety, electric, thermal and mechanical) for the battery system in a electric vehicle context [3]. Nonetheless, there is no widely recognized, fully homogenized or standardized specification transformed in regulation exclusively for battery systems used in non-common applications such as the 3 applications evaluated in BATSS European project: off-road (an excavator), marine (a leisure boat 90 ft), and stationary (a mobile energy storage system) [4].

The availability of a homogenized specification for battery systems in off-road excavators is limited. The market currently relies on bespoke, application-specific designs and evolving best practices rather than a unified standard. As consequence, several industry players and projects have developed their own tailored battery system specifications and solutions reflecting the unique demands of off-road applications like excavators instead of following available standards [5, 6].

Similarly, there is no single homogenized and universally standardized specification exclusively for battery systems used in marine applications. However, several key frameworks, guidelines, and modular standardized systems exist that collectively address the requirements for marine battery systems with a focus on safety, reliability, certification, and configurability [7, 8].

Stationary battery systems are essential for energy storage in grid support, telecommunications, uninterruptible power supplies (UPS), and integration with renewable energy sources which benefit from several well-established, recognized standards that ensure safety, reliability, and performance in fixed installations [9, 10].

The authors made efforts to map out the standardization landscape focusing on three non-common LIB applications: off-road, marine and stationary applications. This paper provides a list of interesting standards to design battery systems for these three applications as well as a representative electric power profile for each of these applications. This paper will assist greatly with any system or component manufacturer of LIB that would like to certify or design their product for these three non-common applications. Besides, this paper contributes to the definition of representative electric power profiles for an excavator, a leisure boat and a mobile energy storage system.

2 Non-common Applications

The present study examines the standardization of systems and components for lithium-ion batteries (LIB) developed for three specialized applications explored in the BATSS European project: off-road (excavator), marine (90 ft. leisure boat), and stationary (mobile energy storage system). Each application features stringent requirements defined by the end user.

2.1 Marine Application

The battery pack is designed for a leisure maritime boat of 90 ft. The design must focus on providing a cycle life above 3500 cycles, fast charging capability above 2C and 700 V voltage platform with a volumetric energy density of at least 230 Wh/L.

2.2 Off-Road

The battery pack is designed for heavy-duty off-road excavators. The design must focus on providing a volumetric energy density of at least 215 Wh/L, a charging capability above 1C, 400 V platform and a cycle life around 2500 cycles.

2.3 Stationary

The battery pack is designed for a mobile energy storage system. The design is customized to allocate the designed battery packs for the off-road application. The application must focus on providing a 650 V platform, volumetric energy density of at least 170 Wh/L, a charging capability above 1C and a cycle life around 3500 cycles.

3 Dynamic Profiles

The definition of each application's electric power profile for common-use of non-common applications is challenging.

The flatness of the sea leads to quite constant common-use electric power profiles on marine applications. In this context, a whole common-use mission profile has been developed based on the final user operation definition, see Fig. 1. The power profile consists of combinations of cruise speed consumption, slow motion consumption near or inside the port, constant energy consumption at anchored moments and charge events from the grid and from diesel engines.

1. Full electric - > Navigation in full electric to get out of the port: duration 45 min.
2. Cruising speed - > Diesel engines charge the batteries: duration 1 h–3 h.
3. Full electric- > Full electric navigation in restricted area: duration 45 min.
4. Cruising speed - > Diesel engines charge the batteries. duration 1 h–3 h.
5. Enjoy time - > Ship is moored and powered only by battery: duration 6 h–12 h.
6. Cruising speed - > Diesel engines charge the batteries: duration 1 h–3 h.
7. Full electric - > Navigation in full electric to get into the port and mooring operation: duration 45 min.
8. Charge - > Shore connection for recharging: duration 12 h.

The representative electric power profile for the off-road application gathers the excavator dynamic energy consumption provided by a manufacturer of electric excavators, see Fig. 2. The power profile consists of the reduced traction movements of the excavator and continuous movement of the excavator shovel.

The representative electric power profile for the stationary application shows the use of a typical mobile energy storage system facilitated by a manufacturer of mobile energy storage systems, see Fig. 3. The typical profile over several hours has low requirements in terms of power mainly ranging between 4 to 10 kW, meaning C-rates between <0.1 up to <0.2C.

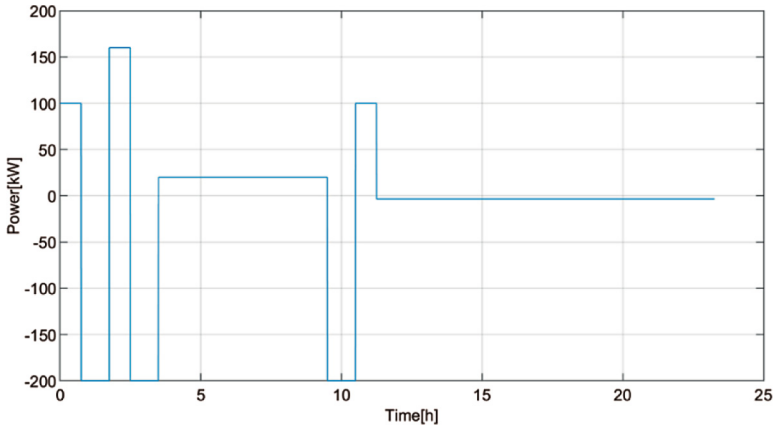


Fig. 1. Marine use case electric profile

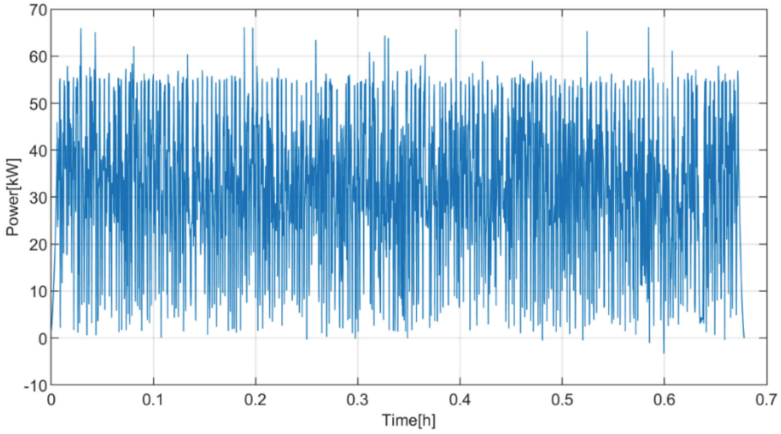


Fig. 2. Off-road use case electric profile

4 Design Standards

The standard selection for the off-road, marine and stationary applications is presented in this section. First of all, mention that the generic UN regulations (38.3, 10 and 100) are taken into account as reference. The standard selection is complementary to these three UN regulations where more specific considerations are provided to these generic regulations.

The complementary standards for the three evaluated applications are gathered in Table 1. The table contains the numbers of the identified standards. Each standard is classified, firstly, based on the system or component that is related to, such as the battery system or lithium-ion battery (LIB), the electrical and electronic components (E/E), the internet of things (IoT) device, the DC/DC, or the switch or contactor. Secondly, the standard is classified based on the field of action such as the safety design aspects, the

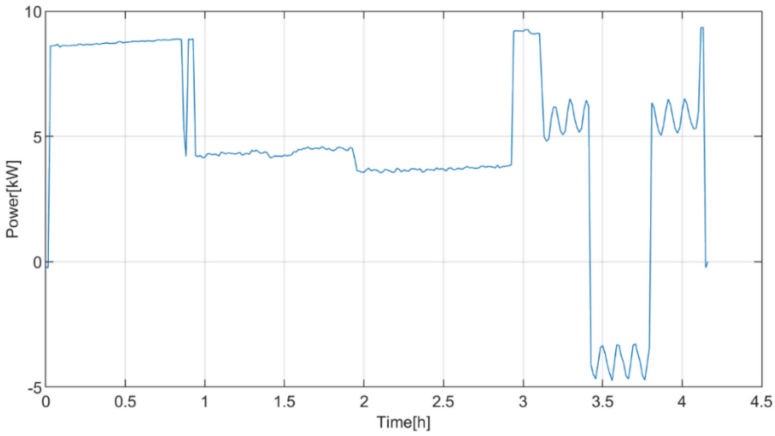


Fig. 3. Stationary use case electric profile

electric/electronic design aspects, the thermal design aspects or the mechanical design aspects. Finally, the applications affected by the norm are specified.

4.1 Safety

The generic safety standards that speak about safety requirements for secondary lithium cells (EN IEC 62619, IEC 62620, EN IEC 63056) are guidelines for any lithium-ion battery system designer. In addition to these, the generic safety standards regarding the design of electronic components and sub-systems that are integrated into battery systems (EN 61508-(1 to 7), EN IEC 62443-(3 and 4)) are mandatory to follow in any use case; and if implemented an IoT, the ISO/IEC 27400 should be added to the list.

As for specific standards that describe properly the specific characteristics of each of the evaluated non-common use cases, there are generalized safety standards for non-common transportation use cases (EN ISO 8846, EN ISO 16315). Nonetheless, these have still room for improvement to gather all the specific safety needs of the non-common transport (marine and off-road) applications. The marine application has specific safety standards related to the batteries themselves and cybersecurity to be kept with the rest of the systems in a ship (EN ISO 23625, ISO 23799). The off-road application has specific standards to speak about cybersecurity to assure a safety operation all the system lifespan (CEN ISO/TR 22100-4). For the stationary use cases, the safety characteristics of non-mobile, building type systems are collected in VDE-AR-E 2510-50.

Table 1. Standard list for off-road, marine and stationary applications

STANDARDS	SYSTEM	FIELD	APPLICATION
EN IEC 62619	LIB	Safety	Three applications
IEC 62620	LIB	Safety	Three applications

(*continued*)

Table 1. (*continued*)

STANDARDS	SYSTEM	FIELD	APPLICATION
EN IEC 63056	LIB	Safety	Three applications
EN 61508-(1 to 7)	E/E	Safety	Three applications
EN IEC 62443-(3 and 4)	E/E	Safety	Three Applications
ISO/IEC 27400	IoT device	Safety	Three applications
EN IEC 60664-1	E/E	Electric	Three applications
EN 61000-6	E/E	Electric	Three applications
IEC 60749-34	DC/DC & Switch	Electric	Three applications
ISO 21782-4	DC/DC	Electric	Three applications
IEC 60068-2-30	Any system	Thermal	Three applications
EN 60529	E/E	Mechanical	Three applications
EN 60068-2-27:2009	Any system	Mechanical	Three applications
EN ISO 8846	E/E	Safety	Off-road & Marine
EN ISO 16315	LIB	Safety	Off-road & Marine
EN ISO 23625	LIB	Safety	Marine
ISO 23799	E/E	Safety	Marine
CISPR 16-2-(1 and 3)	E/E	Electric	Marine
ISO 20653	E/E	Mechanical	Marine
CEN ISO/TR 22100-4	E/E	Safety	Off-road
ISO 16750-4:2023 (updated ISO 12405-2)	E/E	Thermal	Off-road
ISO 16750-3:2023	E/E	Mechanical	Off-road
EN 60721-3-5	LIB	Mechanical	Off-road
VDE-AR-E 2510-50	LIB	Safety	Stationary

4.2 Electric

There are generic electric related standards (EN IEC 60664-1, EN 61000-6) speaking about insulation and electromagnetic compatibility, common for any electronic device development. There are some specifically speaking of the DC/DC aspects (IEC 60749-34, ISO 21782-4), that are common for any use case.

As for the specific standards in terms of electric aspects, the generic ones are enough to describe stationary and off-road use cases. Nonetheless, the marine application is more complex due to the radio communications. The standards CISPR 16-2-(1 and 3) focus on how to measure radio interferences in a ship.

4.3 Thermal

There is a generic standard, the IEC 60068-2-30, that defines procedures for testing the resistance of systems and sub-systems to cyclic humid heat conditions.

As for non-common use cases, the ISO 16750-4:2023 (updated ISO 12405-2) defines the requirements of the tests and environmental conditions that the sub-systems and systems can be exposed in off-road applications.

The fact is that there is not a universal battery thermal management system (BTMS) that can be used in any battery system, and there are few standards to assist on the design of a BTMS, indifferent to the use case.

4.4 Mechanical

There are generic mechanical standards for battery systems and electronic components in any use case (EN ISO 8846, EN 60068-2-27:2009).

As for stationary use cases, they are expected not to require mechanical requirements apart from the structural ones. Therefore, generic ones are considered enough. Marine and off-road use cases, on the other hand, have specific needs. Marine use cases have specific needs regarding the IP (ISO 20653) due to the possibility of being exposed to water. Off-road use cases have specific needs regarding the heavy mechanical vibrations and harsh environmental operative conditions they experience. There are some standards speaking about it (ISO 16750-3:2023, EN 60721-3-5), but still there is a need to further work on it.

5 Conclusions

The design process of battery components and systems for uncommon applications suffer from a lack of regulation. This paper gathers intel on the standardization landscape of battery system design standards for marine, off-road and stationary applications, providing a detailed list of standards and a representative electric power profile for a specific use case of these three types of applications: an excavator for the off-road application, a hybrid leisure boat for the marine application and a mobile energy storage system for the stationary application.

The generated standard list shows that there are several universal standards to design the different components and systems inside a battery system for the evaluated applications. The generated list also shows that there are some specific standards addressing specific requirements of these uncommon applications, however there is still need of further standardization for uncommon applications in terms of mechanical and thermal aspects. This paper aims to assist with regulation definition by identifying the already available standards that can respond to the specific requirements of these three uncommon applications and show potential standardization activity.

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References

1. United nations: Recommendations on the Transport of Dangerous Goods: Manual of Tests and Criteria, Part III, Subsection 38.3: Lithium Metal and Lithium Ion Batteries, New York (2023)
2. United Nations Economic Commission for Europe: Regulation No. 10 – Uniform Provisions Concerning the Approval of Vehicles with Regard to Electromagnetic Compatibility, Geneva (2019)
3. United Nations Economic Commission for Europe: Regulation No. 100 – Uniform Provisions Concerning the Approval of Vehicles with Regard to Specific Requirements for the Electric Power Train, Geneva (2022)
4. Ruiz, V., Pfrang, A., Kriston, A., Omar, N., Van den Bossche, P., Boon-Brett, L.: A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles. Renew. Sust. Energ. Rev. **81**, 1427–1452 (2018). https://doi.org/10.1016/J.RSER.2017.05.195
5. Un-Noor, F., et al.: Off-road construction and agricultural equipment electrification: review, challenges, and opportunities. Vehicles. **4**(3), 780–807 (2022). https://doi.org/10.3390/VEHICLES4030044
6. Mirza, A.Y.: A review of key technology enablers and challenges in megawatt scale on-road and off-road transportation electrification. In: 2024 IEEE Transportation Electrification Conference and Expo, ITEC 2024, Rosemont (2024). https://doi.org/10.1109/ITEC60657.2024.10599054
7. Rasul, M.J.M.A., Kim, J.: Comprehensive review and comparison on battery technologies as electric-powered source in marine applications. J. Energy Storage. **88**, 111509 (2024). https://doi.org/10.1016/J.EST.2024.111509
8. Chin, C.S., Xiao, J., Ghias, A.M.Y.M., Venkateshkumar, M., Sauer, D.U.: Customizable battery power system for marine and offshore applications: trends, configurations, and challenges. IEEE Electrif. Mag. **7**(4), 46–55 (2019). https://doi.org/10.1109/MELE.2019.2943977
9. Hildebrand, S., Eddarir, A., Lebedeva, N.: Overview of Battery Safety Tests in Standards for Stationary Battery Energy Storage Systems. Publications Office of the European Union (2024). https://doi.org/10.2760/08079
10. Hesse, H.C., Schimpe, M., Kucevic, D., Jossen, A.: Lithium-ion battery storage for the grid-a review of stationary battery storage system design tailored for applications in modern power grids. Energies. **10**(12), 2107 (2017). https://doi.org/10.3390/EN10122107

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Improving Zero-Emission Heavy-Duty Vehicles by Modular Distributed Battery-Electric Powertrains

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Abstract. A consortium of OEMs, logistics providers, and R&D organizations initiated the EU-funded ZEFES project to advance zero-emission heavy-duty long-haul transport. It will demonstrate heavy-duty battery-electric and fuel cell vehicles as replacements for ICE vehicles in daily operation. ZEFES implements a distributed powertrain that boosts efficiency and adapts to varying mission demands for range and power, integrating battery-electric prime movers with an electrified trailer or converter dolly. This paper analyzes the dimensioning of the battery-electric powertrains distributed between towing vehicle and trailer, and provides an overview of the vehicle portfolio and logistics missions. It focuses on simulation-based verification of vehicle performance, overall range, and use-case compatibility, using aligned assumptions and a generic e-trailer operation strategy. Results for a truck-dolly-semitrailer (EMS1) combination highlight the distributed powertrain's advantages and dependencies on vehicle configuration, driving profiles, battery capacity distribution, and operational strategies.

Keywords: ZE freight transport · BE trucks · electrically powered semitrailer

1 Introduction

To meet Europe's CO2 reduction targets, battery-electric systems are a promising technology with zero local emissions, also for long-haul applications. Still, the application of the technology currently faces limitations. Battery-electric vehicles (BEV) require high energy capacity for long distances and demanding route topography. Charging either takes several hours or faces a series of challenges in terms of battery technology and life, requirements to the power grid and economic considerations. Charging infrastructure is not available in sufficient quantities with balanced geographic coverage. Integration of large energy storage systems is not suitable due to high costs, high weight at the expense of payload [1]. Production of larger batteries negatively influences the CO2 footprint. To overcome these limitations, different concepts for range-extension were investigated in R&D projects and in the industry, including back-up range extenders [2], battery swapping systems ([3, 4]), and semitrailer with a battery-electric drivetrain

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([5–9]). Within the ZEFES project, the latter is now introduced to daily operation by implementing a modular multi-powertrain concept in various heavy-duty long-haul vehicle combinations. The paper presents the vehicle and powertrain specifications of the battery-electric vehicle units. Based on the use cases, the relevant vehicle categories, and the vehicle requirements defined in the beginning of the project, the vehicle and powertrain parameters are defined by the manufacturers and tier one suppliers. Three use cases demonstrate three different vehicle combinations with modular multi-powertrains consisting of three battery-electric towing vehicles, two electrified semitrailers and one electrified converter dolly. The vehicle specifications provided by the manufacturers are validated via simulation-based assessments of performance, overall range, and suitability for planned missions.

2 Vehicle Portfolio

OEMs, trailer suppliers, and shippers jointly proposed vehicle concepts to meet use-case needs. Three use cases apply modular distributed powertrains to existing cross-border flows currently run with conventional internal combustion engine (ICE) vehicles (see Fig. 1).

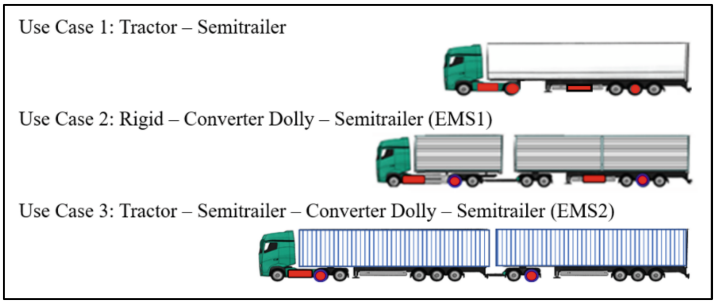


Fig. 1. Vehicle combinations with modular powertrain, driven axles indicated in red

Use case 2, which is presented in more detail in the following chapters, represents a transport flow of parcels operated on the Rhine-Alpine corridor between Munich (DE) area and Eindhoven (NL) area. The distance of a one-way trip is about 675 km. The parcels are transported in three swap bodies on an EMS1 vehicle combination. Because a 6x2 battery-electric rigid cannot cover the full distance, it is paired with an electrified semi-trailer to achieve the required range.

3 Verification of Vehicle Specifications

The simulations enable a first assessment of the battery-electric vehicle specifications. Therefore, the vehicle combinations are simulated with different powertrain configurations and load conditions on varying mission profiles. The paper only presents the results of the EMS1 vehicle combination and the respective use case. Details about the other vehicle combinations can be found in [10].

3.1 Objectives and Specifications

The vehicle specifications are verified according to the objectives and verification criteria defined in the ZEFES project. The main objectives are to advance modular heavy-duty battery-electric vehicles by developing concepts with enhanced energy storage and e-axles distributed between the prime mover and trailer units. Besides several powertrain-related Key Performance Indicators that enable an assessment of the total efficiency of the vehicles, an electrified trailer provides range extension beyond the prime mover's range. To maximize the range extension, one sub-objective is an optimized overall operational strategy of the powertrains that fully utilize the e-trailer's battery capacity. A measurement campaign for reference data on conventional ICE vehicles is planned, but not yet available; therefore, the simulation-based verification uses baseline vehicles comprising a battery-electric prime mover with standard trailer units. The simulations also verify the mission planning of the use cases in terms of the separation in several legs, required charging stops and charging time.

Table 1 shows the basic specifications of the units used in the EMS1 vehicle combination.

Table 1. basic specification of EMS1 vehicle combination

Prime mover chassis	FH 6x2 rigid, GVW: 28 t, GCW: 50 t
Prime mover Battery-electric Powertrain	max continuous power: 300 kW
Prime mover Energy Capacity / Range	540 kWh / 350 km average @ 44t GCW
Dolly Chassis	Standard dolly, curb weight: 2,5 t
Trailer Chassis	3 axle container semitrailer, curb/max. weight: 7,6 t / 39,0 t
Trailer Battery-electric Powertrain	max continuous power: 210 kW peak Torque: 26kN
Trailer Energy Capacity	308 kWh

3.2 Mission Profiles and Simulation Test Matrix

The vehicle combination is simulated with two driving profiles. The Vehicle Energy Consumption calculation Tool (VECTO) provides a long-haul (LH) mission profile in terms of a target speed cycle over distance (see Fig. 2, top) and a generic driver model. The simulation is conducted using the VECTO long-haul cycle (revision VECTO v3.3.11.2675, 2022-04-29) and the mission profile of the real ZEFES use case. Real world driving profiles of the specific use cases are not yet available, thus, synthetic driving profiles were generated using the following input:

– Filtered elevation and slope profiles based on SRTM (Shuttle Radar Topography Mission) data,

– Speed limits based on open street map (limited at 85 km/h),
– driver model with fixed acceleration/deceleration (0.5 m/s^2 if below speed limit, −1.0 m/s^2 if above speed limit).

The reference driving cycle is gained by simulating a battery-electric towing vehicle with a standard dolly and trailer. The resulting driving cycle (see e.g., Fig. 2, bottom) serves as target driving cycle for the modular multi-powertrain simulation. Thus, the driving performance of the reference vehicle combination is reproduced, ensuring the average speed is similar across the vehicle combinations.

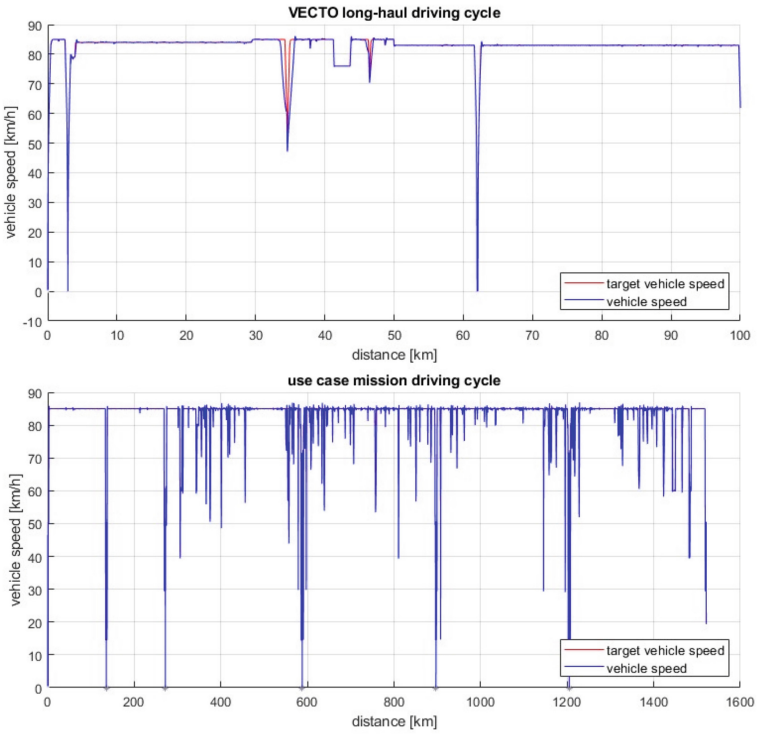


Fig. 2. Simulated speed profile of the EMS1 vehicle combination with a standard semitrailer on the VECTO long-haul mission profile and the use case mission profile

Table 2 shows the simulations that have been conducted. The simulations compare the vehicle combinations including a battery-electric towing vehicle only and the ones with an e-trailer or e-dolly. E-trailers with two installed battery capacities are considered. Depending on the requirements of the use case mission profiles the e-trailer has an installed battery capacity of 205 kWh (tractor – semitrailer with e-trailer) and 308 kWh (EMS1 with e-trailer). In case of the e-dolly only one battery capacity is used in the simulations. Ambient conditions assume 25 °C and sunshine. Within the range 0 °C - 25 °C ambient temperature minimally effects the simulation results, especially the battery performance of the model. The model assumes a good isolation of the battery,

such that it reaches a good operating temperature very fast even under low ambient temperatures. Air conditioning of the driver compartment is deactivated due to lack of data.

The simulations are varied in terms of payload (empty/full). In an initial simulation step the operational strategy of the e-trailer is investigated with respect to its influence on the use of the vehicles' battery capacities and the progress of its state of charge (SOC) over time. The operational strategies result in a minimum, medium and maximum support of the towing vehicle by the e-trailer. The relative power of the e-trailers powertrain depends on the tractive force in the kingpin, the acceleration/deceleration of the vehicle combination, and the road inclination. Details about this investigation can be found in [10].

Table 2. Driving cycles used for the simulation of vehicle combinations including an e-trailer/e-dolly with different installed battery capacity

Vehicle combination	ID	Installed battery capacity of e-trailer/e-dolly			
		None	205 kWh	308 kWh	73,5 kWh
Tractor - semitrailer	PTC1	VECTO LH	VECTO LH	–	–
	PTC2	Use Case 7.3.1	Use Case 7.3.1	–	–
EMS1	PTC3	VECTO LH	–	VECTO LH	–
	PTC4	Use Case 7.2.4	–	Use Case 7.2.4	–
EMS2	PTC5	VECTO LH	–	–	VECTO LH
	PTC6	Use Case 7.2.3	–	–	Use Case 7.2.3

4 Simulation Results

The presented simulation results cover only the EMS1 vehicle combination (PTC3 and PTC4). Results for other configurations appear in [10]. Cargo weight of each vehicle combination is similar independent from the powertrain configuration and the resulting empty vehicle weight. When using an e-trailer, the gross combination weight is increased by 2,500 kg due to the additional battery-electric powertrain including the energy storage unit. All driving cycles start with fully charged energy storage units.

For the VECTO long-haul cycle, both the e-trailer and non-e-trailer configurations are fully loaded with 22,300 kg, resulting in total weights of 45,500 kg and 48,000 kg, respectively. The VECTO long-haul driving cycle is repeated until the energy storage of the towing unit reaches the lower limit of its SOC.

Table 3. Simulation results of EMS1 vehicle combinations on the VECTO long-haul cycle, maximum cargo weight 22,300 kg

ID	Powertrain configuration (PTC)	Total distance [km]	Recuperated energy [kWh]	Tractor		Semitrailer	
				Total energy consumption [kWh]	min. SOC [%]	Total energy consumption [kWh]	min. SOC [%]
PTC3	EMS1 BEV	277.6	−72.89	477	6	–	–
PTC4	EMS1 BEV + e-trailer	356.7 (+28.5%)	−97.56	475	6	174	41

The combination of battery energy capacity in the vehicle units and the distribution of cargo weight between the rigid and the e-trailer does not enable the e-trailer to use its whole energy content before the energy storage of the rigid reaches the lower limit of its SoC. The total distance reached by the vehicle combination is increased by 79.1 km (+28.5%) by using the e-trailer (see Table 3), resulting in an increases amount of recuperated energy of 24.67 kWh (+33.8%). 9.86 kWh were shifted from the towing vehicle (rec. energy: 63.03 kWh) to the e-trailer (rec. energy: 34.53 kWh). Therefore, recuperative braking of the e-trailer can also be used as a parameter in the operational strategy to balance battery energy across both units.

The use case mission is split into several legs, each leg starting with fully charged batteries. This reflects the planning of charging stops at the time this paper was finalized. Later, OEMs/shippers will define detailed stop timings. Due to eventually limited stop time the batteries are not necessarily fully charged. The amount of transferred energy is mainly influenced by charging power and the electric and thermal behaviour of the energy storage. In the use case the vehicle combination with and without e-trailer is driving with a slightly reduced weight of cargo (18,300 kg), resulting in a total vehicle weight of 41,500 kg and 44,000 kg, respectively. Table 4 summarizes the simulation results of both powertrain configurations, with leg-by-leg comparison. Notably, the configuration without the e-trailer cannot complete several legs (marked red).

Table 4. Simulation results of EMS1 vehicle combinations on the use case mission, cargo weight 18,300 kg

Leg of use case mission	ID	Total distance [km]	Recuperated energy [kWh]	Tractor Total energy consumption [kWh]	min. SOC [%]	Semitrailer Total energy consumption [kWh]	min. SOC [%]
Neuss – Oirschot	PTC3	135.3	5.70	213.8	57	-	-
	PTC4	135.3	5.76	170.2	65	64,0	77
Oirschot – Neuss	PTC3	136.4	5.79	221.6	55	-	-
	PTC4	136.4	5.71	175.2	64	67.4	76
Neuss – Wertheim	PTC3	278.6	63.85	535.6	6	-	-
	PTC4	316.3	98.12	435.8	24	232.6	32
Wertheim – Aichach	PTC3	262.5	64.68	536.4	6	-	-
	PTC4	308.8	79.79	418.5	26	234.7	30
Aichach – Wertheim	PTC3	297.8	85.94	557.4	6	-	-
	PTC4	308.1	103.67	398.6	33	216.7	39
Wertheim - Neuss	PTC3	292.4	93.12	564.3	6	-	-
	PTC4	316.3	102.64	425.4	28	221.7	37

For the vehicle combination with the e-trailer simulations with different powertrain management strategies were conducted. For the results shown in the table the e-trailer operational strategy “maximum support” was applied. Additionally, the overall traction power of the vehicle combination is limited to 600 kW (see Fig. 3). This guarantees that average speed is maintained since the additional traction power of the e-trailer is not used to follow the target speed profile more closely. Under these conditions the vehicle combination with PTC4 can complete all legs. Although the operational strategy of the e-trailer was adapted, its battery capacity cannot completely be used. Since higher support from the e-trailer is hardly possible without having more information of the status of the towing vehicles powertrain, overall range of the vehicle combination can only be increased with a higher battery energy capacity in the towing vehicle.

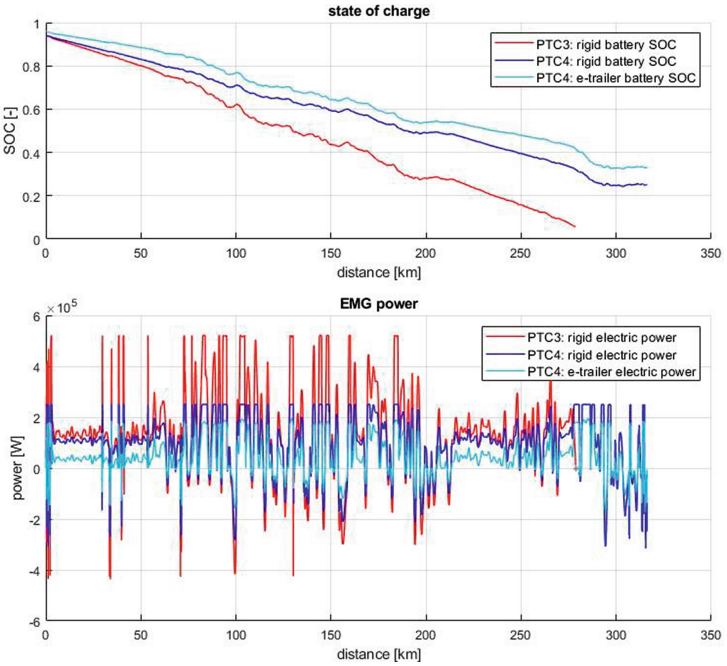


Fig. 3. Simulation results of EMS1 with PTC3 and PTC4 on use case mission leg 3, state of charge over distance, power of electric motor/generator (EMG) over distance

5 Discussion and Conclusions

In terms of the specific energy efficiency, an operational strategy including support by the e-trailer also on flat road segments is not recommended. The specific energy consumption is increased due to the split of the power demand between the EMGs of the e-trailer and the towing vehicle. E-trailer support is not advised when the towing vehicle's EMG operates at low efficiency (e.g., steady-speed driving), since it shifts the operating point to even lower efficiency. The operational strategy should ensure the e-trailer's energy capacity is fully utilized before the towing vehicle's energy storage reaches its minimum SoC. E-trailer support can improve drivability in demanding conditions like driving uphill. An optimal operational strategy is a tradeoff between utilization of the e-trailers energy capacity and the availability of support by the e-trailer over the whole operating range of the vehicle combination. When optimally utilizing the e-trailers energy capacity, it should include an adaptation of the traction support based on the remaining energy capacity of the towing vehicle. The transmission of this information will be possible with the implementation of the latest revision of ISO11992-2:2023. Furthermore, the utilization of the e-trailer battery can be increased by an operational strategy that allows the application of traction power also on flat roads. Overall range can be increased if the driver does not use additional power of the e-trailer for higher acceleration or to drive uphill with maximum speed.

The application of the e-trailer in a vehicle combination with a battery-electric towing vehicle leads to a range extension depending on the energy capacity and the operational strategy of the e-trailer. It increases the specific energy consumption and thus decreases the specific energy efficiency due to the additional weight of the e-trailer powertrain that increases the gross combination weight. Nonetheless, the application of the e-trailer provides additional driving range and thus enables standard truck – semitrailer and EMS setups with zero-emission powertrains to be operated on routes with insufficient coverage of charging infrastructure.

References

1. Verbruggen, F., Hoekstra, A., Hofman, T.: Evaluation of state-of-the-art of full-electric medium and heavy-duty trucks. In: 31th International Electric Vehicle Symposium & Exhibition (EVS), Kobe, Japan (2018)
2. Zander, L., Svens, P., Svärd, H., Dahlander, P.: Evaluation of a Back-up range extender and other heavy-duty BEV-Supporting Systems. World Electr. Veh. J. **13**(6), 102 (2022). https://doi.org/10.3390/wevj13060102
3. Forschungsverbund eHaul: Homepage. https://www.ehaul.eu/. Accessed 25 Aug 2025
4. CATL: Homepage, China's First Battery Swapping Trunk Line for Heavy-Duty Trucks Put into Operation. https://www.catl.com/en/news/6107.html. Accessed 25 Aug 2025
5. Transformers Project: Homepage TRANSFORMERS - Configurable and Adaptable Trucks and Trailers for Optimal Transport Efficiency. https://uniresearch.com/projects/transformers/. Accessed 25 Aug 2025
6. Aeroflex Project: Homepage, AEROFLEX - Aerodynamic and Flexible Trucks for Next Generation of Long Distance Road Transport. https://aeroflex-project.eu/. Accessed 25 Aug 2025
7. ZF Friedrichshafen AG: Homepage, Electrification for Trailers: ZF Presents New Concept as Manufacturers Come on Board. https://press.zf.com/press/en/releases/release_61632.html. Accessed 25 Aug 2025
8. DB Schenker Homepage, eTrailer im Test bei DB Schenker: Signifikant weniger Spritverbrauch. https://www.dbschenker.com/de-de/insights/neuigkeiten-und-storys/presseinformationen/etrailer-im-test-848316. Accessed 25 Aug 2025
9. VAK Group: Homepage, VAK launches a new eco-friendly and energy-efficient eTrailer. https://vak.fi/en/news/vak-launches-a-new-eco-friendly-and-energy-efficient-etrailer/. Accessed 25 Aug 2025
10. Wittig, H., Saroch, L.: ZEFES Deliverable D5.1: System specification for ZE modular multi-powertrain concepts, Brussels (2025)

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Utilization of Public Transport Charging Infrastructure Through Shared Use of Private Electric Vehicles

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Abstract. As European cities expand their electric public transport fleets, bus depots have increasingly been equipped with high-capacity charging infrastructure. However, this infrastructure is often underutilized outside scheduled bus charging times. This paper examines whether such facilities could be opened to private electric vehicles on a commercial basis in Budapest, Hungary as a case study. Technical, legal, and competitive aspects were reviewed, followed by a three-year net present value analysis for two major operators, BKV and MÁV. Results show that this project would be financially viable for both companies. The study highlights both the potential and the limitations of repurposing existing public transport charging assets, emphasizing that feasibility depends on electricity pricing, labor costs, and customer demand. Although the findings are based on Budapest, the methodology is broadly applicable to other urban contexts with similar infrastructure.

Keywords: Electric public transport · charging infrastructure · shared use · bus depot · electric buses

1 Introduction

The history of e-mobility dates back more than 100 years [1]. Over the past decade, there has been a dramatic increase in the number of electric vehicles (EV), with government subsidies in some countries to support the purchase. The EU is also seeing a significant increase in the number of EVs, as it will ban the sale of new passenger cars with internal combustion engines from 2035 to achieve its climate neutrality targets by 2050 [2]. Electric buses have also appeared in urban public transport systems. The first bus line in Budapest was served by a battery-powered electric Austro-Daimler in 1915 [3]. According to an EU research report from 2016, electric buses from 27 manufacturers were in operation in over 60 European cities and this trend is increasing in 2017 [4].

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This paper aims to investigate whether the possible free capacity of public transport companies owned by on-site electric charging stations can be opened to the public. The research was inspired by an UK example, where private EVs can be charged at a bus depot, after a 1 million GBP investment from First Bus company [5]. There is also an old Hungarian precedent relating to diesel fuel filling, whereby private individuals could fill up at the Hungarian bus operator's two filling stations in Budapest, paying a lower price than the market average [6]. The then CEO of Hungarian Volánbusz company also raised the possibility of charging private electric cars at electric bus charging points [7].

As a case study Budapest, capital of Hungary was investigated. Some basic data: on 1 January 2025 the population was 1.685 million [8], increasing by approximately half a million commuters each day [9]. The city is mostly flat with a few small hills; the climate is continental.

2 Methodology

The first step of the research process involves collecting relevant technical and other characteristics of the current electric buses used in the Budapest public transport network. This is followed by financial calculation.

2.1 Technical Characteristics

- BKK Centre for Budapest Transport is the public transport contractor, working together with three companies operating buses as service providers. Two of these currently operate electric buses: Budapest Transport Privately Held Corporation (BKV) and MÁV Passenger Transport Private Company Limited by Shares (previously Volánbusz). For this reason, this paper focuses primarily on these two companies.
- The third service provider, Arriva Hungary Zrt. plans to put 82 Chinese BYD electric buses into service from 2026, along with reserves.
- These operating electric buses are equipped with built-in battery packs and use fully electric propulsion (Battery Electric Vehicles, BEVs).
- Both companies own a bus depot. Depending on the location and frequency of charging, electric buses can be charged at bus depots overnight, at terminal stations or en route [1]. It can be stated that both Budapest operators have opted for a solution involving e-charging stations in bus garages.

Bus Depot No.1.: Budapest Transport Privately Held Corporation (BKV) site: BKV Zrt. ATÜI, Kelenföld Division, 1113 Budapest, Hamzsabégi Street 55. 20 brand new EVOPRO EP080ES Modulo Medio Electric buses were purchased, equipped with 141 kWh capacity battery pack and a range of 130–150 kms, designed and assembled in Hungary, together with the associated charging infrastructure. 18 electric charging stations have been installed here, with CCS Combo 2 (CCS2) plugs. However, due to a series of construction defects, only 7 buses of this type were still in operation in April 2025 [10]. This means that the buses use a maximum of 7 charging stations. 10 electric chargers are available for private charging, both in the evening and during the day. Henceforth, the abbreviation 'BKV' will be used for this company and its bus garage (Fig. 1).

Bus Depot No.2.: MÁV Passenger Transport Private Company Limited by Shares site: Hunyadi Garage, 1117 Budapest, Törökverő Street (Fibula Street). 40 e-charging stations have been installed for the 40 brand-new Mercedes-Benz eCitaro buses (equipped with 243 kWh capacity battery pack and a range of 150–200 kms) which were put into service in 2022. 20 electric chargers are available for private charging during the day only. Henceforth, the abbreviation 'MÁV' will be used for this company and its bus garage (Fig. 2).



Fig. 1. Modulo Electric bus at the BKV depot and sat. view (Budapest, 2025; Photo: Authors)

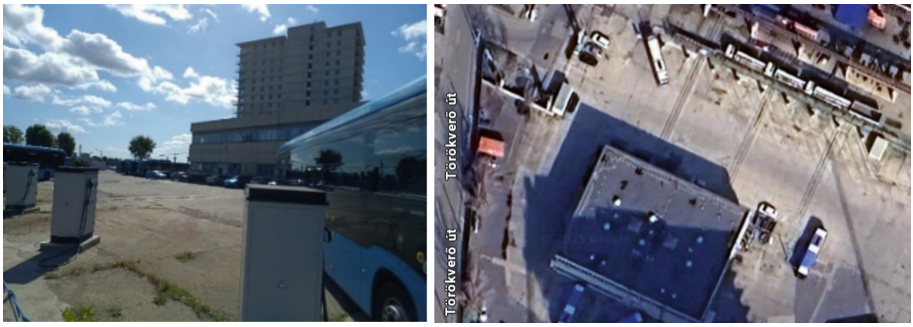


Fig. 2. MB eCitaro buses at the MÁV depot and sat. view (Budapest, 2025; Photo: Authors)

- Due to the unique requirements of operating electric buses, an electric charging station has been installed for every electric bus purchased at each bus depot.
- Both bus depots have an e-charging infrastructure that is also suitable for charging passenger cars or vans. These are smaller than a bus, so they can fit in the charging area. Technically, a passageway for passenger cars could be built here.
- There are periods when chargers are available at both sites, because e-buses are usually charged overnight, but sometimes it is necessary to charge them during the day.
- Both sites are currently operating normally; therefore, private vehicles are not permitted to enter the operational area.

2.2 Other Aspects

- It is legally feasible (permissible) for companies to offer the use of e-charging stations to private BEVs.
- The two companies can set whatever charging rates they want, which could be lower than the current market price. This price reduction is necessary because charging stations are not always available, and public transportation buses have priority.
- Locations accessible to privately owned electric vehicles were identified using data from the community-driven platform PlugShare [11]. Based on this information, it can be stated that in September 2025, there were numerous e-charging stations available near these two bus depots, within a 3 km radius in Budapest. However, not all locations have rapid charging options (DC with CCS2 plug), which are available in the bus garages.

The specific aim of the research is to use cost analysis to determine whether *is it worthwhile for operating bus companies BKV and MÁV to offer their e-charging infrastructure to private BEV users?*

2.3 Profitability Calculation

Using data from 2025, a profitability calculation was performed without accounting for inflation. From a financial perspective, the following assumptions were applied:

- The cost of installing e-charging stations is not taken the into account, since they were built earlier – sunk cost.
- One-time transformation cost was applied, covering the construction of access and exit routes for passenger vehicles, road signs, video surveillance system upgrade, manual arm traffic barriers, and other necessary infrastructure modifications.
- New permanent cost factor is calculated with a due to the following: since public transport infrastructure must be protected, a fully self-service operating model is not permissible under any circumstances in Hungary. Some British theft case studies can be read at [12]. Therefore, at least initially, it will be necessary to employ full-time 'doormen' to monitor the charging stations, prevent non-chargeable vehicles from entering the site and arrange for the towing of vehicles that remain at the station beyond the usual charging time. It is necessary, because unfortunately in some parts of Hungary owners of cars that cannot be charged electrically, regularly park their vehicles in front of electric charging points for extended periods of time. Both bus depots currently have mobile guards, and additional dedicated staff are planned to be assigned.
- Extra maintenance and depreciation costs are also planned for due to increased charging usage.
- Finally, it is assumed that companies will cover the above costs from their own resources.

Net Present Value (NPV) calculation was performed. Cash flows were calculated for a period of 3 years. The alternative cost is set at 5%.

The NPV was calculated using a project revenue and cost structure. The data were obtained through extensive research, and it is assumed that the calculations presented closely reflect reality. Two separate NPV calculations were made for the two companies.

I. **Costs**

1. The one-time transformation cost at the depot (investment in year zero): 25 million HUF at BKV, 30 million HUF at MÁV, because of larger area and more EV charger posts (1 € ≈ 400 HUF).
2. Security (doormen) costs: Calculations were made based on the hiring of new full-time employees, who are paid around the minimum salary. In the case of BKV, due to its 24-h opening hours, 4 full-time and 1 part-time employees are needed to cover the 168 h of working time per week. In 2025, the Hungarian minimum gross salary is 290,800 HUF per month and the total cost for the employer (so-called super gross) is 329,000 HUF per month. Due to legal requirements, night, weekend, and holiday work is subject to additional wages, and other benefits may also apply. Finally, the calculation is based on a salary that is slightly higher than the minimum salary. These were considered with a total salary cost surcharge of 60%. For the sake of simplicity, part-time employment was calculated at half the cost. Additional task of this employee is to control the charging process: a, dedicated lane for the buses; b, physical separation from the bus parking zones; c, barrier for the private charging e-cars.

   Thus, the employer's salary, contribution, and other costs for 4.5 people at BKV is 4.5*329,000*1.6 = 2,369,000 HUF per month. At MÁV, private cars can only be charged during the day and evening. So, 3 full-time employees are hired. The total monthly cost is 1,580,000 HUF. This is the salary cost for the first year. A 5–5% cost increase is considered for the second and third years.
3. Additional repair and depreciation costs: Due to increased charging station usage, an additional amount of 30,000 HUF per charging station per month has been added, in addition to the repair and depreciation costs that were obviously already planned. In the case of BKV, 10 outdoor charging stations are used: 3,600,000 HUF/year. In the case of MÁV, 20 charging stations are used, out of 40: 7,200,000 HUF/year. These cost elements are added in years 1, 2, and 3.

II. **Revenue**

Revenue is generated solely from the difference in electricity prices.

BKV procures electricity through public procurement, with annual contracts. 1 kWh of electricity was 36–37 HUF in 2020 [13] and there was a 257% price increase in 2022 [14]. Therefore, the calculation is based on BKV's estimated electricity cost of 97 HUF/kWh (net price).

MÁV purchases electricity at a net price of 105 HUF/kWh [15].

We acknowledge that time-of-use pricing could improve margins (especially if buses charge mainly overnight and private EVs during daytime) and dynamic tariffs could increase profitability.

When determining the price of charging at the bus depot, it is worth checking the prices of nearby charging points and adjusting them. Since both bus depots have rapid (DC) chargers with CCS2 plugs, the prices at nearby rapid chargers were analyzed. The price list of the three largest Hungarian service providers (listed by [16]) in 2025, gross

prices: MOL Plugee: 259–309 HUF/kWh [17], MVM Mobiliti: 199–380 HUF/kWh [18], E.ON: 199 HUF/kWh, with an additional 18 HUF/min after 60 min charging [19].

Opening hours (for private individuals): BKV: non-stop, MÁV: 16 h a day.

The only unknown factor is the selling price of electricity, which companies are free to set, and which determines their revenue. The selling price can logically fall between the purchase price (BKV: 97 + 27% VAT, MÁV: 105 HUF + 27% VAT) and the cheapest competitor's price (199 HUF gross). In this calculation, it is assumed that the selling price of electricity is 20% cheaper than the cheapest price of 199 HUF, resulting in a gross selling price of 160 HUF/kWh. This represents a discount of 39 HUF/kWh, which is a relatively large discount rate. As a result, BKV's profit from the sale of electricity will be 126–97 = 29 HUF/kWh (net value), while MÁV's profit will be 126–105 = 21 HUF/kWh (net value).

The nominal battery capacity of electric passenger cars typically ranges between 40 kWh and 100 kWh, according to manufacturer data [20, 21]. It is assumed that a customer purchases an average of 40 kWh of energy during a single charge. In this case, the average profit per customer is 40 kWh * 29 HUF = 1,160 HUF (BKV) and 40 kWh * 21 HUF = 840 HUF (MÁV), where 'profit' means the margin achieved on the price difference.

It is also assumed that each customer uses the charging station for an average of 2 h, including the time required for other activities before and after charging. This assumption also includes an approximately 50% reduction in capacity (number of customers), as rapid chargers require a maximum of 1 h of use to charge 40 kWh. Therefore, customer traffic and available revenue are significantly underestimated here compared to the technically possible maximum.

Based on this, each BKV charging station is used by 12 customers in 24 h period, resulting 120 customers per day across 10 stations. For MÁV, 8 customers charge in 16 h per station, leading to an estimated 160 customers served daily across 20 stations. Thus, BKV's profit in one day is 1,160 HUF * 120 customers = 139,200 HUF, and during 355 days of annual operation (as 10 days are reserved for maintenance and other downtime), it is 49,416,000 HUF (in each of the 1st, 2nd, and 3rd years). In the case of MÁV, the daily profit is 840 HUF * 160 customers = 134,400 HUF, and during 355 days of annual operation, it is 47,712,000 HUF (in each of the year 1, 2 and 3).

3 Results

All data is available for calculating the net present value. The results:

$$\mathbf{NPV_{BKV} = +17{,}662{,}000\ HUF}$$
$$\mathbf{NPV_{MÁV} = +24{,}907{,}000\ HUF}$$

In this case study, this project is financially viable also for BKV and MÁV, but due to the size of the companies, profits are minimal.

3.1 Additional Considerations

Detailed cost planning requires further calculations, as no additional taxes have been considered. BKV and MÁV are two separate projects and require two separate decisions.

Other non-financial considerations may also arise as decision factors, which need to be addressed.

3.2 Sensitivity Analysis

The above calculation is highly dependent on the cost of electricity, current labor costs, and the set electricity selling price. Some cases:

- If the company has cheaper night-time electricity or uses solar panels, the profit increases.
- Only rapid charging (DC) was considered; vehicle charging with Type 2 (AC) fast-charging sockets and their applicable pricing were not considered.
- A longer time frame would result in a higher positive NPV, as the most significant costs occur in year 0.

A sensitivity analysis was conducted for electricity prices and charging demand. In the case of +/− 10% volatility of these two parameters, the NPV values change significantly. In all cases NPVs remain positive except when the price of electricity increases by 10%, NPVs become negative.

4 Conclusion

The financial calculations performed confirm that the current technical, human resource, and financial conditions make suitable for the expansion of the service for both companies, i.e., private individuals can also use the existing charging capacity. One reason for this is that both companies purchase electricity at a fairly good price, which means they can sell it more cheaply than the price of charging stations in the area. In addition, the calculation was based on a one-time site conversion cost only in year zero, as the site and charging stations already exist and they are operating normally (sunk cost). A particular advantage is that modern CCS2 rapid charging is already available at both sites. However, the question arises as to whether the average customer will save 39 HUF * 40 kWh = 1,560 HUF (~4 EUR) per 40 kWh charge. Will the driver of an expensive electric car be willing to visit a charging station in a less convenient location for savings of this amount?

To summarize, this study demonstrates that using existing electric bus depot chargers for private EVs is not only a financially sound idea but also a strategically meaningful one. While profits are modest, the wider benefits—environmental, social, and reputational—are significant.

References

1. Szabo, L., Iulia, V.: A brief history of electric vehicles. J. Comput. Sc. Control Syst. **15**(1), 41–46 (2022)
2. European Parliament: Homepage. https://www.europarl.europa.eu/topics/en/article/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained. Accessed 28 Mar 2026

3. A közösségi közlekedés jövője–REKK Energy Futures V: Homepage. https://rekk.hu/downloads/events/Corvinus_REKK_BKV_0403.pdf. Accessed 28 Mar 2026
4. ZeEUS project: Homepage. https://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf. Accessed 29 Mar 2026
5. May, T.: First Bus Opens Public Electric Charging Hub at Summercourt Bus Depot. Bus-News (2024)
6. Baka, F.Z.: Olcsón adja a gázolajat a BKV, mégis kevesen tankolnak náluk. Menedzsment Fórum (2017)
7. Kruchina, V.: Korunk ipari forradalma – az elektrifikáció lehetőségei az autóbuszos közösségi közlekedésben. Magyarbusz Info (2023)
8. Hungarian Central Statistical Office: Homepage. https://www.ksh.hu/stadat_files/nep/en/nep0034.html. Accessed 28 Mar 2026
9. Koltai, L., Varró, A.: Ingázás a budapesti agglomerációban. Új Munkaügyi Szemle. **1**(3), 26–37 (2020)
10. BKV: Homepage. https://bkv.hu/hu/jarmuveink/autobusz/modulo-ep-080-es-c68e. Accessed 28 Mar 2026
11. PlugShare: Homepage. https://www.plugshare.com. Accessed 28 Mar 2026
12. Titcomb, J.: The crime wave threatening electric car sales. The Telegraph (2025)
13. BKV: Homepage. https://static.bkv.hu/files/procurements/2347_17341.pdf. Accessed 28 Mar 2026
14. Állami Számvevőszék: Homepage. https://www.asz.hu/dokumentumok/25048.pdf. Accessed 28 Mar 2026
15. Ludányi, J.: A villanybusz-flotta eddigi üzemeltetési tapasztalatai a Volánbusznál. Magyarbusz Info (2023)
16. Tudjukki: Homepage. https://www.tudjukki.hu/tippek/elektromosauto-toltok/mennyibe-kerul-egy-elektromos-auto-toltese. Accessed 28 Mar 2026
17. Mol Plugee: Homepage. https://molplugee.hu/hu/araink. Accessed 28 Mar 2026
18. MVM Mobiliti: Homepage. https://www.mobiliti.hu/emobilitas/nyilvanos-toltes/mennyiert-tolthetek-regisztralt-ugyfelkent/dijak. Accessed 28 Mar 2026
19. EON: Homepage. https://www.eon.hu/hu/e-mobilitas/driveon.html. Accessed 28 Mar 2026
20. EVadatbázis: Homepage. https://evadatbazis.hu. Accessed 28 Mar 2026
21. Evergy: Homepage. https://www.evergy.hu/tudastar/elektromos-auto-akkumulator-mukodes-ar-elettartam. Accessed 28 Mar 2026

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Sustainable Aviation Fuel Adoption Strategies Under Regulatory Blending Mandates

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Abstract. The European Union's "ReFuelEU Aviation" regulation, under the Fit for 55 package, mandates a phased increase in Sustainable Aviation Fuel (SAF) use across EU airports, setting ambitious targets for decarbonizing aviation. However, the regulation provides limited guidance on how airlines can operationalize these requirements given uneven SAF availability, infrastructure readiness and cost differentials. This study develops an optimization model to support airlines in planning SAF deployment across their network in a cost-effective and regulation-compliant manner. The model minimizes total fuel procurement costs while ensuring compliance with SAF blending thresholds. It incorporates airport-level SAF availability, fuel pricing, emissions intensity and policy constraints, enabling airlines to evaluate blending strategies that satisfy both environmental targets and logistical feasibility. Scenario analysis explores the impacts of policy mechanisms such as differentiated mandates, financial incentives and supply disruptions. Applied to a regional European airline operating in Greece, where SAF distribution infrastructure is expanding, the model provides actionable insights into how SAF targets can be met without compromising operational viability. The results highlight the importance of flexible, data-informed policy design that accounts for network heterogeneity and evolving market conditions.

Keywords: Sustainable Aviation Fuel · Optimization Model · Airline Operations · Policy · Aviation

1 Introduction and Background

Decarbonizing aviation is one of the biggest challenges in the shift to a low-carbon transport systems. Unlike road or rail, aviation depends on liquid fuels because of the high energy requirements of long-haul flights and slow fleet turnover. Sustainable Aviation Fuels (SAF) are seen as a key pillar of the industry's plan to reach net-zero emissions by 2050, with the International Air Transport Association (IATA) estimating that SAF could deliver around 65% of the sector's total reductions [1]. Regulatory efforts are already underway: e.g. the European Union's ReFuelEU aviation mandate requires increasing SAF shares at EU airports (e.g. 2% in 2025, rising to 6% by 2030) [2, 3]. However, supply remains constrained, with production costs projected to remain two to three times higher than conventional jet fuel until at least 2030 [4]. Scaling SAF to expected demand (~17

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Mt./year) will require $19–45 billion in capital investment by 2030 [5]. The debate is therefore shifting toward designing policies that balance cost efficiency, competitive neutrality, and environmental ambition.

A growing body of literature examines SAF deployment across multiple dimensions. Large-scale deployment can deliver significant emissions reductions but is constrained by capital requirements and supply chain limitations, while European projections to 2030 confirm up to 80% lifecycle emission reductions alongside cost and supply uncertainties [6, 7]. Across the literature, cost emerges as the primary barrier, alongside challenges related to certification, supply chains, and policy design, with substantial investment needs and limited alternative decarbonization pathways [8, 9]. Policy design plays a critical role: quotas can ensure uptake but at high economic cost, whereas subsidies may lead to under-delivery if not properly calibrated; coordination across policy layers remains challenging, and SAF continues to be economically disadvantaged under CORSIA without additional incentives [10–12]. Market structure and competition effects depend on SAF mandate levels and may disproportionately affect full-service carriers, while airlines simultaneously face cost pressures and emerging passenger willingness to pay for sustainable aviation [13–15]. Operational and technological constraints further shape deployment, including blending and logistics challenges and lifecycle emission reductions of up to 78%, while alternative technologies such as hydrogen and electrification offer higher long-term potential, with SAF remaining the most scalable near-term solution; cross-sector comparisons also confirm the suitability of e-kerosene for aviation [16–18]. Persistent bottlenecks in feedstock availability, scaling, certification, and financing reinforce SAF as the central decarbonization lever, while highlighting fragmented perspectives across disciplines [19].

Building on this literature, this study develops an optimization model that integrates costs, carbon pricing, subsidies, blending mandates, and airport-level constraints into a unified airline-level decision framework. The model minimizes total fuel procurement and compliance costs while satisfying operational demand and regulatory requirements, explicitly accounting for lifecycle emissions and policy incentives. Compared with prior work focusing on individual dimensions, the proposed approach provides a prescriptive tool that captures these factors jointly within real airline networks, generating actionable insights for policy design.

The remainder of the paper is structured as follows. The next section presents the methodology and model formulation, followed by results and sensitivity analyses. The discussion and conclusions section interprets the findings in light of policy and industry implications and the directions for future research.

2 Methodology

The optimization framework is designed to support airline decision-making under Sustainable Aviation Fuel (SAF) blending mandates. It is formulated as a Linear Programming (LP) problem, minimizing the total cost of fuel procurement and compliance across the airline's network. The model relies on the following sets, parameters, and decision variables, which are defined to capture the operational, economic, and regulatory dimensions of fuel procurement:

$d_{i,t}$ (t) Fuel demand for the airline at airport i in period t
$c_{i,f,t}$ (€/t) Fuel purchase price at airport i for fuel f in period t
$l_{i,f,t}$ (€/t) Uplift/handling cost at airport i for fuel f in period t
γ_t (€/tCO2e) Carbon price (ETS/CORSIA) in period t
CI_f (tCO2e/t) Lifecycle carbon intensity of fuel f
(higher for JET, lower for SAF)
$a_{i,t}$ (€/t) SAF-specific incentive or subsidy at airport i in period t
$\underline{\rho}_t^{net}$ (0–1) Minimum network-wide SAF share mandated in period t
$\overline{\beta}$ (0–1) Maximum allowable SAF blend ratio per ASTM certification
F {JET, SAF} Fuel types
I Set of airports i
T Set of periods t

Based on these definitions, the optimization objective is to minimize the airline's total fuel-related costs, expressed as follows (Eq. 1):

$$minZ = \sum_{t\in T}\sum_{i\in I}\sum_{f\in F}\left(\left(c_{i,f,t} + l_{i,f,t}\right) + \gamma_t \cdot CI_f\right) \cdot u_{i,f,t} - \sum_{t\in T}\sum_{i\in I}(\alpha_{i,t} \cdot u_{i,SAF,t}) \tag{1}$$

The term $(c_{i,f,t} + l_{i,f,t}) \cdot u_{i,f,t}$ represents the direct fuel purchase cost together with the airport-specific uplift or handling charges for fuel type f at airport i in period t. The expression $\gamma_t \cdot CI_f \cdot u_{i,f,t}$ captures the carbon compliance cost under ETS or CORSIA, calculated as the carbon price γ_t multiplied by the lifecycle carbon intensity of the fuel and the quantity uplifted. Finally, the term $\alpha_{i,t} \cdot u_{i,SAF,t}$ represents SAF-specific incentives or credits, reducing the effective cost when SAF is used.

The optimization problem is subject to the following constraints, which ensure that operational requirements, regulatory mandates, and technical limits are satisfied:

$$\sum_{f\in F} u_{i,f,t} = d_{i,t} \quad \forall i \in I, t \in T \tag{2}$$

$$\sum_{i\in I} u_{i,SAF,t} \geq \underline{\rho}_t^{net} \sum_{i\in I}\sum_{f\in F} u_{i,f,t} \quad \forall t \in T \tag{3}$$

$$u_{i,SAF,t} \leq \overline{\beta} \sum_{f\in F} u_{i,f,t} \qquad \forall i \in I, t \in T \tag{4}$$

$$u_{i,f,t} \geq 0 \qquad \forall i \in I, f \in F, t \in T \tag{5}$$

Constraint (2) ensures that total fuel uplift at each airport and time period exactly matches the operational fuel demand of scheduled flights. This reflects the operational requirement that aircraft must be adequately fuelled at their departure point. Constraint (3) enforces compliance with network-wide SAF mandates, requiring that the share of SAF used across the airline's total fuel consumption in each period is at least equal to the regulatory quota. This structure reflects regulations such as ReFuelEU Aviation, which mandate aggregate SAF use at the airline level rather than at each airport individually. Constraint (4) sets a local blending cap for SAF at each airport and period, representing technical and certification limits (currently 50% under ASTM standards). This prevents unrealistic allocations where SAF would exceed allowable blending ratios. Constraint (5)

imposes non-negativity conditions on all fuel allocation variables, ensuring physically meaningful solutions.

The decision variable of the model is $u_{i,f,t}$ which denotes the tons of fuel f (conventional jet or SAF) uplifted at airport i in period t. The model outputs include the quantities of jet fuel and SAF uplifted at each airport. To examine the effects of tightening mandates, sensitivity analysis is performed on parameter $\underline{\rho}_t^{net}$.

The model is implemented in Python, using pandas for data handling, numpy for numerical operations, and SciPy's linprog with the HiGHS solver for optimization. A Linear Programming (LP) formulation is adopted because the problem structure, minimizing fuel procurement and compliance costs subject to demand balance, blending mandates, and certification limits, can be represented entirely with linear relationships. This ensures scalability across multiple airports and planning periods while remaining computationally efficient. The resulting framework provides a decision-support tool that integrates cost, policy, and operational considerations to guide airlines in navigating SAF adoption.

3 Results

3.1 Data Collection

The analysis relies on a combination of real operational data and publicly available sources. Table 1 summarizes the model inputs for Sky Express [20] ATR operations across six Greek airports (Athens–ATH, Heraklion–HER, Rhodes–RHO, Mykonos–JMK, Santorini–JTR, Thessaloniki–SKG) for a representative summer day, which reflects the airline's busiest period. Sky Express is a regional Greek carrier operating a mixed fleet of Airbus and ATR aircraft. The focus of this study is placed exclusively on the ATR 42–500 and ATR 72–600 fleet, as these turboprops are primarily deployed on domestic routes linking the Greek mainland with island destinations. The Airbus fleet, in contrast, is mainly used for international services and was therefore excluded from the analysis. The choice of a summer day reflects the seasonality of Greek air transport, where demand is strongly driven by the touristic peak season, resulting in higher flight frequencies and fuel demand across the domestic ATR network.

Fuel demand parameters were derived from Flightradar24 [21] Premium data on Sky Express ATR departures by origin airport and season. Distances between airport pairs were calculated as great-circle distances and multiplied by manufacturer block fuel consumption rates of 1.56 kg/km for the ATR 42–500 and 1.68 kg/km for the ATR 72–600, as reported in the official ATR performance brochures [22]. Fuel purchase prices ($c_{i,f,t}$) for conventional Jet A-1 and SAF were taken from the EASA EU SAF Market Outlook (2024) [23], with SAF values including a markup for insular locations to reflect higher logistics costs. Uplift and handling charges ($l_{i,f,t}$) were estimated based on ground handler tariffs (e.g., Swissport, Skyserv, Olympic Handling) and were adjusted for airport size and remoteness. The carbon price (γ_t) was based on the EU ETS average price for 2024, approximately 80 €/tCO_2e, as reported by the International Carbon Action Partnership (ICAP) [24]. Lifecycle carbon intensities (CI_f) were set to 3.15 tCO_2e/t for Jet A-1 and 0.95 tCO_2e/t for SAF, consistent with the McKinsey Clean Skies for Tomorrow study [25] and EU ETS reporting factors. SAF subsidies ($a_{i,t}$) were

Table 1. Model inputs

	$d_{i,t}$	$c_{i,JET,t}$	$c_{i,SAF,t}$	$l_{i,JET,t}$	$l_{i,SAF,t}$	γ_t	CI_{JET}	CI_{SAF}	$a_{i,t}$	$\underline{\rho}_t^{net}$	$\overline{\beta}$
Airport											
ATH	21.67741	734	2085	9	10	80	3.15	0.95	80	0.02	0.5
HER	0.967475	734	2185	12	14	80	3.15	0.95	80	0.02	0.5
JMK	0.684088	734	2185	14	16	80	3.15	0.95	80	0.02	0.5
JTR	1.834249	734	2185	14	16	80	3.15	0.95	80	0.02	0.5
RHO	0.724637	734	2185	14	16	80	3.15	0.95	80	0.02	0.5
SKG	1.930932	734	2085	12	14	80	3.15	0.95	80	0.02	0.5

introduced as an assumed value of 80 €/t, reflecting the scale of support mechanisms under the EU ETS free allocation and innovation funding schemes [26]. The mandated SAF share ($\underline{\rho}_t^{net}$) was fixed at 2% for 2025, as established by the ReFuelEU Aviation regulation [27]. Finally, the maximum SAF blending share ($\overline{\beta}$) was set to 50%, in line with the technical specification ASTM D7566 and supporting guidance from IATA [28]. These inputs were harmonized into a single dataset to ensure consistency across airports and periods.

3.2 Optimization Results

The initial optimization with a blending mandate of 2% shows that compliance can be achieved by allocating SAF entirely at the airline's main hub in Athens. This outcome reflects both the concentration of fuel demand at the hub and the cost-efficiency of meeting regulatory requirements by focusing SAF deployment where volumes are highest. At this mandate level, no SAF is allocated to the secondary airports in the network.

To further explore how results change under different regulatory conditions, a sensitivity analysis was conducted on the mandate parameter $\underline{\rho}_t^{net}$. As the SAF requirement increases, the model demonstrates that Athens remains the primary location for SAF allocation until the local blending cap is reached. Beyond this point, SAF adoption begins to expand to secondary airports, gradually distributing across the network. This progression highlights the dual role of mandates: while they guarantee greater use of SAF, they also increase the economic burden on airlines by forcing uptake at airports where costs may be higher or supply chains less developed.

Overall, the results illustrate how blending mandates shape both the cost structure and spatial distribution of SAF use. Concentrating allocations at a hub minimizes costs at lower mandate levels, but higher requirements necessitate broader adoption, revealing the trade-offs between efficiency and compliance flexibility. Figure 1 summarizes the optimization results across the scenarios, showing the distribution of SAF between airports and the network-level shares under varying mandates.

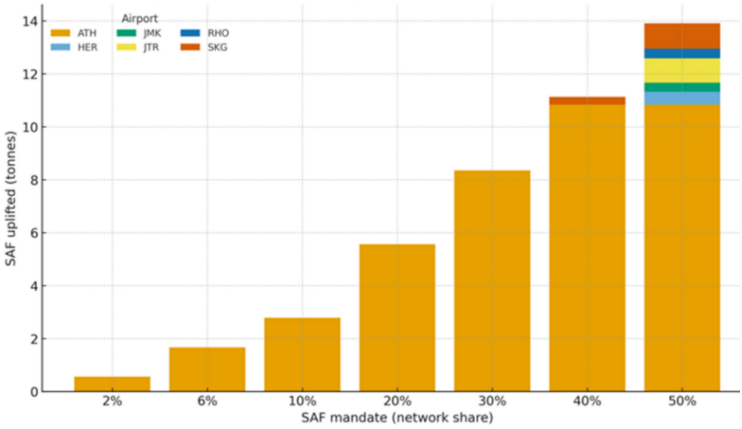


Fig. 1. SAF allocation by airport across mandate scenarios

4 Discussion and Conclusions

The results show how airlines respond to SAF blending mandates under realistic conditions. At moderate levels, compliance is most cost-effective by concentrating SAF at the main hub, where demand and logistics allow efficient allocation. As mandates tighten, the 50% ASTM blending cap becomes binding, requiring distribution across secondary airports. While this ensures broader SAF uptake, it introduces uneven cost burdens, particularly for smaller airports with less developed supply chains.

These findings highlight the importance of flexible policy design. Network-wide mandates, such as those under ReFuelEU, enable cost-efficient allocation, whereas airport-specific quotas increase costs and logistical complexity by limiting economies of scale at hubs. At the same time, infrastructure and supply chain investments at secondary airports are needed to avoid bottlenecks as mandates rise, while targeted subsidies may help mitigate cost pressures and support regional connectivity.

The interaction between mandates and carbon pricing is also critical. Higher carbon prices under ETS or CORSIA increase the attractiveness of SAF, whereas lower prices reduce incentives beyond minimum compliance, underscoring the need for coordinated policy instruments, including SAF credits, multipliers, or adjusted carbon price trajectories. Hub-based strategies favor hub-and-spoke airlines, while point-to-point carriers may face higher costs, highlighting the need to avoid competitive imbalances in policy design.

Overall, while blending mandates drive SAF adoption, achieving cost efficiency and environmental effectiveness requires complementary measures, including certification progress toward higher blending ratios, infrastructure investment, targeted subsidies, and coordinated carbon pricing. The model integrates costs, carbon pricing, blending limits, and quotas, showing that SAF use concentrates at hubs under low mandates and expands to secondary airports as requirements tighten, revealing trade-offs between efficiency and compliance. Future research could incorporate uncertainties in SAF prices, carbon markets, and supply reliability, as well as demand elasticity, airline competition, and

multi-period dynamics. Also, it could include a more detailed assessment of SAF logistics and the full fuel lifecycle (well-to-wheel), validation against real airline decisions, and broader case studies to strengthen policy relevance beyond regional carriers.

References

1. IATA: Developing Sustainable Aviation Fuel (SAF). https://www.iata.org/en/programs/sustainability/sustainable-aviation-fuels/. Accessed 30 Sep 2025
2. Congress.gov: Sustainable Aviation Fuel (SAF): An Overview of Current Laws and Legislation Introduced in the 118th Congress. https://www.congress.gov/crs-product/IF12757. Accessed 30 Sep 2025
3. IATA backs call by European airlines to soften green fuel mandate. https://www.reuters.com/sustainability/climate-energy/iata-backs-call-by-european-airlines-soften-green-fuel-mandate-2025-03-27/ (2025)
4. World Economic Forum: The cost of sustainable aviation fuel: Can the industry clear this key hurdle? https://www.weforum.org/stories/2025/07/the-cost-of-sustainable-aviation-fuel/. Accessed 30 Sep 2025
5. Derrick, M.: WEF & Kearney: US$45bn Needed to Meet Global SAF Demand. https://energydigital.com/sustainability/wef-kearney-us-45bn-needed-to-meet-global-saf-demand. Accessed 30 Sep 2025
6. Staples, M.D., Malina, R., Suresh, P., Hileman, J.I., Barrett, S.R.H.: Aviation CO2 emissions reductions from the use of alternative jet fuels. Energy Policy. **114**, 342–354 (2018). https://doi.org/10.1016/j.enpol.2017.12.007
7. Kousoulidou, M., Lonza, L.: Biofuels in aviation: fuel demand and CO2 emissions evolution in Europe toward 2030. Transp. Res. Part D. **46**, 166–181 (2016). https://doi.org/10.1016/j.trd.2016.03.018
8. Xu, Y., Zhang, Y., Deng, X., Lee, S.-Y., Wang, K., Li, L.: Bibliometric analysis and literature review on sustainable aviation fuel (SAF): economic and management perspective. Transp. Policy. **162**, 296–312 (2025). https://doi.org/10.1016/j.tranpol.2024.11.014
9. Chiaramonti, D.: Sustainable aviation fuels: the challenge of decarbonization. Energy Procedia. **158**, 1202–1207 (2019). https://doi.org/10.1016/j.egypro.2019.01.308
10. Zheng, S., Wang, C., Jiang, C.: Carrot or stick? Environmental and welfare implications of sustainable aviation fuel policies. Transp. Res. Part B. **188**, 103062 (2024). https://doi.org/10.1016/j.trb.2024.103062
11. Scheelhaase, J., Maertens, S., Grimme, W., Jung, M.: EU ETS versus CORSIA – a critical assessment of two approaches to limit air transport's CO2 emissions by market-based measures. J. Air Transp. Manag. **67**, 55–62 (2018). https://doi.org/10.1016/j.jairtraman.2017.11.007
12. Jiang, C., Liu, Y.: The role of sustainable aviation fuel in CORSIA: an economic analysis. Energy Econ. **143**, 108238 (2025). https://doi.org/10.1016/j.eneco.2025.108238
13. Xia, S., Ma, H., Hu, R., Jiang, C., Xiao, Y.: The impact of sustainable aviation fuel quota mandates on the optimal on-airport fuel facility ownership. Transp. Res. Part A. **200**, 104667 (2025). https://doi.org/10.1016/j.tra.2025.104667
14. Chen, R., Yang, H., Wang, K., Jiang, C.: Impacts of a sustainable aviation fuel mandate on airline competition — full-service carrier vs. low-cost carrier. Transp. Res. Part B. **190**, 103098 (2024). https://doi.org/10.1016/j.trb.2024.103098
15. Reisdorf, A.R., Kummer, S., Soklaridis, S.: Opportunities and challenges arising from european sustainable aviation fuel regulations: a case study approach. J. Air Transp. Res. Soc. **5**, 100085 (2025). https://doi.org/10.1016/j.jatrs.2025.100085

16. Zhang, Z., Wang, X., Ding, S., Gan, C., Li, W., Yang, X.: Safety management and carbon footprint optimization of sustainable aviation fuel during storage and transportation. Energy Convers. Manag. **345**, 120403 (2025). https://doi.org/10.1016/j.enconman.2025.120403
17. Shoukat, R., Redondi, R.: GHG emissions evaluation of conventional, electric, hybrid, biofuel, and hydrogen aircraft. J. Air Transp. Res. Soc. **4**, 100067 (2025). https://doi.org/10.1016/j.jatrs.2025.100067
18. Galimova, T., Lagouvardou, S., Kian, H., Breyer, C.: Comparing sustainable fuel adoption in the energy transition for maritime and aviation transport. Renew. Sust. Energ. Rev. **224**, 116124 (2025). https://doi.org/10.1016/j.rser.2025.116124
19. Wandelt, S., Zhang, Y., Sun, X.: Sustainable aviation fuels: a meta-review of surveys and key challenges. J. Air Transp. Res. Soc. **4**, 100056 (2025). https://doi.org/10.1016/j.jatrs.2024.100056
20. SKY express: Official Website. https://www.skyexpress.gr/el. Accessed 30 Sep 2025
21. Flightradar24: Live Flight Tracker - Real-Time Flight Tracker Map | Flightradar24. https://www.flightradar24.com/premium. Accessed 30 Sep 2025
22. ATR: ATR 42-600 Aircraft | ATR Aircraft. https://www.atr-aircraft.com/aircraft-services/aircraft-family/atr-42-600/. Accessed 30 Sep 2025
23. EASA: EU SAF Market Report | EASA. https://www.easa.europa.eu/en/domains/environment/refueleu-aviation/eu-saf-market-report. Accessed 30 Sep 2025
24. ICAP: Allowance Price Explorer | International Carbon Action Partnership. https://icapcarbonaction.com/en/ets-prices. Accessed 30 Sep 2025
25. McKinsey & Company: Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (2020)
26. European Commission: Free allocation - Climate Action. https://climate.ec.europa.eu/eu-action/carbon-markets/eu-emissions-trading-system-eu-ets/free-allocation_en. Accessed 30 Sep 2025
27. EU: Regulation - EU - 2023/2405 - EN - EUR-Lex. https://eur-lex.europa.eu/eli/reg/2023/2405/oj/eng. Accessed 30 Sep 2025
28. IATA: Fact Sheet 2 Sustainable Aviation Fuel: Technical Certification (2023)

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Stakeholder Perspectives in Building and Deployment of Megawatt Charging Systems to Support the Decarbonization of the Heavy-Duty Transport in Europe

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Abstract. Megawatt charging systems (MCSs) are crucial for the decarbonization of heavy-duty transport in Europe and their deployment is massively supported by public authorities and initiatives. However, while MCS is creating hype and gaining momentum as an expected game changer in the long-haul heavy-duty logistics, the stakeholder perspectives and needs are far from unified. The divergence mainly stems from different priorities, geographic operational realities and varied business models, concerning all value chain industrial actors and policy makers. This study provides a systematic review of various stakeholder perspectives collected through surveys and interviews, which have been conducted in ongoing EU projects such as FLEXMCS - *Flexible Megawatt Charging Systems, open software architectures, and planning modules creating multi-charger hubs for the European electric mobility system* - and MACBETH - *Multipoint megAwatt Charging for Battery Electric Truck Hubs*. The outcomes serve to cluster opinions and identify potential bottle necks and gaps for a rapid and seamless implementation of MCS in Europe.

Keywords: megawatt charging · battery electric trucks · charging infrastructure

1 Introduction

Electrifying road transport is a key priority for reducing mobility-related emissions in Europe, supporting the EU Green Deal's goal for climate neutrality by 2050. The European Commission, together with ALICE technology platform and the freight logistics sector, are working to accelerate electric truck adoption for zero-emission (ZE) long-haul

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transport [1]. Rapid and effective deployment of MCSs along the TEN-T corridors is essential for this transition. MCS technology is already on the market, with early deployments from manufacturers like Tesla, Fortescue, BYD, Power Electronics, Alpitronic and Kempower [2]. Since 2021, several demonstration projects on battery and fuel cell electric trucks have been launched under the "Towards Zero Emission Road Transport (2ZERO) Partnership". However, challenges persist, including interoperability, grid integration, communication standards, and thermal management, which affect stakeholder user experiences [3, 4]. Identifying system actors and understanding their current and future needs is crucial.

This work provides an overview of stakeholder perspectives on MCS deployment in Europe, drawing on insights from ongoing EU projects such as FLEXMCS and MACBETH. The paper also maps MCS ecosystem actors, their needs, and potential use cases for heavy-duty vehicles (HDV).

2 State of the Art and Learnings from Running Projects

2.1 ZEFES Project

The ZEFES project aims to develop Battery Electric Trucks (BET) and interoperable MCSs for real-world, cross-border logistics, with demonstration sites in Belgium, Luxembourg, and Spain supporting five routes. The project unfolds in three phases: identifying stakeholder needs, developing vehicles and charging solutions, and evaluating results- coordinated with the HoLa project. BETs logistics planning is a complex process involving factors such as drive and charge schedules, energy pricing, and infrastructure limitations. Digital platforms are essential, but challenges persist: limited charging stations, inconsistent electricity pricing, and complex multi-stakeholder development. Delays stem from underestimated timeframes and costs. Carriers must optimize routing and load management despite uncertain energy costs. By 2026, project results will shape future logistics and BET expansion strategies. Surveys have revealed key obstacles for BET infrastructure, including accurately forecasting energy needs, ensuring technology reliability and compatibility, securing sufficient grid power, and establishing reservation system for coordinated energy use and supply [5].

2.2 HoLa Project

Two high-performance MCS charging points were installed and used in logistics operations at four locations. Initially, two Combined Charging System (CCS) charge points for trucks were built at five locations along the A2 between Berlin and the Ruhr region, three on the motorway and two in logistics hubs, maximizing specification limits. These sites enabled early integration of electric trucks and tested the real usage of fast charging of electric trucks. By project end, ten CCS and eight MCS points across five locations supported real-life testing and formed the basis for nationwide expansion of this technology. Lead times and costs were underestimated, causing delays. Technical standards decision took long lead time and repeatedly revised, requiring rework. The ZEFES project benefited from insights gained in the HoLa project.

2.3 E-Charge Project

E-Charge is a Swedish system innovation project involving a large consortium to develop, test and demonstrate battery electric long-haul trucks in real logistics flows. Tests in Sweden align with drivers' schedule: 4.5 h driving, 45 min rest and charging, followed by another 4.5 h driving. MCS-supported commercial logistics flows are planned to start in spring 2026 with three MCS charging stations. Phase two started already in 2024, with 38 partners collaborating to put 200 long-haul heavy-duty BETs in operation by 2027. As this scale-up began before the first phase was completed, showing strong industry confidence and stakeholder commitment. Like HoLa and ZEFES, the project has been delayed due to technical issues, mainly related to standardization.

3 Megawatt Charging Ecosystem and Use Cases

3.1 Description of the Main Actors in MCS Ecosystem

The transition to ZE long-haul trucking hinges on a complex ecosystem of actors spanning the transport and energy sectors. A lack of suitable charging infrastructure for HDVs is already "a significant barrier" perceived by truck manufacturers and fleet operators, one that threatens to slow down fleet electrification [6]. Unlike passenger electrical vehicle charging, the deployment of MCS infrastructure for trucks involves many interdependent stakeholders as identified in Fig. 1. Coordination among these diverse actors is crucial, as no single entity can deliver an effective charging network alone.

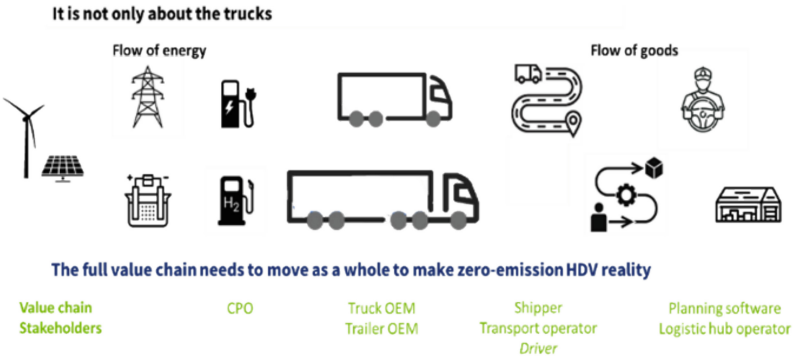


Fig. 1. Value chain around MCS charging

In 2020 the German Automobile association published a study [7] including a roles model for charging infrastructure as seen on Fig. 2. Charging use-cases for truck charging are private, semi-public and public sites, as described below. Additionally, fleet operators might also be depot operators, which implies that Charge Point Operators (CPO) and E-Mobility Service Providers (EMSP) are in different relationships with the site operator. The key roles of each ecosystem player are described in Table 1 and Fig. 2.

The needs and requirements of the ecosystem were investigated through a multi-stakeholder survey and targeted interviews within ZEFES, FLEXMCS and MACBETH

Table 1. Key roles in MCS ecosystem

Player	Role
Front-end CPO	Plan, install, and maintain charging station.
Back-end CPO	Manage software systems for power load and data exchange with EMSP.
Front-end EMSP	Establish interface with users, set B2B pricing, and manage contracts.
Back-end EMSP	Run customer management software, provide apps for access and payment, manage communication with back-end CPO.
OEM (original equipment manufacturers)	Provide trucks with standard charging plugs and communication system.
End User	Truck driver (Logistics provider) and fleet manager using an access tool (App, Card etc.) from EMSP dispatcher.
Site Partner	Host charging stations and may offer site-related service.
Investor	Fund the construction and operation of charging infrastructure.
Distribution System Operator (DSO)	Supply regional power infrastructure.
Energy Supplier	Produces or trades power to site partners and investors.

projects. A more detailed analysis of stakeholder consultation and a summary of findings can be found in Chapters 4 and 5.

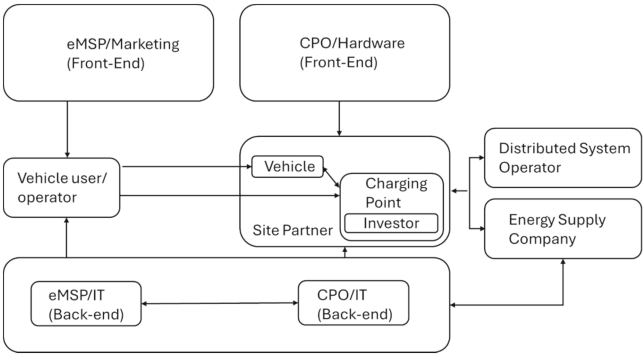


Fig. 2. Roles Model of BET charging system

3.2 Description of the Use Cases from Present Perspectives

MCS charging is designed to deliver higher power levels for HDVs, marine, and aircraft applications. It enables full BET recharging in 45 min, matching the driver's mandatory break after 4.5 h of driving. In case a 15-miute break is taken earlier, the mandatory break can be reduced to 30 min. Compared to CCS, MCS will offer significantly higher power and can charge during shorter breaks, thus improving BET flexibility and features a more robust communication protocol [8]. A study in Germany simulating daily trips of over 2,000 BETs found that low-power depot charging will remain the dominant solution, while high-power charging is a key enabler of long-haul routes [9]. Therefore, MCS may replace CCS as the standard interface in the long term for both fast and slow BET charging (Table 2).

Table 2. Key use cases in MCS

Use Case	Description	Stakeholders
Public	High-power charging (0.7–0.8 MW) at truck stops along the highway or peri-urban areas to avoid logistics delays. Also used for overnight or slow charging (50–100 kW), most probably in separate parking areas. May also be available for slow charging in low-demand period.	Logistic Service Provider (LSP)/Haulier/ End user, CPO, EMSP, DSO, Energy supplier
Semi-public	Charging at warehouses, depots, or terminals where the trucks load or unload. Power levels vary based on stop duration and needs, for example low power levels for overnight charging.	LSP/ Haulier/ End user, CPO (Either LSP or external service provider), EMSP, DSO
Private	Charging at terminals or depots, mainly overnight at lower power. High-power is possible if expected usage and utilization justifies investment.	LSP/ Haulier/ End user, DSO
Safe parking	Safe parking locations are offered to protect both the driver and the cargo. Early MCS adoption is likely due to long-distance customers already paying for this service.	LSP/ Haulier/ End user, CPO, Site Partner

4 Challenges and Barriers for the Adoption of MCS

4.1 Standardization and Security

MCS is built upon several standards across the charging system: ISO 5474-3 for the vehicle, IEC TS 63379 for the cable and connector between the vehicle and the charger, IEC 61851–23-3 for the charger, and ISO 15118-10 for communication protocol. IEC TS

63379 and IEC 61851–23-3 are specifically developed for MCS. CharIN recommends using ISO 15118-20 communication protocol exclusively for optimal user experience and security [8]. To achieve a high level of cyber security, TLS 1.3 (Transport Layer Security) should be used for encrypted communication. Though it may not be necessary for all scenarios, for example where the infrastructure is under strict operational control.

4.2 Perspective of MACBETH Project

Stakeholder consultations with 65 organizations highlight technical, operational, and regulatory factors shaping early MCS deployment in Europe. OEMs report that long-haul MCS-compatible BE-HDVs are entering the market, with 700–750 kW models expected by 2026 and > 1 MW prototypes already in testing. Development began years ago, driven by incentives despite limited charging infrastructure. Current battery technologies are approaching acceptable long-haul ranges (500–700 km), and OEMs do not plan larger batteries due to weight and payload penalties. Instead, they expect mission-specific truck configurations.

Standardization remains a major bottleneck. OEMs delayed MCS launches until ethernet-based protocols were finalized and stress the need for EU-wide alignment on standards and certification [10, 11]. Remaining technical concerns include ergonomics heavy, liquid-cooled cables and interest in robotic assistance. Noise and connector durability issues are largely manageable. CPOs confirm a shift toward megawatt-scale charging, but deployment is uneven: Northern and Western Europe are progressing, while Southern and Eastern regions face limited fleets, weak grid capacity, and slow permitting. Rising CCS performance (e.g., 700 A) creates uncertainty about when to invest in MCS, which remains costlier and is expected to have low utilization for several years. CPO strategies focus on corridor networks and logistics hubs; some consider mixed hubs with Light-Duty Vehicles (LDVs) to improve early utilization, while others prefer truck-only layouts for safety and maneuverability. Motorway service areas and safe and secure truck parking facilities (SSTPAs) warn that high-power charging reduces parking capacity, already scarce across Europe.

Grid connection challenges long delays, high fees, and volatile electricity prices are the biggest obstacles to HDV charging sites. Operators are exploring collective grid requests, cable pooling, and partnerships with local generation or storage. Reservation and access-control systems are emerging to manage power allocation and reduce exposure to price volatility. Digital integration is increasingly important. Stakeholders prioritize reservation systems with pricing incentives, better prediction of charging needs from vehicle data, improved fleet and hub management, and cross-border roaming. Logistics planning tools need visibility of EU-wide charging infrastructure to support Alternative Fuels Infrastructure Regulation (AFIR)-driven deployment.

Interviews also show that MCS scalability depends on aligning deployment models with regional market maturity. Southern and Eastern Member States argue that uniform AFIR distance targets and funding rules are unrealistic given their grid constraints, land limitations, and low utilization. They call for differentiated incentives and more flexible implementation, including exceptions to the 3 km TEN-T exit rule.

Looking ahead, stakeholders broadly view MCS as the long-term HDV standard but expect CCS to remain relevant for at least a decade. A long transition with dual inlets

and hybrid CCS + MCS hubs is anticipated, though estimates for how long dual-plug trucks will be needed vary widely—from the mid-2030s to several decades.

4.3 Findings from FLEXMCS Project

The FLEXMCS stakeholder consultation gathered input from 53 respondents across 10 groups in the charging ecosystem. Their feedback highlights that the main barriers to MCS deployment are systemic rather than technological, with the central challenge being delivering sufficient power where and when it is needed. AFIR sets public charging targets but does not guarantee grid upgrades or mandate MCS rollout. Grid operators face voltage limits, long connection queues, and limited visibility into future demand, resulting in delays and costly reinforcements. CPOs frequently adjust or postpone projects due to grid constraints, sometimes relying on temporary battery storage. Logistics operators encounter unpredictable depot connections and inconsistent site conditions, complicated investment planning and charging routines.

Administrative complexity, limited digitalization, and fragmented permitting processes further slow deployment. Restricted access to land and grid data complicates site selection, and even approved hubs must align with freight flows and accommodate long vehicles. Amenities important for overnight charging often fall outside EU funding. Many hubs lack adequate public charging space and require reconfiguration. Reliable operations depend on predictable access, guaranteed charging, short waits, and transparent pricing. Due to network limits, fleets may need additional vehicles or revised logistics models to maintain service levels. *These insights point to five policy priorities*:

- Link infrastructure targets power delivery. Designated corridor hubs should include pre-agreed grid connection pathways, anticipatory reinforcements at strategic nodes, and flexible connection options supported by active energy management.
- Harmonize and accelerate permitting and grid connections. Establish a standardized, cross-border process with clear service levels, a single contact point, and unified technical checklists. Align grid requests, building permits, and environmental approvals to run in parallel, supported by anticipatory grid investments.
- Scale financing and de-risk early utilization. Increase co-funding for depot charging critical for medium-range missions and for MCS hubs on core corridors to bridge early revenue gaps. OEM incentives can accelerate rollout of MCS-compatible vehicles.
- Enforce interoperability and harmonized standards. Require real-time availability, reservation status, transparent pricing, ISO-compliant communication, and roaming across networks, consistent with AFIR's upfront pricing rules.
- Align road-freight rules with charging. Update driving and rest-time provisions to reflect high-power and overnight charging. Provide targeted funding for basic amenities at corridor hubs to support compliant rest periods.

Stakeholders emphasize the urgent need for unified MCS standards. Key technical challenges include heat and noise management, battery strategies for ultra-fast charging, and ensuring interoperable and flexible equipment. Reliable high-power public charging will depend on reservation systems integrated with fleet/transport planning tools.

To scale these solutions, corridor-level governance is essential. Public authorities, grid operators, CPOs, OEMs, and users must coordinate site prioritization, share grid and freight data, and streamline permitting to accelerate deployment.

5 Conclusions and Recommendations

Europe's large-scale deployment of MCS for battery-electric heavy-duty vehicles depends not only on technology but on a mix of technical, infrastructural, economic, regulatory, and operational factors. Insights from EU projects such as ZEFES, HoLa, and E-Charge, along with MACBETH and FLEXMCS consultations, show that long-haul BEV logistics is feasible and advancing, but progress varies widely across Member States. Rollout strategies must therefore reflect regional differences in grid capacity, land availability, market maturity, and the distribution of zero-emission trucks. Overall, Europe is entering a pivotal stage in the shift to zero-emission long-haul freight. MCS could become the backbone of high-power truck charging, but only if policy, market incentives, and technology evolve together. Coordinated action combining technical readiness with targeted support, digital integration, and logistics-aligned infrastructure planning can reduce uncertainty, speed up the transition, and enable a reliable, interoperable MCS network that supports widespread BEV adoption.

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References

1. Transport & Environment (T&E): Truck CO2: Europe's chance to lead: Position paper on the CO2 standards for heavy-duty vehicles (2023)
2. Safayatullah, M., Elrais, M., Ghosh, S., Rezaii, R., Batarseh, I.: A comprehensive review of power converter topologies and control methods for electric vehicle fast charging applications. IEEE Access. **10**, 40753–40793 (2022). https://doi.org/10.1109/ACCESS.2022.3166935
3. Shoman, W., Yeh, S., Sprei, F., Plötz, P., Speth, D.: Battery electric long-haul trucks in Europe: public charging, energy, and power requirements. Transp. Res. Part D. **121**, 103825 (2023). https://doi.org/10.1016/j.trd.2023.103825
4. Mohamed, A., et al.: Hierarchical control of megawatt-scale charging stations for electric trucks with distributed energy resources. IEEE Trans. Transp. Electrific. **9**, 4951–4963 (2023). https://doi.org/10.1109/tte.2022.3167647
5. Van Damme, S., Huschebeck, M., Loewendorf, H.: ZEFES – Deliverable report – D1.5 supply Chain needs. CORDIS (2023)
6. Bernard, R., et al.: Charging solutions for battery-electric trucks. ICCT White Paper. http://theicct.org. Accessed 20 Mar 2026
7. FAT: Anforderungen an eine elektrische Lade- und Wasserstoffinfrastruktur für gewerbliche Nutzfahrzeuge mit dem Zeithorizont 2030. https://publica.fraunhofer.de/handle/publica/300917 (2021). Accessed 20 Mar 2026
8. CharIN: White Paper Megawatt Charging System (MCS) version 2.0. https://mobilityportal.eu/wp-content/uploads/2025/05/250508_whitepaper_megawatt_charging_system_2.0.pdf (2025). Accessed 20 Mar 2026

9. Plötz, P., Sgaramella, A., Link, S., Speth, D., Gnann, T.: Future demand and costs of megawatt charging for battery electric trucks. Transp. Res. Part D. **130**, 104078 (2024). https://doi.org/10.24406/publica-4927
10. EU: Market Readiness Analysis – Expected Uptake of Alternative Fuel Heavy-Duty Vehicles Until 2030 and Their Corresponding Infrastructure Needs. Publications Office of the European Union (2025). Accessed 20 Mar 2026
11. Backhaus, R.: Charging concepts for battery-electric trucks and buses. MTZ Worldw. **86**, 8–13 (2025)

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Resource Efficiency, Structural Redundancy, and Capacity Redundancy in Charging Network Designs

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Abstract. Transport electrification depends on charging networks that are both cost-efficient and resilient to disruptions. Economic incentives drive deployment toward high utilization and return on investment, producing resource-efficient networks that meet expected demand but lack redundancy. This study evaluates structural redundancy (spatial configuration) and capacity redundancy (excess charging capacity) in charging networks using synthetic freight data for Sweden under localized station failures. Results indicate that structural redundancy exceeds 98% across all network sizes (80–200 stations) under single-station failures and increases from about 86% to nearly 99% under localized multi-station failures as network size grows. Capacity redundancy remains low under single failures but reaches about 15–21% under multi-station failures for a backlog clearance horizon of 6 h. Redundancy is spatially uneven, with structural limitations in sparse regions and capacity pressures along major freight corridors. These findings highlight the need for planning beyond coverage-based targets and targeted public support to ensure structural robustness and system resilience.

Keywords: charging infrastructure planning · robustness · resilience · redundancy · route-based network design

1 Introduction

Transport accounts for about 23% of the EU's greenhouse gas emissions [1]. Electrification is a key strategy for freight decarbonization, but its adoption depends on the availability of reliable and extensive charging infrastructure.

Effective planning of charging infrastructure requires aligning deployment with charging demand and the enablement of electric operations along routes. Transport routes—defined by the geometry and weight of vehicle flows along the road network—determine how much energy vehicles consume, when they are likely to need charging, and where stations should be placed to meet that demand [2]. Moreover, stations interact within a network: nearby stations may share demand, while new stations can enable additional routes and increase

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demand elsewhere. These interdependencies highlight the need for route-based, rather than traffic-based, planning [3].

Infrastructure deployment reflects competing priorities. Private actors aim to maximize revenue by locating stations in high-demand areas [4], while public authorities pursue climate targets [5], coverage, and access. Given these priorities, economic incentives produce highly resource-efficient networks designed to meet expected demand while minimizing idle infrastructure. However, such networks often lack redundancy, with little or no excess capacity or alternative pathways to absorb and recover from disruptions [6]. In transport systems, resilience is broadly understood as the ability to maintain or recover acceptable performance under disruptions arising from station failures, and is closely linked to the presence of redundancy in the network [7,8].

In charging networks, two forms of redundancy are particularly relevant. *Structural redundancy* reflects structural robustness and refers to the ability of the network to maintain BEV route feasibility under the failure of one or more charging stations. *Capacity redundancy* refers to the presence of additional charging capacity at individual stations, enabling them to accommodate redistributed demand over time under station failures. Without capacity redundancy, redistributed demand may lead to service degradation, while sufficient capacity limits its duration and supports recovery to acceptable service levels.

The objective of this study is to evaluate structural and capacity redundancy in charging networks under localized station failures, and to analyze how these dimensions jointly shape BEV route feasibility and service performance under redistributed demand and resulting backlog and recovery dynamics.

2 Literature Review

Research on **placement optimization** of BEV charging infrastructure spans node-, flow/path-, and trajectory-based demand representations, as well as user-, destination-, and route-oriented formulations [9,10]. Charging station siting is typically formulated as a facility-location problem or addressed using metaheuristics and simulation-based methods. While these models aim to maximize accessibility, coverage, or demand capture, they often rely on simplified assumptions about energy use and travel behavior, or become computationally intensive at scale. The Route-Based Network Demand (RBND) method [11] used in this study provides a scalable, simulation-driven alternative that generates resource-efficient networks while supporting failure scenario analysis.

In most placement models, **resilience** is addressed implicitly through redundancy in siting or service-quality constraints [10], without explicitly modeling localized station-failure scenarios. Recent work considers resilience through robust or stochastic optimization under predefined scenarios [12], or evaluates performance degradation under disruptions using simulation or graph-based approaches [13,14]. However, these approaches are often centralized and computationally intensive, with limited support for scalable, route-level analysis or post-optimization assessment. This study addresses this gap by quantifying both structural and capacity redundancy in resource-efficient networks.

Queuing theory is widely used to analyze congestion and capacity in charging systems and has been widely applied for station sizing and service performance evaluation [15,16]. These approaches typically rely on probabilistic representations of arrivals and service processes, often analyzed under steady-state assumptions, to estimate service quality and resource requirements. However, they are primarily suited for normal operating conditions and do not explicitly capture disruption-induced demand redistribution or resulting temporal imbalances between demand and capacity. This highlights the need for approaches that directly model these dynamics, enabling more realistic evaluation of capacity requirements under failure scenarios.

3 Methodology and Experimental Setup

3.1 Robustness and Resilience Definitions

BEV-Feasible Route: A route is BEV-feasible if, given the energy use and charging without detours, the state of charge of the vehicle along the route is always non-negative.

k-Resilient Route: Given the maximum range r of the vehicle and the charging opportunities at stations along its route, the route is k-resilient if under the failure of any (incl. consecutive) k charging stations no two consecutive remaining stations on the route are separated by more than r along the route. Route k-resilience is an upper-bound on BEV-feasibility that depends on a charging plan.

Structural Redundancy: Structural redundancy is a robustness quality and refers to the ability of the charging network to sustain k-resilience of routes under station failure scenarios. A station-level metric for it is the *station vitality level* $v(s)$, i.e., the percent of transport work (in tkm) of routes which pass the station s and require the station's availability for the k-resilience of the routes. A network-level metric for it is the percent of transport work of k-resilient routes.

Capacity Redundancy: Capacity redundancy is a resilience quality and refers to the additional chargers at stations that are required to absorb and recover from station failure scenarios within controlled service quality degradation. Provided that vehicles are placed on a backlog queue when all chargers are occupied and served from the queue when chargers become available, a station's service quality measure is its *maximum backlog clearance horizon* H. The minimum extra chargers $ec(s, H)$ required at a station s are defined as the smallest capacity increase that ensures all backlog is cleared within H. The station is under stress if backlog occurs and no vehicle experiences a waiting time exceeding H.

k-Station Failure Scenarios: To evaluate the relevant and the worst case failures for a set of routes on a charging station network, a k-station failure scenario is defined as the failure of a station s and any $k-1$ other stations that appear in a consecutive sequence along some routes.

3.2 Resource-Efficient and Resilient Charging Network Designs

The baseline charging infrastructure networks are constructed using an improved version of the RBND method [11], a greedy, simulation-driven heuristic. RBND incrementally expands the network by selecting, at each step, the candidate element that yields the highest marginal utility when added. Utility is evaluated by simulating the full Transport Electrification (TE) scenario with the candidate included, capturing its contribution to served charging demand and the network's structural redundancy under k-failure scenarios. The locally optimal greedy expansions do not guarantee global optimality, but effectively balances runtime and solution quality for large-scale applications. The resulting networks serve as resource-efficient and resilient baselines for failure analysis.

The TE scenario consists of five main components: (1) a *transport route dataset*, encoding vehicle movements over a segmented road network of 5 km segments; (2) a *battery electric vehicle (BEV) model*, specified by battery capacity and initial state-of-charge (SoC); (3) an *energy use model*, which estimates segment-level consumption as a function of transport weight and segment length; (4) a *charging infrastructure network*, representing the placement of stations along the road network; and (5) a *probabilistic charging model* where charging only happens on stations along a route in relation to optimistic and rational *Just-in-Time and Just-Enough (JITJE)* charging station and amount choices. Specifically, given the energy use of a transport route and the charging network, JIT stations are defined as stations along the route where the remaining energy is insufficient to reach the next downstream charging opportunity or the end of the route. The JE amount is defined as the minimum of the available battery capacity, the maximum deliverable within rest-time constraints, and the energy needed to complete the route. With respect to a JIT station choice and a JE charging amount choice for a transport route, *alternative charging stations* are defined as upstream stations along the route where within the available battery capacity constraint the same JE amount could be charged, thereby providing an equivalent feasibility effect for completing the remaining journey. Charging demands and events are, for simplicity, with equal probability distributed among JIT stations choices and their alternatives. In addition, charging demand is further represented in time by assigning route departures to discrete time slots and mapping charging events to such slots based on travel time and charging duration(amount), enabling the construction of station-level temporal load profiles and estimation of concurrent charging demand.

3.3 Robustness and Resilience Analysis Case Study

The methodology follows a workflow: charging networks are constructed using RBND, baseline demand and capacity are estimated under normal operation, and failure scenarios simulate feasibility impacts and demand redistribution. Structural redundancy is evaluated through k-resilient routes, while capacity redundancy is estimated as additional chargers required to clear backlog within a horizon H. Results are aggregated to derive station- and network-level indicators.

Table 1. Structural and capacity redundancy across network sizes and backlog clearance horizons.

			Network size				Backlog clearance horizon (hour)
Redundancy	Metric	Failure	80	120	160	200	
Structural	tkm % of k-resilient routes	Single	98.25	98.42	99.99	99.99	
		Multiple	85.64	96.13	98.50	98.71	
Capacity	% of extra chargers required	Single	1.47	1.07	0.94	0.88	3
			0.17	0.00	0.00	0.00	6
			0.04	0.00	0.00	0.00	9
		Multiple	27.42	39.92	36.75	38.18	3
			14.75	21.33	17.64	18.35	6
			10.17	14.08	12.53	11.77	9

The study area is Sweden. The transport route dataset is derived from an improved synthetic route generation method based on calibrated origindestination freight flows between 1,675 NUTS-3 regions [17]. Routes are refined to interregion node pairs and weighted by trip counts in four freight weight classes. The data contains 1.07 million annual routes carrying 10.5 million trips. Annual route counts are converted to daily demand and distributed across time slots. Charging networks of 80, 120, 160, and 200 stations are generated. Parameters include a 500 kWh battery, 375 kW charging power, a maximum rest stop duration of 45 min, and an initial SoC of 50%. Vehicles consume 0.068–0.034 kWh/tkm depending on weight. Redundancy is evaluated under single- and localized multi-station ($k = 5$, defined as a station and its four nearest neighbors) failure scenarios. Capacity redundancy is assessed using a backlog clearance horizon H, with $H = 3, 6$, and 9 hours, and results are aggregated using the 90th percentile to represent near worst-case conditions.

4 Results

Network Redundancy Analytics: Table 1 summarizes structural and capacity redundancy across network sizes and failure scenarios. Structural redundancy remains high under single-station failures, with over 98% of transport work k-resilient across network sizes. Under multi-station failures, it is lower, at about 85% for the 80-station network but increases with network size, reaching 99% for the largest network.

Capacity redundancy shows a contrasting pattern. Under single-station failures, the percentage of extra chargers required is low and approaches zero for larger networks, especially at higher backlog clearance horizons. In contrast, multi-station failures impose substantial capacity requirements. For a short backlog clearance horizon ($H = 3$), additional capacity ranges from 27% to 39%, reflecting overload. As the backlog clearance horizon increases ($H = 6, 9$), these requirements decrease, indicating that temporal flexibility reduces the need for additional infrastructure. Capacity redundancy under multi-station failures shows a non-monotonic pattern, with the highest additional capacity at intermediate network sizes (around 120 stations). This is consistent with an increase in structural redundancy, where more transport work remains k-resilient and is redistributed under failure. **Spatial patterns of structural redundancy for robustness:** Fig. 1 shows the spatial distribution of station-level structural redundancy under multi- failure scenario, where symbol size represents transport work (tkm) and color indicates the share of vital transport work. As the network expands, stations are added near high-demand locations, reducing route dependency on individual stations and lowering their share of vital transport work, reflected in a transition from darker to lighter colors. However, some stations in isolated northern areas retain high shares of vital transport work due to limited nearby charging options and are associated with lower transport work.

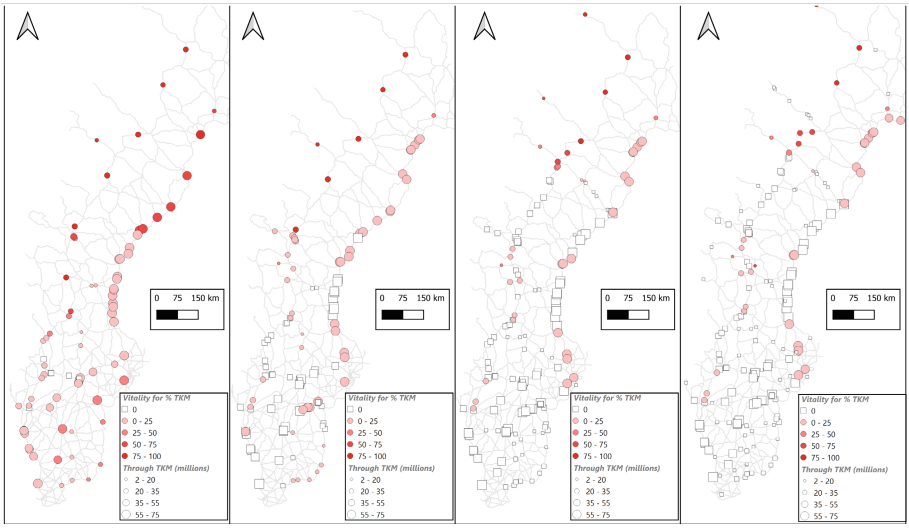


Fig. 1. Structural Redundancy under multi-station localized failure scenario for 80 (left), 120, 160 and 200 (right) stations.

Spatial Patterns of Capacity Redundancy Requirements for Resilience: Figure 2 shows the spatial distribution of station-level capacity

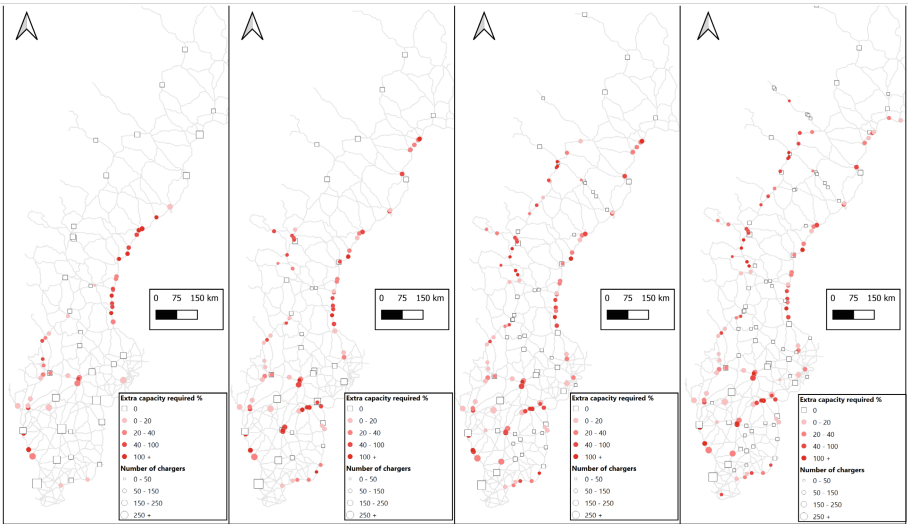


Fig. 2. Percent of extra chargers required under multi-station localized failure scenario with backlog clearance horizon of 6 h for 80 (left), 120, 160 and 200 (right) stations.

redundancy under multi-station failure ($H = 6$), where symbol size represents baseline chargers and color indicates the percentage of extra capacity required. Stations without nearby charging options remain low in extra capacity, as limited demand is redistributed under disruption. As the network expands, stations added near existing locations receive redistributed demand, increasing capacity requirements. With further expansion, demand is distributed across more nearby stations, reducing capacity needs at individual locations. Higher capacity requirements are observed along major demand routes.

5 Discussion and Conclusions

Structural and capacity redundancy play distinct but coupled roles in charging network resilience, with structural redundancy reflecting robustness in preserving route feasibility and capacity redundancy enabling recovery from disruption-induced demand imbalances. However, improvements in structural redundancy may increase capacity stress at intermediate network sizes before further densification distributes demand more evenly. Redundancy also remains spatially uneven, indicating that planning must extend beyond coverage-based targets to account for both structural and capacity requirements.

Two limitations should be noted. First, rerouting is not modeled, so vehicles remain on their original routes even when stations are unavailable. Second, capacity needs are expressed in terms of maximum extra chargers which may overstate minimal requirements. Future studies could incorporate rerouting and investigate the coordination of transports and smart charging of fleets across stations under normal and failure scenarios which can likely substantially reduce

normal and excess capacity requirements. Such actions are other interventions for normal operations and resilience management.

Structural and capacity redundancy are complementary dimensions of resilience, yet existing regulatory frameworks such as AFIR emphasize coverage and accessibility with limited attention to them. Since private actors prioritize efficiency and return on investment, ensuring robustness through structural redundancy and recovery through capacity redundancy under failure scenarios requires public support. The framework developed here quantifies both redundancy dimensions, providing tools for policy interventions beyond coverage targets and guiding reinforcement where resilience gains are greatest.

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References

1. Statista: Greenhouse gas emissions in the EU by sector (2023). https://www.statista.com/statistics/1325132/ghg-emissions-shares-sector-european-union-eu/
2. Saqib, E., Gidófalvi, G.: Methodology for continuous planning of charging infrastructure under uncertainty and change. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRAconference 2024. LNMOB. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-89444-2_91
3. Saqib, E., Gidófalvi, G.: Dynamic adaptive charging network planning under deep uncertainties. Energies **17**, 5378 (2024). https://doi.org/10.3390/en17215378
4. McKinsey: Fast-charging EV infrastructure (2023). https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/shaping-the-future-of-fast-charging-ev-infrastructure
5. European Parliament, Council of the European Union: Regulation (EU) 2023/1804 on alternative fuels infrastructure. Official Journal of the European Union (2023). https://eur-lex.europa.eu/eli/reg/2023/1804/oj
6. Cats, O., Jenelius, E.: Planning for the unexpected: the value of reserve capacity for public transport network robustness. Transp. Res. Part A **81**, 47–61 (2015). https://doi.org/10.1016/j.tra.2015.02.013
7. Jenelius, E., Mattsson, L.-G.: Resilience of transport systems. In: Vickerman, R. (ed.) International Encyclopedia of Transportation, pp. 258–267. Elsevier (2021). https://doi.org/10.1016/B978-0-08-102671-7.10719-5
8. Leviäkangas, P., Aapaoja, A.: Resilience of transport infrastructure systems. J. Infrastruct. Developm. **1**(1), 80–90 (2015). https://doi.org/10.32783/csid-jid.v1i1.11
9. Pagany, R., Ramirez Camargo, L., Dorner, W.: A review of spatial localization methodologies for electric vehicle charging infrastructure. Int. J. Sustain. Transp. **13**(6), 433–449 (2019). https://doi.org/10.1080/15568318.2018.1481243
10. Kchaou-Boujelben, M.: Charging station location problem: a comprehensive review on models and solution approaches. Transp. Res. Part C **132**, 103376 (2021). https://doi.org/10.1016/j.trc.2021.103376

11. Saqib, E., Gidófalvi, G.: Route-based charging infrastructure planning under uncertainty: a heuristic approach for improving network demand and electrification impact. Environmental Research: Infrastructure and Sustainability (2026). https://doi.org/10.1088/2634-4505/aea899
12. Foda, A., Mohamed, M., Farag, H., El-Saadany, E.: A resilient battery electric bus transit system configuration. Nat. Commun. **14**, 8279 (2023). https://doi.org/10.1038/s41467-023-43924-6
13. Abdelaty, H., Foda, A., Mohamed, M.: The robustness of battery electric bus transit networks under charging infrastructure disruptions. Sustainability **15**(4), 3642 (2023). https://doi.org/10.3390/su15043642
14. Wang, H., Abdin, A.F., Fang, Y.-P., Zio, E.: Resilience assessment of electrified road networks subject to charging station failures. Comput.-Aided Civil Infrastruct. Eng. **37**(3), 300–316 (2022). https://doi.org/10.1111/mice.12736
15. Zhang, W., Chen, L.: Capacity design of EV charging stations using real data and queuing optimization. Digital Power **2**(2) (2025). https://doi.org/10.36922/dp.4225
16. Hosseini, M., MirHassani, S.A.: Selecting optimal location for electric recharging stations with queue. KSCE J. Civ. Eng. **19**, 2271–2280 (2015). https://doi.org/10.1007/s12205-015-0153-2
17. Speth, D., Sauter, V., Plötz, P., Signer, T.: Synthetic european road freight transport flow data. Data Brief **40** (2022). https://doi.org/10.1016/j.dib.2021.107786

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Design of a Long Life Bi-directional Off-board Battery Electric Vehicle Charger

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Abstract. Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) have reshaped the power semiconductor landscape by outperforming silicon (Si) MOSFETs, silicon carbide (SiC) MOSFETs, and superjunction devices across a variety of applications and disrupting the order of merit of semiconductor technology choice. Their unique combination of low conduction losses, high switching speeds, and reverse voltage blocking capability enables more compact converter designs and innovative circuit topologies.

In this paper, the design of a bidirectional off-board EV charger featuring a GaN-based totem-pole power factor correction (PFC) stage is presented. The goal was to achieve an operational lifetime of 120,000 h, significantly exceeding the industry norm of 8,000 h, allowing the charger to outlast multiple EV life cycles. This work details the constraints imposed by lifetime, thermal, and performance requirements, outlines the design trade-offs and solutions implemented, and presents an algorithm for extending the lifetime of the device. The results highlight the unique capabilities of the GaN HEMTs in delivering efficient, high power density EV chargers.

Keywords: GaN HEMTs · Battery Electric Vehicle · Long Life Electronics · V2X · Bidirectional Charger

1 Introduction

Many countries are facing a dual challenge: Transitioning to electric mobility while at the same time integrating an increasing amount of intermittent renewable energy resources to the grid. Both processes present significant engineering challenges on their own merit; combined, they threaten the stability of the electric grid [1]. Of particular interest is the interaction between the sharp drop-off in solar energy production between mid-day and dusk and the concurrent rapid increase in demand caused by workers returning home (the cooking peak). This phenomenon is amplified by increasing electric mobility adoption, since returning workers will be plugging in their cars in their home chargers when returning home [2]. Utilizing the electric car fleet as an energy buffer turns the mobility electrification into an opportunity for enabling further intermittent energy source penetration in the grid [3].

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Large scale Vehicle-to-Everything (V2X) adoption requires a new generation of bidirectional chargers, capable of much longer longevity to account for increased operational time during the day [4]. The design and optimization of bidirectional chargers is an active research topic, with various strategies pursued [5]. The strategy to be pursued in each use case depends on the particular challenges of each application. For this paper, a single-phase off-board bidirectional charger is presented, taking into consideration specific constraints imposed by lifetime, thermal and performance requirements and characteristics. Additionally, based on the charger design, an algorithm for mean time to failure (MTTF) estimations is presented.

2 Related Work

A bi-directional battery charger can be broken down into two components: The PFC stage and the DC/DC stage. For the PFC stage, recent work on bidirectional single phase AC/DC front ends converges on totem-pole-based solutions that can both source and sink grid current with high power factor and quick response to changing loads. Niu et al. [6] show that appropriate PWM logic and variable-frequency operation can maintain soft-switching and low loss in both directions, positioning BLTP as a strong candidate for V2G/G2V at moderate power levels. Control strategies increasingly leverage both predictive and adaptive methods. For example, Makhamreh et al. [7] implement MPC on a multilevel (PUC5) bidirectional PFC to minimize grid-current error and stabilize multiple DC outputs—evidence that multilevel front ends can combine bidirectionality with reduced device stress and smaller total harmonic distortion while Lassioui et al. [8] hybridize MPC with PI in an interleaved TP-PFC, reporting better transient behavior, which is critical when toggling between charge and discharge modes in grid-interactive scenarios.

The DC/DC stage of EV chargers has also received significant attention in recent years, with research converging on two dominant topologies: the LLC resonant converter and the Dual Active Bridge (DAB). Garcia Perez et al. [9] provide a comprehensive classification of DAB design methodologies, including transformer parameterization, modulation schemes, and optimization approaches. Building on this, Deepti et al. [10] analyze the efficiency of DABs under single-phase-shift (SPS) control, identifying operating regions where switching losses and circulating currents dominate. On the other side, LLC converters remain the industry's mainstay for on-board chargers due to their soft-switching and high efficiency [4]. When bidirectionality is required, a CLLC setup is used instead [11].

3 Methodology and Analysis

3.1 Modes of Operation

Depending on the place of operation, we categorize an EV charger as private/residential, commercial and public, referring to installation at a private dwelling, a corporate environment (i.e. free charging for employees or charging for the company fleet), or a public installation (i.e. at a highway or at a public parking garage). We also identify four plus one (the EV being unconnected and the charger thus inactive)

possible modes of operation:

- Unconnected: The charger is not connected to a battery and is thus inactive.
- G2V: The charger is connected to the car and is used to charge the battery for mobility use.
- Standby: The charger is connected to both the car and the grid but does not participate in V2X operations.
- V2XHL: The charger is used for V2X operations at half load, either because of low needs or to protect the battery/or charger.
- V2XFL: The charger is used for V2X operations at full load.

V2X operations include both charging and discharging to meet grid needs. From the chargers' perspective, there is no difference in degradation speed between charging and discharging.

3.2 Design Choices

Even if bidirectionality was not a requirement, at the 3.7 kW power level passive bridges or half-passive bridges would not have been taken into consideration, since at this power level the thermal losses from the diodes would both reduce both device efficiency and device lifetime [12].As thus, the selection of a fully active topology does not undermine operation as a simple charger and does not come at an additional material or complexity cost. The choices are thus to be made between the various active circuit topologies with an additional choice of semiconductor technology.

Si IGBT and Si MOSFETs could be quickly dismissed as semiconductor technologies: IGBTs are utilized for much higher power applications, whereas Si MOSFETs would require a complex control scheme and would be less efficient than GaN HEMTs or SiC MOSFETs [13]. The choice between SiC MOSFETs and GaN HEMTs at the 3.7 kW power level comes down to design priorities: GaN HEMTs can operate at a higher switching frequency and minimize losses while SiC offer simpler circuit design and control schemes [14]. GaN technology was the final selection, since GaNs have slightly better bi-directional performance. Between a non-interleaved and interleaved design, we proceeded with an interleaved design, since at this power level it allows for better thermal management and longer device life (Fig. 1).

3.3 Final Design

GaN HEMTs and an interleaved totem-pole PFC were selected for their high efficiency [15] and low EMI [16] in our required power range. A low EMI footprint also allows for less harmonic distortion filtering (i.e. smaller filter). An isolated gate driver with dual output and dead time control was chosen, since it allows for the most flexible control. An active filtering solution was also selected in order to extend the DC-link's capacitor lifetime [17] and reduce device size. Given the relatively low power of the charger, GaN components are also adopted in the DC/DC stage for a uniform, high-efficiency design.

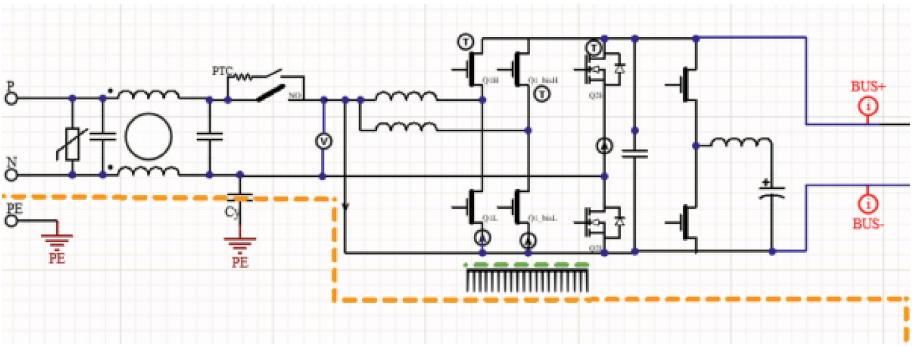


Fig. 1. Circuit diagram of the proposed charger

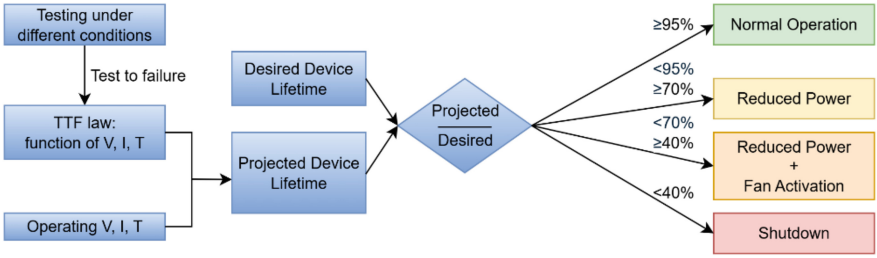


Fig. 2. Lifetime extension algorithm

3.4 Cooling Strategy

Due to the requirement for a long lifetime, fully active cooling is not realistic; The fan would inevitably fail [18]. This was not in line with our plan for a maintenance free charger. As thus, a semipassive cooling strategy was pursued. This led to two developments: Firstly, the design of the heatsink was adjusted to account for the fact that it will have to rely on natural convection most of the time. Secondly, a rationing strategy for cooling was developed. Given our limited available measurements (in situ monitoring is not practical for Rdson or Vth to directly estimate RUL), we developed an algorithm to extend device lifetime through temperature measurement only.

To achieve this, we first developed a thermal model for the device through heatsink and (whole) device simulation. Secondly, test to failure testing for the GaNs devices was undertaken. We proceeded to map the various operational current voltage and temperature combinations to the expected total lifetime of the device (adjusting for the most hostile use case) and developed the following algorithm (Fig. 2):

- If the device is expected to reach 95% of the desired total lifetime under the current conditions, the device continues to operate normally.
- If the device is expected to reach between 70% and 95% of the design lifetime under the current conditions, power derating is activated to reduce stress.
- If the device is expected to reach between 40% and 70% of the design lifetime under the current conditions, the fan is activated.

- For an expected lifetime of 40% or less of the design lifetime, the charger is deactivated. In case of extreme temperature (above 110 °C), the charger also shuts down.

To make sure that there is no oscillation between states, OFF-delay logic is applied, with a 5-min wait time before protective measures are lifted (Table 1).

4 Results

4.1 Use Case

Thanks to working with industrial partners through the ARCHIMEDES project, we had access to usage data we could use to construct the following profiles for a charger's annual operation:

Table 1. Time spent annually in each operating mode by use case. Unit used is hours; Percentage of total time in parentheses

Mode of Operation	Residential	Commercial	Public
Unconnected	4430 h (50%)	6640 h (76%)	6110 h (70%)
G2V Full Load	350 h (4%)	260 h (3%)	1310 (15%)
Standby	350 h (4%)	260 h (3%)	0
V2X Half Load	700 h (8%)	540 h (6%)	305 (3.5%)
V2X Full Load	2970 h (34%)	1080 (12%)	1000 (11.5%)

It is interesting to note that, rather counterintuitively, for a bidirectional charger it is the residential use case that is most demanding: This is due to the fact that the car is plugged in for a large part of the day and this available for energy arbitrage operations. This has also been noted by other authors as well [19]. Given that operation at half power reduces steady state delta temperature compared to ambient by half [20] and the charger is expected to function with passive cooling for most of the time (and as such, a high delta temperature), we expect operation at half load not to degrade the device much [21] (Table 2).

4.2 Impact of Cooling Algorithm

Our simulations show that our simple algorithm can extend lifetime significantly, at a cost of availability of full power. While analysis is still on-going, we can present the following results for mean ambient temperature of 20 °C with simple seasonal variation:

We notice that lifetime can be significantly extended by the algorithm, and fan activation remains relatively low: This is because of the "lifetime hours" budget saved by operating in half power without active cooling. This significant difference appears because the aging of GaN HEMTs is more sensitive to higher temperatures than that of SiC MOSFETs [22, 23].

Table 2. Time distribution required to achieve extended lifetime

Desired Lifetime as % of lifetime at full power	Time spent at full power	Time spent at half power	Time spent at half power plus cooling
100%	100%	0%	0%
110%	89%	7%	4%
120%	79%	13%	8%
130%	71%	18%	11%
140%	64%	22%	14%
150%	58%	26%	16%

5 Conclusions

It is relatively early to draw conclusions about the benefits of GaN HEMT technology since it is still a relatively new technology with devices often not having operated enough to validate the results of simulations and accelerated aging tests. Also, the technology is rapidly developing, and the failure statistics of today's devices will not be applicable to tomorrow's devices. However, GaN HEMTs appear to be capable of enabling the breakthrough from reliability (8000 operational hours) to long life (15 years device lifetime).

In this paper we show that device life can be significantly extended through selective power degrading and cooling, allowing engineers to extend lifetime without having to overengineer the heatsink or the power electronics. On going work will focus on a case-by-case validation through simulating the effects of differing mean ambient temperatures and differing seasonal temperature variations. Future work will focus on refining the cooling algorithm and incorporating economic analysis into its design.

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References

1. Abdelaziz, M.A., Ali, A.A., Swief, R.A., Elazab, R.: Optimizing energy-efficient grid performance: integrating electric vehicles, dstatcom, and renewable sources using the hippopotamus optimization algorithm. Sci. Rep. **14**(1), 28974 (2024). https://doi.org/10.1038/s41598-024-79381-4
2. Powell, S., Cezar, G.V., Min, L., Azevedo, I.M.L., Rajagopal, R.: Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption. Nat. Energy. **7**(10), 932–945 (2022). https://doi.org/10.1038/s41560-022-01105-7
3. Kohole, Y.W., Wankouo Ngouleu, C.A., Fohagui, F.C.V., Tchuen, G.: A comprehensive comparison of battery, hydrogen, pumped-hydro and thermal energy storage technologies for hybrid renewable energy systems integration. J. Energy Storage. **93**, 112299 (2024) https://www.sciencedirect.com/science/article/pii/S2352152X24018851

4. Wouters, H., Martinez, W.: Bidirectional onboard chargers for electric vehicles: state-of-the-art and future trends. IEEE Trans. Power Electron. **39**(1), 693–716 (2024) https://ieeexplore.ieee.org/document/10265141
5. Kumar, P. et al.: A comprehensive review of vehicle-to-grid integration in electric vehicles: powering the future. Energy Convers. Manage. X. **25**, 100864 (2025) https://www.sciencedirect.com/science/article/pii/S2590174524003428
6. Niu, P., Guo, J., Gao, Z., Yan, J., Gao, S.: Research on improved technology of totem-pole bridgeless pfc circuit based on triangular current mode. Energies. **18**(14), 3886 (2025) https://www.mdpi.com/1996-1073/18/14/3886
7. Makhamreh, H., Kanzari, M., Trabelsi, M.: Model predictive control of a puc5-based dual-output electric vehicle battery charger. Sustainability. **15**(19) (2023) https://www.mdpi.com/2071-1050/15/19/14483
8. Lassioui, A. et al.: A combined mpc and pi control strategy for bidirectional interleaved totem pole pfc converters in electric vehicle g2v and v2g applications. In: E3S Web of Conferences, vol. 601, p. 00050 (2025) https://www.e3s-conferences.org/articles/e3sconf/pdf/2025/01/e3sconficegc2024_00050.pdf
9. Garcıa Perez, R.A., Munoz-Cruzado-Alba, J., Galvan Dıez, E., Carrasco Solıs, J.M.: Classification of design methodologies of dual active bridge-based resonant converters for battery energy storage systems. Electronics. **13**(23) (2024) https://www.mdpi.com/2079-9292/13/23/4748
10. Deepti, T., Deepa, K., Alexander Stonier, A., Peter, G., Anoop, A., Ganji, V.: Development and efficiency analysis of dual active bridge converter employing sic devices using tms 320f280039. IET Circuits Devices Syst. **2025**(1), 6336609 (2025) https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/cds2/6336609
11. Malan, W.L., Vilathgamuwa, D.M., Walker, G.R.: Modeling and control of a resonant dual active bridge with a tuned cllc network. IEEE Trans. Power Electron. **31**(10), 7297–7310 (2016). https://doi.org/10.1109/TPEL.2015.2507787
12. Mayer, R., Berrehil El Kattel, M., Jeske, E., Oliveira, G.: S.V.: efficiency evaluation of a bridgeless totem-pole power factor correction rectifier using Gan and insulated gate bipolar transistor devices for battery charger. Int. J. Circuit Theory Appl. **49**(4), 1133–1146 (2021) https://onlinelibrary.wiley.com/doi/abs/10.1002/cta.2894
13. Joshi, V., Pande, P., Jadli, U., Chaturvedi, M., Nautiyal, P., Bisht, C.: Performance comparison of si, sic and Gan based power mosfet/hemt using dc-dc boost converter. AIP Conf. Proc. **2978**(1), 020001 (2024). https://doi.org/10.1063/5.0183660
14. Prado, E.O., Bolsi, P.C., Sartori, H.C., Pinheiro, J.R.: An overview about si, superjunction, sic and Gan power mosfet technologies in power electronics applications. Energies. **15**(14), 5244 (2022) https://www.mdpi.com/1996-1073/15/14/5244
15. Huang, Q., Huang, A.Q.: Review of Gan totem-pole bridgeless pfc. CPSS Trans. Power Electron. Appl. **2**(3), 187–196 (2017). https://tpea.cpss.org.cn/uploads/soft/171027/20173187.pdf
16. Zhou, L., Wu, Y., Honea, J., Wang, Z.: High-efficiency true bridgeless totem pole pfc based on Gan hemt: design challenges and cost-effective solution. In: Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 1–8 (2015). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7149192
17. Pradeep Kumar, V.V., Fernandes, B.G.: Switching strategy for improving the lifetime of dc-link capacitor in a fault-tolerant active power decoupling topology. IET Power Electron. **11**(1), 52–61 (2018) https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-pel.2017.0202

18. Jin, X., Ma, E.W.M., Chow, T.W.S., Pecht, M.: An investigation into fan reliability. In: Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM-2012 Beijing), pp. 1–7 (2012). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6228836
19. Menchaca Santos, D., Th¨une, P., Zepter, J.M., Marinelli, M.: Business cases for degradation-aware bidirectional charging of residential users and heavy-duty vehicle fleets. eTransportation. **23**, 100389 (2025) https://www.sciencedirect.com/science/article/pii/S2590116824000791
20. Volosov, V. et al.: Positive bias temperature instability in sic-based power mosfets. Micromachines. **15**(7), 872 (2024) https://www.mdpi.com/2072-666X/15/7/872
21. Li, X. et al.: A thermal boundary resistance measurement method based on a designed chip with the heat source separated from the temperature sensor. Appl. Phys. Lett. **122**(7), 073501 (2023). https://doi.org/10.1063/5.0137965
22. Yu, L.C., Dunne, G.T., Matocha, K.S., Cheung, K.P., Suehle, J.S., Sheng, K.: Reliability issues of sic mosfets: a technology for high-temperature environments. IEEE Trans. Device Mater. Reliab. **10**(4), 418–426 (2010). https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5580064
23. Wu, Y., Chen, C.Y., del Alamo, J.A.: Activation energy of drain-current degradation in Gan hemts under high-power dc stress. Microelectron. Reliab. **54**(12), 2668–2674 (2014) https://www.sciencedirect.com/science/article/pii/S0026271414003990

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Multi-port Megawatt Charging System (MCS) Hub Optimization Framework for Light and Heavy-duty Electric Vehicles

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Abstract. The road freight electrification requires charging hubs that can meet diverse operational needs at highway rest areas and logistics depots. These charging sites must accommodate both heavy-duty trucks and passenger vehicles, with charging demand varying across use cases such as long-haul rest breaks, overnight depot charging, and mixed urban–highway operations. To enhance flexibility and resilience, hub layouts may also integrate battery energy storage systems (BESS). This paper presents an integrated optimization framework for multi-port Megawatt Charging System (MCS) hubs that serve both heavy-duty (MCS) and light-duty (CCS) vehicles. The framework effectiveness is demonstrated through a case study on a 100 m × 100 m demo site. In the demonstration, the pareto-optimal layouts achieved installation costs of approximately €16.1 million, cabling losses of 28.4–28.7 kWh, and compact land use of 4.1%. Sensitivity analysis highlighted system efficiencies up to 98.9%, with balanced trade-offs between unit cost (0.3–0.55 €/kW) and charging port availability (52–55%). These findings illustrate the potential of systematic optimization to enable scalable, cost-efficient deployment of MCS infrastructure.

Keywords: Electric Road Transport · MCS · Charging Infrastructure Planning · Multi-Objective Optimization

1 Introduction

The electrification of heavy-duty transport (HDV) is essential to achieving net-zero targets, as trucks contribute nearly one-third of on-road CO_2 emissions while representing only a minor share of vehicle fleets [1, 2]. There is a critical barrier to large-scale adoption is the lack of high-power charging infrastructure. The emerging Megawatt Charging System (MCS) standard, supporting up to 3.75 MW charging (1,250 V, 3,000 A), is designed to enable rapid recharging during regulated breaks and thus facilitate long-distance battery-electric trucking [3, 4]. However, the enormous total installation

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and operational costs of megawatt-scale charging hubs present significant challenges. The levelized infrastructure costs for MCS project can be reduced to € 0.03–0.07/kWh by 2050 under high-utilization scenarios, with annual European network investments of € 6.6–10.8 billion [5]. In parallel, cost analyses at the grid and network level show that locational differences in grid tariffs and network charges may lead to significant variation in per-charge cost across jurisdictions. For instance, a comparative study between Poland and Germany reveals that network cost differentials can reach as much as 2.6 cents/kWh, which for a 500-kWh truck battery translates to a €13 per charge difference, and in certain cases over € 40 per charge when total electricity pricing differences are included [6]. These economic anomalies can lead to underutilization of charging site in some regions and overloading in others, aggravating grid integration and planning complexity. To address these challenges, the design of a multi-port MCS hub that can simultaneously serve both HDV and LDV leveraging spatial, electrical, and economic synergies—is a promising pathway to improving utilization and reducing cost. There are extensive research has been conducted on EV charging infrastructure optimization spans network siting/sizing, station deployment. The traditional methodology is to formulate multi-objective siting/deployment with metaheuristics (GA/NSGA-II/III) to minimize cost and travel/queuing impacts while meeting demand and grid limits using GA-based cost minimization and subsequent NSGA-III variants for multi-objective deployment [7]–[10]. However, traditional optimization is implemented to search an optimal location for a EV charging station in a region rather than how to arrange components within a site i.e., transformer/BESS/converters/dispensers routing, cabling distances, thermal/safety clearances, and land use. MCS-relevant studies emphasize grid-side integration and component design but provide limited treatment of fine-grained spatial layout.

In this paper, an integrated optimization framework for multi-port MCS hub design is presented that simultaneously addresses the optimized spatial placement of energy components within the site layout. The framework incorporates a mathematical model capturing spatial layout, cable energy loss, land utilization, and thermal and operational safety constraints. A stochastic multi-objective metaheuristic solution strategy is employed to resolve trade-offs among total installation cost, cabling energy losses, and operational flexibility. The effectiveness of the approach is demonstrated through a highway-oriented case study of a 100 m × 100 m rest area site, comprising 31 components including a 7 MVA transformer, 600 kWh BESS units, five 1.2 MW converters, and both MCS and CCS dispensers. The optimization yielded multiple Pareto-optimal layouts, with further sensitivity analysis highlighting how variations in system efficiency, grid pricing, and charging port utilization rates influence hub configuration. These results provide insights for scalable and cost-efficient deployment of MCS hubs.

2 Proposed Multi-Objective Optimization Methodology

Figure 1 illustrates the proposed multi-objective optimization framework for the spatial design and sizing of a Multi-port MCS hub, integrating agent-based modeling, model-in-loop (MIL), and evolutionary layout optimization. At the top level, an agent-based load profile generator simulates port-wise energy demand based on road topology, HDV traffic data, truck models, and driving patterns. The resulting load profiles, along with transport

route information, are passed to the MIL-based optimal design module, which determines transformer sizing, BESS capacity, and converter ratings under given technical and economic constraints.

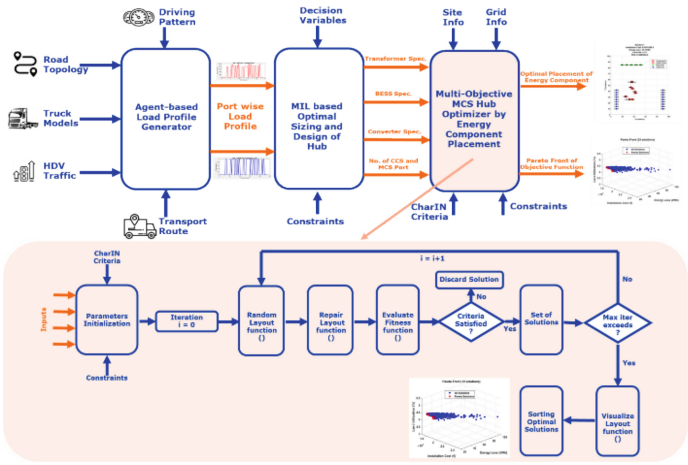


Fig. 1. Overall diagram of layout optimization framework for multiport megawatt charging station

The defined decision variables and constraints are processed by the Multi-objective MCS Hub Optimizer, which determines optimal component placement to minimize installation cost, cable energy loss, and land utilization. After parameter initialization based on CharIN criteria, candidate layouts are iteratively generated, repaired to satisfy spatial constraints, and evaluated through a fitness function. Feasible solutions are retained to form a Pareto front of non-dominated designs, enabling stakeholders to select configurations that balance economic, technical, and spatial performance requirements.

3 Mathematical Formulation of Objective Functions

The aim of this optimizer is to optimize the spatial layout of multiple energy components (transformers, converters, switchgears, batteries, MCS and CCS ports) within a bounded 2D site (X × Y) unit, minimizing cost, energy loss, and land usage, subject to physical, electrical, thermal, and safety constraints. The detail of mathematical formulation is discussed in following subsection:

3.1 Decision Variables

The decision variables showed in Eq. (1) in the MCS hub optimizer define the spatial placement of energy and charging components within a bounded 2D site. These variables are continuous, representing the x and y coordinates of each component. Let x is the decision variable of N number of energy components.

$$\boldsymbol{x} = \left[x_1, y_1, x_2, y_2, \ldots\ldots\ldots, x_N, y_N, \right] \epsilon \, \boldsymbol{R}^{2N} \tag{1}$$

Here, each (x_i, y_i) represents the coordinate of the center position of i^{th} component on the layout and $\boldsymbol{x} \in [0, X]^N \times [0, Y]^N$. The demo site is considered as a 2D plane with $(X \times Y)$ unit.

3.2 Evaluate Fitness Function

The evaluate fitness function is the core of the optimization logic, used to score each layout based on a multi-objective evaluation. Its purpose is to quantify the performance of a candidate layout in terms of three primary objectives: total installation cost, energy loss, and land utilization.

Objective Function Formulation: The function begins by reshaping the layout vector into (x, y) positions and retrieving component sizes and costs. It then computes installation cost by using following Eq. (2) – (7).

$$C_{comp} = \sum_{i=1}^{N} c_i \tag{2}$$

$$C_{cab} = \sum_{i=1}^{N} \sum_{j=i+1}^{N} w_i * w_j * d_{ij} * *Cable\ unit\ cost(€/m) \tag{3}$$

$$d_{ij} = \left\| P^i(x_i, y_i) - P^j\left(x_j, y_j\right) \right\| = \sqrt{\left(x_i - x_j\right)^2 - \left(y_i - y_j\right)^2} \tag{4}$$

$$C_{const} = A_{used} * Construction\ unit\ cost\left(€/m^2\right) \tag{5}$$

$$A_{used} = (x_{max} - x_{min}) \times (y_{max} - y_{min}) \tag{6}$$

$$C_{install} = C_{comp} + C_{cab} + C_{const} + C_{log} \tag{7}$$

Here, c_i denotes the component purchase cost, w_i, w_j are the weighting factor for component cable distance. Moreover, d_{ij} represents the distance between components for cabling. The used area for construction A_{used} is estimated by using minimum and maximum usage of site dimensions in XY direction. Energy loss in the cable is evaluated by calculating the electrical distance between all pairs of power components using a predefined loss factor per meter area using Eq. (8). Lower-level headings remain unnumbered; they are formatted as run-in headings.

$$E_{Loss} = \sum_{i=1}^{N} \sum_{j=i+1}^{N} d_{ij} * I_{ij}^2 * Per\ unit\ resistivity\ (\Omega/m) * t_{act} \tag{8}$$

$$A_u = \frac{\sum_{i=1}^{N} l_i * h_i}{A_{site}} * 100 \tag{9}$$

$$optimize\ f(x) = k_i C_{install} + k_{loss} E_{Loss} + k_u A_u + Pf \tag{10}$$

Penalty Factor: Penalty terms are also included for violations such as overlapping components, insufficient spacing between converters (thermal penalty), and breaches of safety distances between power components and MCS/CCS ports. The penalty factor is estimated for components (Pf_{comp_th}) and ports (Pf_{port_sf}). These factors depends on the threshold distance for thermal penalty and operational safety penalty such as d_{comp_th} is the threshold distance for thermal penalty and d_{port_sf} represents the same for the operational safety penalty. For instance, the MCS port should be maintain d_{MCS} distance, otherwise the penalty factor for that should be added to the Pf which influence the objective function. The weighting factors (k_i, k_{loss}, k_u) can be defined as priority among total cost, cable energy loss, and land utilization.

Constraints: Constraint variables enforce critical spatial relationships and safety requirements. Fixed distance parameters mandate specific separations between key power components: d_{comp_th} meters between power components. The port arrangement constraints maintain exact spacing patterns d_{MCS} meter intervals for MCS ports in a linear configuration and d_{CCS} meter spacing for CCS ports in a columnar arrangement. Safety buffers establish minimum clearance zones: d_{MCS_sf} meter radius around MCS ports and d_{CCS_sf} meter radius around CCS ports from all power equipment, while thermal constraints require converters to maintain at least d_{comp_th} meter separation to prevent overheating.

4 Case Study Results and Discussions

This case study investigated the optimal spatial layout of a multi-port Megawatt Charging Station (MCS) hub designed to support simultaneous charging for both heavy-duty electric trucks and passenger electric vehicles. The layout optimization is performed on a bounded site area of 100 m × 100 m, within which all energy and charging components must be placed subject to physical, electrical, and regulatory constraints. Table 1 summarizes the components, including their dimensions, power/energy ratings, costs, and associated indices used in the layout vector. The weighting factors are defined $k_i = 50\%$, $k_{loss} = 30\%$, $k_u = 20\%$. The approach can be scaled hierarchically from individual hub optimization to regional network though cluster coordination. Component libraries can be reused, while parallel computing handles increased complexity. Multi-objective Pareto fronts aggregate across scales, maintaining optimality from single hubs to national networks. The optimization settings overview for different hub scales is shown in Table 2 below:

Thus, parallel computing is recommended to avoid computation complexity. The initial layout for small hub is generated using a hybrid rule-based and randomization method that ensures realistic placement and electrical connectivity. The transformer is positioned randomly within the site, followed by directional placement of BESS units and switchgear using fixed radial distances (e.g., 30 m from transformer to BESS, 8 m from BESS to switchgear). Converters are arranged in a grid near the switchgear, and charging ports are aligned in uniform rows and columns to ensure accessibility. Minimum spacing and safety distances are enforced through geometric constraints and repair functions. The best 2 optimized layout for multiport megawatt charging station is listed in Table 3 below:

Table 1. Components of multiport megawatt charging station considered for layout optimization

	Unit	Unit Capacity	Dimension	ID	Unit Price
Transformer	1	7 MVA	4*3	[1]	50
HV-LV Switchgear	1	–	3*2	[2]	35
BESS	2	600 kWh	3*2.5	[3, 4]	45
Power Converter	5	1.2 MW	1.8*1.2	[5–9]	25
MCS Dispenser	5	1.1 MW	1.2*0.6	[10–14]	12
CCS Dispenser	18	350 kW	0.6*0.4	[15–32]	6

Table 2. Optimization settings for charging hub optimization at different scale

	Pop. Size	Max. Iter	Components	Variables	Runtime
Small Hub (Case Study)	100	20	31	70	1 min
Medium Hub	400	50	75	150	15 min
Large Hub	1000	100	150	300	120 min

Table 3. The best 2 layout optimization solutions for multiport MCS

	TCO (mil. €)	Cable Energy Loss (kWh)	Land Utilization (%)
Solution 1	16.134	28.73	4.1
Solution 2	16.146	28.59	4.1

Figure 2(a) illustrates the Pareto front comprising 32 non-dominated solutions, optimized across three objectives: installation cost, energy loss, and land utilization. Pareto-optimal layouts (in red) represent the best trade-offs, exhibiting minimal energy loss and cost within compact land use boundaries, compared to the broader set of feasible solutions (in blue). Figure 2(b) presents the sensitivity-based Pareto front for multiport MCS layout solutions, highlighting the trade-offs among cost (€/kW), efficiency, and charging port availability. There is a clear inverse relationship that is observed, where higher efficiency and port availability are generally associated with lower cost. The color gradient represents normalized objective values, revealing that optimal solutions cluster in the low-cost, high-efficiency region, thereby guiding designers toward configurations with balanced operational and economic performance.

There are three preferred solutions for balanced operational and economic performance e.g. (1) minimum cost solution, (2) maximum efficiency solution, and (3) maximum charging port availability solution. The summary of the solutions is shown in Table 4 below:

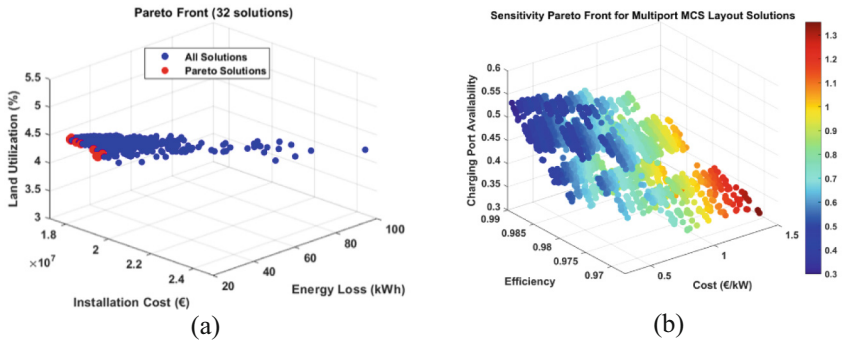


Fig. 2. 3D pareto front of performance indices trade-off for all possible solutions (a) trade-off between total installation cost, cabling energy loss, land utilization. (b) trade-off between the system efficiency (considering only cabling energy loss), unit cost, and charging port availability.

Table 4. The optimal performance indices for balanced operational and economic performance of Solution 1

	Minimum Cost	Maximum Efficiency	Maximum Port Availibility
System Efficiency (%)	98.5	98.9	97.97
Unit cost (€/kW)	0.3	0.4	0.55
Charging Port Availability (%)	52.63	52.21	54.67

5 Conclusions

This paper introduced and implemented an integrated optimization framework for the spatial design and configuration of multi-port Megawatt Charging System (MCS) hubs serving both heavy-duty and light-duty electric vehicles. The framework combined agent-based demand modeling with a multi-objective evolutionary optimizer to minimize installation cost, cabling energy losses, and land utilization under technical and operational constraints. The case study demonstrated that optimized layouts can significantly reduce total installation cost, with best solutions achieving approximately €16.1 million compared to less efficient alternatives exceeding €17 million. Cable energy losses were consistently minimized to around 28.4–28.7 kWh, while maintaining compact land use of 4.1% across all Pareto-optimal solutions. Furthermore, sensitivity analysis revealed that balanced designs can deliver system efficiencies up to 98.9%, with favorable trade-offs in cost per kW and charging port availability. These findings underscore the potential of systematic optimization to enhance cost-efficiency, reliability, and scalability of MCS infrastructure deployment.

References

1. Energy, Climate Change, and Environment, European Commission: Heavy-duty Vehicles. https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/heavy-duty-vehicles_en. Accessed 01 Sep 2025
2. Boston Consulting Group: Impact Assessment of the Transition to Zero Emission Trucks in Europe. Presented on Transport and Environment. https://www.transportenvironment.org/uploads/files/20230919-Transport-Environment_EU-Truck-CO2-Standards_Final_Report_TE_vF.pdf. Accessed 01 Sep 2025
3. Jentzsch, R., Danieli, M.: Megawatt charging system: charging at 3.75 MW, the next step in electromobility. In: VECTOR Informatik GmbH, Translation of a German Publication in Emobility Technology (2024) https://cdn.vector.com/cms/content/know-how/_technical-articles/Megawatt_Charching_System_MCS_202411_TechnicalArticle_EN.pdf
4. FAIST: Megawatt Charging System (MCS): Infrastructure Readiness for High Power Electrification (2025). https://www.faistgroup.com/news/megawatt-charging-systems-mcs/. Accessed 01 Sep 2025
5. Plotz, P., Sgaramella, A., Link, S., Speth, D., Gnann, T.: Future demand and costs of megawatt charging for battery electric trucks. In: 38th Electric Vehicle Symposium (EVS38), Gothenburg, Sweden (2025) https://publica-rest.fraunhofer.de/server/api/core/bitstreams/c7b00dbe-d594-4ccf-9e01-6f70eecb5ca0/content
6. Heildermeier, J., Jahn, A.: The power of moving loads: cost analysis of megawatt charging in Europe. In: Project Report by Regulatory Assistanct Project (RAP) (2024) https://euagenda.eu/upload/publications/rap-jahn-hildermeier-cost-analysis-megawatt-charging-2024-feb.pdf
7. Lazari, V., Chassiakos, A.: Multi-objective optimization of electric vehicle charging station deployment using genetic algorithms. Appl. Sci. **13**, 4867 (2023). https://doi.org/10.3390/app13084867
8. Abdullahi, M.R., Lu, Q.-C., Hussain, A., Tripura, S., Xu, P.-C., Wang, S.-C.: Location optimization of EV charging stations: a custom K-means cluster algorithm approach. Energy Rep. **12**, 5367–5382 (2024). ISSN 2352-4847). https://doi.org/10.1016/j.egyr.2024.09.075
9. Erdogan, N., Kucuksari, S., Murphy, J.: a multi-objective optimization model for EVSE deployment at workplaces with smart charging strategies and scheduling policies. Energy. **254**, 124161 (2022). ISSN 0360-5442,). https://doi.org/10.1016/j.energy.2022.124161
10. Mohammed, A., Saif, O., Abo Adma, A., M.: Multi-objective optimization for sizing and placing electric vehicle charging stations considering comprehensive uncertainties. Energy Inform. **7**, 131 (2024). https://doi.org/10.1186/s42162-024-00428-x

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Ending the Queue Anxiety: Standardized Reservation and Queue Management for Electric Vehicle Charging Stations as a Strategic Enabler of Sustainable Mobility

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Abstract. The rapid spread of electric mobility is a cornerstone of the European Union's strategy to achieve climate neutrality by 2050. However, the growing prevalence of electric vehicles (EVs) challenges charging infrastructure through waiting times, congestion, and user dissatisfaction. While infrastructure expansion has received much attention, less emphasis has been placed on user-oriented solutions for managing access. This paper presents results of the SeQueRe project ("Standardized Management of Queues and Reservations for EV Charging Stations"), which addresses these issues with an interoperable framework for digital queuing and reservation systems. Based on customer journey mapping and qualitative interviews, the study identifies key user needs such as transparency, fairness, and planning security. Personas reveal mobility patterns including long distance travelers, commuters, and urban users, each with specific requirements. Results show that acceptance of digital queues depends on perceived fairness and clear communication, while reservations are valued by users requiring high planning security. By integrating user needs early, SeQueRe advances a socio technical approach that reduces "queue anxiety" and promotes efficient infrastructure use. The findings underscore the importance of user centered design for scaling sustainable electric mobility across Europe.

Keywords: EV Charging Management · Queuing Theory · Reservation Systems · User-Centric Mobility · Digital Infrastructure Interoperability

1 Introduction

Decarbonizing transport is a key challenge for European climate policy, with electric vehicles (EVs) as a central solution [1]. However, the uptake of EVs depends not only on vehicle technology but also on the availability and reliability of charging infrastructure. Despite ongoing expansion, users frequently encounter waiting times, congestion, and unreliable information on charging station availability [2] [3].

While research and policy have long focused on range anxiety [4, 5], a new challenge is emerging: queue anxiety, referring to uncertainty and stress related to waiting

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for charging opportunities. Unlike range anxiety, which can be mitigated through infrastructure expansion, queue anxiety requires coordinated access management addressing predictability, fairness, and efficiency [6, 7].

Existing studies primarily address technical and economic aspects of charging infrastructure [6, 8], while user perceptions of access management remain underexplored. In particular, digital queuing and reservation systems are often implemented in isolated, operator-specific solutions, limiting interoperability and scalability.

Addressing this gap, the SeQueRe project investigates standardized frameworks for digital queue and reservation systems at public charging stations. This paper presents empirical insights into user needs, acceptance conditions, and design implications for user-oriented charging management systems.

1.1 The SeQueRe Project

Against this backdrop, the SeQueRe project ("Standardized Management of Queues and Reservations for EV Charging Stations") aims to develop a holistic, standardized framework for digital queuing and reservation functions. The project is carried out by a consortium of academic and industrial partners in Germany and is funded by the German Federal Ministry for Digital and Transport (BMDV) under the Electromobility Funding Directive, coordinated by NOW GmbH and implemented by Project Management Jülich (PtJ).

By combining technical development with user-centered methods such as customer journey mapping, qualitative interviews, and personas, SeQueRe aims to reduce queue-related uncertainty, optimize infrastructure utilization, and accelerate the transition to sustainable mobility.

1.2 Aim and Contribution of This Article

This article presents the initial empirical results of SeQueRe, focusing on user needs and requirements for digital queue and reservation systems. Specifically, it addresses the following research questions:

1. What are the most important needs and problems of EV users with regard to charging infrastructure?
2. How can digital queuing and reservation functions meet these needs?
3. What implications does this have for the design of user-oriented charging management systems?

By answering these questions, the paper contributes to the broader discussion on connected transport systems, urban infrastructure management, and zero-emission vehicles. It promotes a socio-technical perspective by linking insights from user experience research with the development of interoperable digital systems for electric mobility.

2 Methodology

To ensure methodological transparency and analytical rigor, additional details on sampling, data collection, and analysis procedures are provided. Participants for the qualitative phases were recruited through purposive sampling, aiming to capture a diverse

range of electric vehicle users with regard to mobility patterns, technological affinity, and socio-demographic background.

In the initial phase, customer journey mapping was based on qualitative data collected through interviews, focus groups, and an online survey conducted along different stages of the user journey. In total, 60 participants took part in the online survey (51 male, 7 female, 2 diverse), primarily from Germany and Austria. The sample covered urban (50%), suburban (33%), and rural (17%) contexts and was characterized by a relatively high level of education (73% with a university degree) and income levels predominantly above €4,000 per month.

In the subsequent qualitative phase, in-depth interviews combined with prototype testing were conducted with 10 participants (8 male, 2 female). These sessions were carried out remotely and lasted up to 60 min. Participants interacted with click-dummy prototypes for both queuing and reservation systems and evaluated functionality, usability, and perceived value.

All qualitative data were transcribed, coded, and analyzed using a thematic analysis approach. An initial coding framework was developed deductively based on the research questions and iteratively refined through inductive category development. Coding consistency was ensured through researcher alignment and iterative discussion.

Furthermore, methodological triangulation was applied by combining customer journey mapping, survey data, semi-structured interviews, and prototype testing. This multimethod approach strengthens internal validity by linking user perceptions, behavioral expectations, and interaction-based feedback with prototypical system designs.

3 Results

3.1 Analysis of the Customer Journey

The customer journey analysis revealed recurring challenges across all phases of the charging process. Users reported fragmented information due to reliance on multiple apps, leading to reduced trust in data reliability. During planning and decision-making, inaccurate or outdated availability information resulted in inefficient routing and uncertainty. At charging stations, the absence of transparent queue management caused stress related to unpredictable waiting times. These issues frequently led to dissatisfaction, with charging experiences negatively affecting overall perceptions of electric mobility and contributing to queue anxiety.

3.2 User Requirements from Semi Structured Interviews

The analysis revealed five key requirement categories. First, transparency in real-time data on availability, waiting times, and costs was essential for building trust. Second, fairness, particularly adherence to first-come-first-served principles—was strongly emphasized. Third, planning certainty was important for users with structured mobility patterns. Fourth, cost sensitivity limited willingness to pay for additional services. Fifth, ease of use and integration were central, with clear preferences for embedding queue and reservation systems into in-vehicle navigation rather than relying on external apps. These findings are consistent with broader mobility research highlighting the importance of trust, perceived control, and usability for technology acceptance [5, 7].

3.3 Personas

To illustrate user diversity, three user types were identified: long-distance travelers (planning-oriented), commuters (routine-focused), and urban users (flexibility-oriented). While all groups emphasize transparency and fairness, their preferences differ in terms of planning needs and system usage. Long-distance travelers prioritize predictability and efficiency, commuters value seamless integration into daily routines, and urban users prefer simplicity and spontaneous access. These differences highlight the need for differentiated system design rather than one-size-fits-all solutions.

3.4 Acceptance of Queuing and Reservation Systems

The in-depth interviews combined with prototype testing revealed clear differences in acceptance. The digital queue achieved a higher rating (mean 4.8) and was perceived as particularly useful for fast charging on highways, as it enables digital registration, real-time monitoring, and transparent allocation of charging access. In contrast, reservations received a lower rating (mean 2.7) and were viewed more critically due to limited flexibility, potential misuse, and inefficiencies in cases of non-compliance.

Survey results ($n = 60$) support these findings, identifying transparency of waiting times (72%) and improved planning capability (67%) as key drivers of acceptance for queuing systems, particularly in peak demand situations such as holiday periods (83%) and long-distance travel (63%). For reservation systems, planning capability (67%) and avoidance of waiting times (45%) were perceived as benefits, but overall acceptance remained more ambivalent.

3.5 Conditions for Acceptance

Several conditions were critical for user acceptance. Transparency and reliability were essential, particularly regarding waiting times, queue positions, and the availability of charging points. Integration into in-vehicle systems was strongly preferred over external apps. Cost transparency was also important, while willingness to pay remained limited (57% for queuing, 43% for reservations).

Flexibility and fairness further shaped acceptance. Users emphasized the importance of first-come-first-served principles and expressed concerns about rigid reservation schemes. Mechanisms to handle unforeseen delays, such as traffic conditions, were considered necessary to ensure practical usability and trust.

3.6 New Challenges

Despite the overall positive perception of digital queues, several challenges emerged. Users questioned how queues could be effectively enforced in physical spaces and raised concerns about non compliance, such as ignoring notifications or occupying chargers longer than necessary. Fears about inequalities, for instance preferential treatment for premium users, also surfaced. Regarding reservations, participants pointed to generally low willingness to use or pay for the service, the risk of underutilization of infrastructure when reservations were not honored, and the complexity of integrating dynamic adjustments into real traffic situations.

3.7 Summary of Results

Overall, the findings indicate that digital queuing systems have strong potential to reduce uncertainty and improve fairness, particularly in high-demand contexts. Reservation systems, in contrast, were accepted only in specific use cases. Across all analyses, transparency, reliability, and integration emerged as key conditions for user acceptance.

4 Discussion

4.1 From Infrastructure Provision to User-Centered Systems

The results of this study underscore a crucial shift in the debate on electric mobility: while early discussions focused on vehicle range and charging station density, the user experience has emerged as an equally crucial factor. Our findings show that fear of queues is increasingly replacing range anxiety as the main barrier to the seamless adoption of electric vehicles. This is consistent with recent studies that highlight the importance of perceived control and reliability for the acceptance of technologies [5, 7]. The conclusion is clear: expanding infrastructure alone is not enough. Without user-oriented management systems, congestion and uncertainty at charging stations will continue to undermine public confidence in electric mobility.

4.2 Acceptance Dynamics of Queuing and Reservation Systems

An important contribution of this research lies in the differentiated understanding of acceptance dynamics between queuing and reservation functions. While digital queues were evaluated positively by most participants, reservations were met with considerably more skepticism. This divergence can be explained by users' preference for flexibility combined with transparent and fair allocation mechanisms. Queuing systems were perceived as preserving spontaneity while providing structure, whereas reservations were associated with rigidity and a higher risk of inefficiencies or misuse.

These findings are in line with broader research on electric mobility and user acceptance, which emphasizes that mobility-related decisions are shaped not only by technical functionality but also by usability, reliability, and users' everyday mobility practices [5, 9]. In this sense, the lower acceptance of reservation systems suggests that perceived loss of flexibility can outweigh potential efficiency gains.

At the same time, the findings show that willingness to pay for additional digital charging services remains limited. Rather than interpreting this as a purely economic issue, the results indicate that users primarily understand such functions as part of a reliable charging infrastructure and expect them to be seamlessly integrated into existing services.

Overall, acceptance is not solely determined by objective system performance, but by the extent to which system logic aligns with users' expectations of fairness, transparency, and practical usability in dynamic charging situations.

4.3 Sociotechnical Implications

The results underline the inherently sociotechnical nature of charging infrastructure systems. User acceptance is shaped not only by technical functionality but also by social expectations regarding fairness, trust, and rule compliance. Concerns about queue enforcement or reservation misuse illustrate that digital solutions must be embedded in reliable and transparent governance structures to be perceived as legitimate. This supports the view of electric mobility as a socio-technical transition in which behavioral, institutional, and technological elements interact [10].

At the same time, the findings demonstrate that different user groups assign varying importance to these factors. Long-distance travelers prioritize planning certainty and reliability, while urban users value simplicity and flexibility. This heterogeneity highlights the need for differentiated system designs that accommodate diverse mobility patterns rather than relying on uniform solutions.

From a technical perspective, the implementation of digital queuing and reservation systems requires interoperable architectures and standardized communication across stakeholders. Within the SeQueRe project, this is addressed through a system design that connects user interfaces with backend systems of charge point operators and service providers via a central platform. In this sense, successful implementation depends not only on technical standardization, but also on user-centered design and institutional trust.

4.4 Limitations and Future Research

This study has several limitations. First, while the interview-based methodology is rich in qualitative insights, it has limited generalizability due to the sample size and geographic focus. Future research should conduct large-scale surveys or field trials to validate the findings for broader populations. Second, the study focused primarily on user perceptions; subsequent phases of SeQueRe will test technical feasibility and system integration to enable a more comprehensive assessment of socio-technical performance. Finally, willingness to pay and behavioral adaptation under real-world conditions remain open questions. While our participants were reluctant to pay, actual usage patterns under different pricing structures could provide more nuanced insights. Experimental pilot projects combined with behavioral economics approaches could provide valuable insights into these dynamics.

4.5 Contribution to Literature

This work contributes to the literature in several ways. First, it empirically documents the emergence of queue anxiety as a distinct and increasingly relevant barrier to the adoption of electric vehicles, complementing existing research that has predominantly focused on range anxiety. Second, it provides a comparative analysis of user acceptance of queuing and reservation systems, demonstrating a clear preference for solutions that ensure transparency and fairness while maintaining flexibility in usage. Third, the findings are embedded in a broader socio-technical perspective, highlighting the role of trust, governance, and user heterogeneity in the design and implementation of charging management systems. Taken together, these contributions offer both empirical and

conceptual insights that support the development of user-oriented, interoperable charging solutions and inform infrastructure planning and policy-making in the context of sustainable mobility transitions.

5 Conclusion

This paper examined challenges of charging infrastructure management in the context of Europe's transition to zero-emission mobility. While earlier debates focused on vehicle range and infrastructure density, the findings show that user experience—particularly queue anxiety—has become a critical factor for EV adoption.

Based on customer journey mapping, interviews, and prototype testing, three key requirements for user acceptance were identified: transparency, fairness, and planning certainty. Digital queuing systems were perceived as particularly promising, as they provide structured and transparent access to charging infrastructure, especially in high-demand situations such as long-distance travel. Reservation systems, by contrast, were accepted only in specific contexts and remain limited by concerns about flexibility and fairness.

The results highlight that effective charging management requires not only technical solutions but also user-oriented system design that reflects diverse mobility patterns. In this context, interoperable and transparent digital systems can contribute to reducing uncertainty, improving infrastructure utilization, and supporting the broader transition toward sustainable electric mobility.

References

1. European Commission: Fit for 55: Reaching the EU's 2030 Climate Target on the Road to Climate Neutrality. European Commission, Brussels (2021)
2. Gnann, T., Funke, S., Jakobsson, N., Plötz, P., Sprei, F., Bennehag, A.: Fast charging infrastructure for electric vehicles: Today's situation and future needs. Transp. Res. Part D. **62**(1), 314–329 (2018)
3. Kley, F., Wietschel, M., Dallinger, D.: Evaluation of European electric vehicle support schemes. Energy Policy. **39**(10), 6662–6674 (2011)
4. Neubauer, J., Wood, E.: The influence of range anxiety and charging infrastructure at home, at work, and in public on the simulated usage time of battery electric vehicles. J. Power Sources. **257**(1), 12–20 (2014)
5. Li, R., Long, E., Chen, H., Geng, J.: An overview of factors influencing consumers' purchase intention for battery electric vehicles. Renew. Sust. Energ. Rev. **78**(1), 318–328 (2017)
6. Funke, S., Árpád, F., Sprei, T., Plötz, P.: How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison. In: Transportation Research Part D Transport and Environment, pp. 224–242 (2019)
7. Sprei, F.: Disrupting mobility. Energy Res. Soc. Sci. **37**(1), 238–242 (2017)
8. Zhang, X., Xie, J., Rao, R., Liang, Y.: Policy incentives for the adoption of electric vehicles in different countries. Sustainability. **6**(11), 8056–8078 (2014)
9. Haustein, S., Nielsen, T.: European mobility cultures: a survey-based cluster analysis in 28 European countries. J. Transp. Geogr. **54**(1), 173–180 (2016)
10. Geels, F., Sovacool, B., Schwanen, T., Sorrell, S.: Sociotechnical transitions for deep decarbonization. Science. **357**(6357), 1242–1244 (2017)

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Airline Companies' Strategies to Enhance the SAF Market for Aviation: An International Benchmarking and Comparative Application to the Brazilian Context

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Abstract. This paper investigates the strategies followed by airlines to stimulate sustainable aviation fuel (SAF) production and consumption. The objective is to identify patterns of airline engagement with SAF and analyze how Brazilian air carriers position themselves relative to their European counterparts, recognizing that airlines are not only fuel consumers but also drivers of innovation and investment. The methodology consists of a content analysis designed to identify trends in media discourse and a comparative assessment of six selected airlines: Air France-KLM, Lufthansa, and Ryanair from Europe; and Azul, GOL, and LATAM from Brazil. Our findings indicate that airline strategies vary widely across regions. Globally, companies adopt both supply and demand-side approaches. Supply-side measures are more prevalent and include purchase agreements, R&D support, and partnerships with SAF producers. On the demand side, pricing mechanisms such as differentiated fares are used. While European airlines are primarily concerned with operational issues, Brazilian carriers emphasize long-run feasibility. Therefore, this study provides insights to support the maturity of airline strategy towards SAF production and adoption in Brazil.

Keywords: SAF · Airline Companies · Brazilian Aviation Market

1 Introduction

Given its near-exclusive reliance on fossil fuels – reflected in its 2.5% share of global energy-related CO_2 emissions in 2023 [1] – aviation poses a major challenge for global decarbonization [2]. In this context, sustainable aviation fuels (SAF) have emerged as the primary alternative for reducing greenhouse gas (GHG) emissions, as they are compatible with existing aircraft technologies [3]. In response, major regulatory bodies have begun implementing mandates to accelerate the transition to sustainable fuels.

The European Union (EU) has taken a leading role in developing policies to promote SAF production. The ReFuelEU Aviation Regulation establishes mandatory blending

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targets, starting at 2% in 2025 and rising to 70% by 2050. Aviation has also been incorporated into the EU Emissions Trading System (ETS), ensuring a coordinated approach to sectoral decarbonization. In addition, the EU is investing heavily in SAF production, targeting both supply and demand [4]. By contrast, Brazil recently enacted legislation establishing a national SAF program (ProBioQAV), with a more gradual blending trajectory—beginning at 1% in 2027 and reaching 10% by 2037 [5]. Unlike the EU, Brazil's mandate is based on GHG emissions reduction rather than fixed blending quotas.

Beyond regulatory action, many airlines are proactively advancing SAF adoption. Rather than merely complying with policy, carriers are setting voluntary targets, forming partnerships with fuel suppliers, and investing in research and development (R&D). By prioritizing sustainability and market leadership, airlines are helping to stimulate the SAF market and accelerate the transition to low-carbon aviation.

This paper examines the role of airlines in the SAF market, focusing on the Brazilian and EU aviation sectors. It adopts a two-step methodology. First, Sect. 2 presents a content analysis of media discourse on sectoral environmental strategies and airline SAF positioning. Second, Sect. 3 provides an analysis of six airlines: Air France-KLM, Lufthansa, and Ryanair in Europe, and Azul, GOL, and LATAM in Brazil.

2 Content Analysis: Airlines and the Environment

This section adopts a content analysis methodology, utilizing the Media Cloud platform to examine the media discourse surrounding airline environmental strategies. By analyzing extensive online news sources, this method provides a data-driven comparison of how these topics are framed in Brazil and in Europe.

Our sample is based on a comparative corpus of media articles, covering from January 1st, 2015 to September 9th, 2025. For the Brazilian corpus, data was collected from Portal Brasil, Jornal Correio do Brasil, and various national and local digital news outlets (comprising 1,653 sources). The European corpus, we sourced prominent organizations, including Reuters, The Guardian, the BBC, The Brussels Times, Euronews and Euractiv, as well as national online news websites across EU member states (2,745 data points). Employing a multilingual approach, this study applied a search query, with adapted keywords, across both regions to capture the environmental discourse in aviation. In a second approach, we conducted a media discourse analysis by airline, incorporating 'SAF' as a specific descriptor.

Figure 1 exhibits the monthly keyword frequency derived from the initial query, revealing a largely similar trajectory across both regions for much of the study period. A notable peak is observed in the European corpus in late 2023, coinciding with the adoption of the ReFuelEU Aviation regulation in October – a likely driver for the increased media coverage. However, this trend shifted in 2024, when the Brazilian corpus surpassed the European one, maintaining a higher volume thereafter, suggesting that the sustainability agenda in the aviation sector has recently gained significant momentum in Brazil.

In comparison, the Brazilian corpus returned 7,932 total occurrences, while the European one recorded 8,739 occurrences. The European narrative prioritizes the "why",

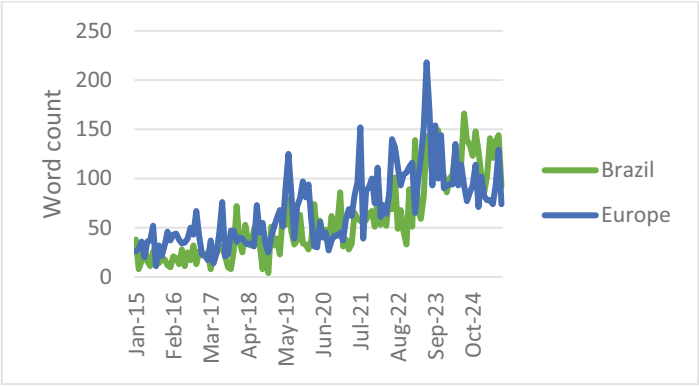


Fig. 1. Monthly word frequency from Media Cloud queries: Brazil vs. Europe (2015–2025)

centering on environmental terminology, such as 'climate' and 'emissions'. In Brazil, the discourse is anchored in the "who" – focusing on the primary actors leading the process, namely, the 'government' and large national companies. This difference indicates that Brazil is in the stage of formulating and negotiating its public policies, while the European debate reflects a more established regulatory environment where the focus has shifted toward accountability and environmental outcomes.

Furthermore, the airline-specific word clouds (Fig. 2) reflects the broader findings of the corpora. To ensure comparability across all case studies, terms from the original multi-language sources were translated into English.

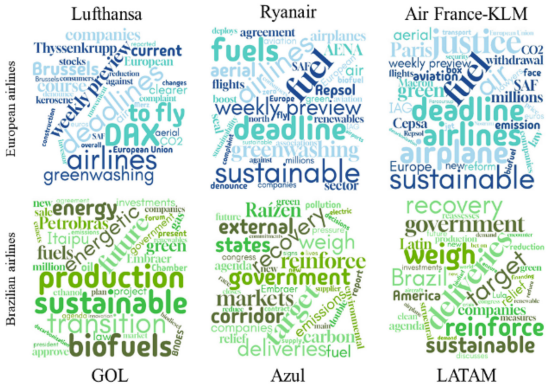


Fig. 2. Word clouds – European and Brazilian airlines (2015–2025)

In the European context, resulting word clouds highlight the prevalence of sustainability-related terminology. The emergence of politically charged keywords like 'Paris', 'Brussels', and 'justice' suggests that the corporate narrative is aligned with the EU's regulatory landscape. Furthermore, the presence of 'greenwashing' indicates a heightened awareness of the public and reputational risk; as well as 'deadline'

implies concerns with operational feasibility. Interestingly, the inclusion of industrial partners such as Cepsa and Repsol reflects a transition toward concrete supply-chain collaborations.

In contrast to the European carriers, the content analysis for the Brazilian airlines reveals a prospective discourse. While fundamental sustainability terms remain prevalent, the frequent appearance of words such as 'future' and 'agenda' indicates a narrative centered on Brazil's potential for SAF production. Furthermore, the prominence of sectoral drivers – including 'government', 'Petrobras' and 'BNDES' (Brazil's National Development Bank) – suggests that a collaborative project of national industrial development is taking place.

The overall media content analysis indicates that while both regions share an environmental focus, the discourse is also intertwined with policy and operational frameworks. This became particularly clear through the analysis of the airline companies, which suggests that airlines themselves can play a much larger role in shaping SAF regulation.

3 Airline Strategies and Initiatives for SAF

Airlines seek different strategic approaches to comply with emerging environmental regulations while simultaneously pursuing competitive advantages through greener service offerings. In this context, airlines are no longer merely end-users of fuel, but increasingly act as drivers of demand creation, innovation, and market development for SAF. Their strategies extend beyond operational compliance and include a combination of market-based instruments, technological engagement, and coordination across the value chain, reflecting varying degrees of commitment and risk exposure.

The literature highlights that cooperation involving airlines can be classified into three main categories. First, partnerships with industrial input providers, including SAF producers and aircraft manufacturers, allow airlines to signal demand and secure supply through mechanisms such as offtake agreements [6, 7]. Second, collaboration with service providers along the SAF value chain, particularly airports and fuel distributors, supports the development of infrastructure and operational integration. Third, cooperation with government and institutional actors facilitates regulatory alignment for SAF deployment [8].

In recent years, SAF mandates have driven airlines to plan their reduction of GHG emissions. Given the global pressure for decarbonization and some room for competitive gains for airlines that set SAF usage above mandates, companies have sought, for example, partnership with fuel suppliers and investment in R&D.

In methodological terms, we build up an analytical framework to capture different levels of strategy engagement. These include Passenger SAF Contribution Programs, which represent demand-side mechanisms with limited financial exposure; Purchase Agreements, which reflect supply-side commitments and help to reduce uncertainty; R&D and/or Financial Support, which strengths innovation without direct capital investment; and Strategic Alliances and Public-Private Partnerships (PPPs), which involve long-term cooperation and investments associated with sunk costs. Table 1 summarizes these strategic engagements for the six airlines analyzed, classifying each initiative as active, prospective or absent, based on the companies' disclosed actions and positioning.

Table 1. Airlines' initiatives in the SAF sector

Airlines	Passenger SAF Contribution Programs	Purchase agreement	R&D and/or financial support	Strategic alliances and PPPs
Air France-KLM	Active	Active	Active	Active
Lufthansa	Active	Prospective	Active	Active
Ryanair	Absent	Prospective	Active	Absent
Azul	Absent	Prospective	Absent	Prospective
GOL	Absent	Absent	Absent	Absent
LATAM	Absent	Absent	Active	Prospective

As for Table 1, Air France-KLM stands out as the only airline with all listed strategies in place. Pioneer in SAF adoption, it has become the world's largest SAF user in 2022 – accounting for 17% of global production. The company's goal is a minimum 10% SAF blend on all flights by 2030 [9], to be achieved by combined demand-side instruments: SAF contributions embedded in ticket prices with the option for additional voluntary contributions; and active purchase agreements with producers such as Neste and DG Fuels (2023–2036), and TotalEnergies (2023–2030). In parallel, it participates in R&D initiatives, such as the Clean Aviation Joint Undertaking. Notably, since 2017, Air France-KLM is the only airline in the sample engaged in a national-level public-private partnership (PPP) named Engagement for Green Growth (ECV), dedicated to structuring the SAF value chain in France, reinforcing its leading role in the institutional development of SAF [10].

Similarly, Lufthansa adopts a diversified strategy, although with important differences compared to Air France-KLM. The company has set a net-zero target for 2050, with SAF as its main strategy to achieve it. Lufthansa also engages in passenger SAF programs through its 'Compensaid' platform launched in 2019, allowing passengers to offset emissions with SAF, and has since 2023, offered a "Green Fare" fully allocated to SAF integration. However, its purchase agreements remain largely at a prospective stage, structured as non-bidding instruments such as Memorandum of Understanding (MoUs) and Letters of Intent (LoIs) with fuel producers such as Shell and OMV. On the other hand, Lufthansa demonstrates strong engagement in innovation by participating in European research consortia and supporting technological development through its Innovation Hub and its partnership with the Swiss clean technology company Synhelion, which constitutes a strategic alliance, involving equity participation, preferential access to future SAF supply, and joint development of production technologies [11].

In contrast, Ryanair, the only low-cost carrier among the two European airlines analyzed, adopts a more limited approach, strongly oriented toward cost efficiency and regulatory compliance. As Europe's largest carrier by passenger numbers [12], Ryanair has committed to net-zero emissions by 2050. The airline also aims for a 12.5% SAF blend on all flights by 2030. The company does not maintain active passenger contribution programs and its SAF agreements remain at a prospective stage, based on MoUs

with multiple suppliers such as OMV, Shell, Repsol and Enilive. Nevertheless, it shows engagement in R&D, particularly through its partnership with Trinity College Dublin to develop the Sustainable Aviation Research Centre. This center, which focuses on SAF innovation and certification, has already received €1.5 million in funding, with an additional €2.5 million to be fully invested by 2030 [13].

In the Brazilian context, Azul presents a strategy that is still under consolidation. The company does not have active passenger contribution programs, and no structured R&D initiatives without capital investment were identified. Having said that, Azul targets carbon neutrality by 2045 and it actively engages in energy transition and decarbonization debates, collaborating with government bodies on biofuel legislation [14]. To meet the 2027 mandate, Azul estimates its fleet will consume about 25 million liters of SAF. Its purchase agreements with Raízen, a Brazilian bioenergy company, are classified as prospective, as no binding contracts have been formally signed. However, the airline focuses on the future supply of SAF derived from second-generation ethanol, and joint development of production and logistics capabilities in Brazil. Additionally, its engagement with the Brazilian Union of Biodiesel and Biojetfuel (Ubrabio) involves participation in industry coordination efforts, including policy advocacy and regulatory alignment, contributing to the structuring of the national SAF ecosystem [15].

GOL also targets net-zero emissions by 2050, but shows limited engagement in SAF-related strategies. Although the airline launched Latin America's first pilot project using the book and claim system for SAF compensation in 2024, in partnership with Vibra Energia and the Dutch producer SkyNRG [16] – this remains its primary initiative in the area. The company has discontinued its emissions compensation program (#MeuVooCompensa) and does not hold direct SAF purchase agreements, relying predominantly on book and claim mechanisms. Furthermore, no relevant R&D initiatives or strategic alliances involving sunk costs were identified, indicating a more passive positioning and limited involvement in structuring the SAF value chain.

LATAM presents an intermediate strategy, combining the absence of market-based instruments with relevant engagement in R&D and regional coordination. LATAM also aims for net-zero emissions by 2050, with a target of integrating SAF into its operations at a 5% rate by 2030, prioritizing South American production. LATAM and Airbus also co-financed a Massachusetts Institute of Technology (MIT) study for decarbonizing aviation, which identified Brazil as the highest potential for SAF production in Latin America, supported by feedstock availability and biofuel expertise. Furthermore, LATAM participates in strategic alliances at a prospective stage, as seen by its partnership with Ecopetrol in Colombia, aimed deploying SAF in the region, indicating a focus on building future capabilities and fostering regional value chain coordination [17].

4 Conclusion

Like any other promising new technology, SAF carries high expectations regarding its environmental benefits, but also faces significant uncertainty due to its different production pathways and challenging financial feasibility. We highlight, in this paper, the key differences between two countries/regions – Brazil and the EU – that have chosen to implement mandates to regulate the SAF market. Based on a word-counting

approach and a benchmarking analysis of both markets, we find that European airlines are primarily concerned with operational issues such as financial feasibility, subsidies, and access to SAF production. In contrast, concerns in Brazil are more related to long-run feasibility which has been argued by the private sector to depend heavily on the lack of public incentives, such as funding and subsidies. However, some uncertainty coexists with a structural opportunity: Brazil is positioned in global debates as a potential leader in SAF production and export, given its bioenergy capacity and feedstock availability. In this context, airline strategies are relevant for linking potential supply to actual market development.

The comparative analysis reveals a divergence in the strategic maturity of airlines across Brazil and Europe. Driven by regulatory frameworks, public funding, and public-private coordination, European carriers tend to adopt more proactive approaches, particularly through supply-side strategies such as long-term purchase agreements and participation in technological development. In contrast, Brazilian airlines remain at earlier stages of market maturity, with strategies that are often prospective and less capital-intensive, reflecting the country's still-evolving regulatory framework. Taken together, these results reinforce the idea that national policy design is a key driver of corporate behavior, and that coordinated institutional support can play a critical role in enabling the expansion of the SAF market.

Regarding airline-specific strategies, some companies (Air France-KLM and Lufthansa) adopt a two-fold approach, ranging from passenger contribution programs to direct engagement in SAF production in cooperation with private-sector partners. Other companies (Ryanair, Azul, and LATAM) demonstrate a more uneven configuration of commitment: while some are currently relying on non-bidding purchase agreements with SAF producers, others support R&D initiatives in the SAF sector. Finally, GOL relies primarily on market-based solutions, particularly through a book-and-claim framework.

References

1. International Energy Agency (IEA): Homepage. https://www.iea.org/reports/aviation. Accessed 12 Sept 2025
2. Cybulsky, A., Allroggen, F., Shao-Horn, Y., Mallapragada, D.S.: Challenges of decarbonizing aviation via hydrogen propulsion: technology performance targets and energy system trade-offs. ACS Sustain. Chem. Eng. **12**(46), 164615 (2024)
3. Klimczyk, W., Jasiński, R., Niklas, J., Siedlecki, M., Ziółkowski, A.: Sustainable aviation fuels: a comprehensive review of production pathways, environmental impacts, lifecycle assessment, and certification frameworks. Energies. **18**(14), 3705 (2025). https://doi.org/10.3390/en18143705
4. ReFuelEU Aviation: Homepage. https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en. Accessed 30 Sept 2025
5. Brazil: President Lula sanctions the Future Fuel Law to promote sustainable mobility. Government of Brazil (2024). https://www.gov.br/planalto/pt-br/acompanhe-o-planalto/noticias/2024/10/presidente-lula-sanciona-lei-do-combustivel-do-futuro-para-promover-a-mobilidade-sustentavel. Accessed 30 Sept 2025
6. Ecer, F., Tanrıverdi, G., Yaşar, M., Görçün, Ö.F.: Sustainable aviation fuel supplier evaluation for airlines through LOPCOW and MARCOS approaches with interval-valued fuzzy neutrosophic information. J. Air Transp. Manag. **123**, 102705 (2025). https://doi.org/10.1016/j.jairtraman.2024.102705

7. Oliveira, A.V.M., Caliari, T., Narcizo, R.R.: An empirical model of fleet modernization: on the relationship between market concentration and innovation adoption by airlines. Res. Transp. Bus. Manage. **43**, 100704 (2022). https://doi.org/10.1016/j.rtbm.2021.100704
8. Ng, K.S., Farooq, D., Yang, A.: Global biorenewable development strategies for sustainable aviation fuel production. Renew. Sust. Energ. Rev. **150**, 111502 (2021). https://doi.org/10.1016/j.rser.2021.111502
9. Air France-KLM Newsroom: Homepage. https://www.airfranceklm.com/en/newsroom/air-france-klm-reaffirms-its-commitment-decarbonization-aviation-through-use-sustainable. Accessed 26 Sept 2025
10. ICAO Projects: Homepage. https://www.icao.int/SAF/stakeholder-action-groups-projects-french-engagement-green-growth-ecv-sustainable-aviation-fuels. Accessed 30 Sept 2025
11. Lufthansa Group: Homepage. https://www.lufthansa.com/. Accessed 30 Sept 2025
12. EBSCO: Homepage. https://www.ebsco.com/research-starters/business-and-management/ryanair-ltd. Accessed 29 Sept 2025
13. Ryanair Group: Annual Report 2025. https://investor.ryanair.com/wp-content/uploads/2025/05/Ryanair-2025-Annual-Report.pdf. Accessed 29 Sept 2025
14. Azul: Azul highlighted in ceremony sanctioning the Future Fuel Law. Press release, São Paulo (2024). https://share.google/YXcfiOxCx9CRQc4pa. Accessed 29 Sept 2025
15. Ubrabio: Homepage. https://ubrabio.com.br/2024/08/15/azul-linhas-aereas-se-torna-nova-associada-da-ubrabio. Accessed 29 Sept 2025
16. GOL, Vibra Energia: GOL, with support from Vibra, launches pioneering SAF compensation initiative in Brazil. São Paulo (2024). https://www.vibraenergia.com.br/sites/default/files/2024-06/gol-com-apoio-da-vibra-lan%C3%A7a-iniciativa-para-conpensacao-pioneira-de-saf-no-brasil.pdf. Accessed 29 Sept 2025
17. LATAM Mobility: Homepage. https://latamobility.com/en/ecopetrol-and-latam-airlines-strengthen-sustainable-aviation-in-colombia/. Accessed 25 Feb 2026

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National Stock-Flow Model of Critical Materials in Electric Vehicles for Europe

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Abstract. This work presents a dynamic modelling framework to project the evolution of electric vehicle (EV) fleets in Europe and their recycling potential. The model integrates historical data, survival probabilities, and cross-border trade flows to estimate national EV stocks under scenario-based pathways. Fleet projections are translated into battery cohorts, allowing the quantification of capacity, chemistry shares, and the embedded content of critical raw materials. The results highlight the maximum recovery potential of lithium, nickel, cobalt, and manganese, revealing both technological substitution trends and geographic asymmetries. These insights support the planning of recycling infrastructure and policies to secure resources in the transition to electric mobility.

Keywords: Critical Materials · Recovery Potential · Electric Vehicles

1 Introduction

The transition to electric mobility in Europe is rapidly expanding battery electric vehicle (BEV) fleets, making it increasingly important to characterize their evolution in terms of sales, stock, and embedded battery technologies. This work develops a dynamic national stock-flow model for Europe that projects BEV sales and in-use stock and translates these results into battery capacity, chemistry, energy density, and embedded critical material stocks. The framework provides a country-level basis for analyzing how EV deployment shapes the spatial and temporal distribution of battery-related material stocks across Europe.

2 Methodology

The framework is a dynamic stock-flow model combining sales diffusion, probabilistic survival, and cross-border vehicle redistribution. Historical and projected BEV sales are used to estimate national in-use stocks, which are then translated into battery capacity, chemistry, mass, and embedded critical material stocks by cohort year.

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2.1 EV Sales and Future Projections

To capture the dynamics of EV adoption across European countries, historical annual sales data for battery electric vehicles (BEVs) were compiled for the period 2011–2024 from official European datasets [1]. Although the main focus of this study lies on the EU-27 member states, the model was extended to include the United Kingdom, Norway, Iceland, Switzerland, Turkey, and Liechtenstein to better reflect European market trends and increase geographic completeness.

Future sales up to 2045 were projected by combining historical data with the International Energy Agency (IEA) Net Zero Emissions (NZE) scenario, which assumes 98% of vehicle sales are electric by 2035 [2]. Country-level sales trajectories were estimated using a logistic growth curve:

$$f(t) = \frac{K}{1 + e^{-r.(t-t_0)}} \tag{1}$$

where t is the year, $f(t)$ the projected BEV sales, K the saturation level, r the growth rate, and t_0 the inflection year. This equation captures the S-shaped diffusion pattern of EV adoption: initial slow uptake, accelerated growth, and saturation near each country's sales capacity. A root-finding routine determines r and t_0 such that the curve passes exactly through the last historical sales value and the scenario-specific 2035 target, smoothly bridging historical data to long-term projections without overestimation. This approach aligns with established literature on S-curve models for technology diffusion and EV forecasting [3].

2.2 Dynamic EV Stock Model

Annual EV stock is computed using a cohort-based stock model, in which vehicles enter the stock in their year of sale and remain until retirement. This year-of-sale matrix structure preserves technological cohorts and is commonly used in fleet modelling [4].

EV Survival Model.
Vehicle survival is represented using Weibull cumulative functions parameterized to describe the probability of remaining in use over time.

$$CDF(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{2}$$

This probabilistic approach avoids assuming a fixed lifetime and better captures variation in vehicle durability and usage patterns across Europe. Survival is modeled through two components: a technological component related to battery durability, and a behavioral component reflecting country-specific vehicle turnover patterns. The technological component varies across three EV development periods: 2011–2016 (early-generation EVs), 2017–2022 (improved durability with wider NMC diffusion), and 2023 onwards (increasing LFP adoption and longer expected lifetimes). Period-specific Weibull parameters were assigned from the literature [4–6]. The behavioral component uses country-specific Weibull parameters derived from conventional vehicle lifespan data to capture cross-country differences in fleet turnover [4]. Assuming independence between both

drivers, joint survival is calculated as the product of the technological and behavioral components:

$$F(t) = CDF_{Tech}(t) \cap CDF_{Behaviour}(t) = CDF_{Tech}(t) \because CDF_{Behaviour}(t) \quad (3)$$

Dynamic Flows - Exports and Imports

To represent second-hand market dynamics, vehicles leaving domestic fleets for behavioral reasons while remaining technically viable are redistributed across countries instead of being treated as immediate end-of-life. Bilateral export shares are derived from historical used-vehicle trade patterns, with an additional Rest-of-World category, allowing the estimation of imports received by each country:

$$I_Z(t) = \Sigma_i^N \ (\%_{i-Z}.E_i(t)) \quad (4)$$

where I_Z is the number of vehicles imported by country Z in year t, $\%_{i_Z}$ is the historic percentage of exports from country i to country Z and $E_i(t)$ represents the number of exports of country i in year t.

The resulting net stock of each country is therefore determined by domestic sales, survival, and cross-border trade flows. This mechanism captures the contribution of second-hand trade to fleet growth, particularly in lower-income countries [3].

2.3 Battery Stock Characterization

EV stock was further characterized by assigning battery-specific parameters to each cohort. These parameters depend on the year of manufacture, allowing the technological evolution of batteries to be reflected consistently across the fleet.

Battery Capacity

Historical average battery capacities for 2011–2024 were compiled from EAFO [1]. Future capacities were projected using a linear regression, capped at an average of 100 kWh to avoid unrealistic long-term growth. This assumption is consistent with EV design trade-offs related to cost, weight, and charging requirements [2].

Battery Chemistry Share

Battery chemistry shares were reconstructed from a combination of sources. Early years (2011–2014) were estimated from representative EV model sampling, intermediate years (2015–2019) were based on Ricardo Energy & Environment reports [7, 8], and recent years (2022–2023) were based on IEA data [9, 10]. Future projections follow the IEA 2030 outlook [9], including emerging chemistries such as sodium-ion (Na-ion), NMCA, and LNMO; after 2030, shares are held constant due to uncertainty in longer-term technological transitions.

Battery Energy Density and Weight

Each battery chemistry was assigned a representative cell-level gravimetric energy density (Wh/kg) based on literature values. Combined with projected battery capacities, these values were used to estimate battery mass by cohort. Representative ranges for LFP,

LMO, NCA, NMC variants, and emerging chemistries were compiled from academic and industry sources [11].

Material Composition
The final step of fleet characterization translated battery stock into embedded material stock. Using IEA-reported material intensities per kWh for major chemistries (NMC, NCA, LMO, LFP) [9], complemented by derived values for LNMO, NMCA, and Na-ion, the model estimated the mass of critical raw materials (Li, Ni, Co, Mn) embedded in national EV fleets. These values represent theoretical embedded stock rather than recovered material output.

3 Results and Discussion

This section presents the main outcomes of the dynamic EV fleet and battery model under the Net Zero Emissions (NZE) scenario, chosen to represent the maximum projected EV landscape and the associated material recovery potential. The analysis is structured into three parts: (i) international export—import flows, (ii) national EV stock projections, and (iii) the maximum theoretical recovery of critical materials.

3.1 Export and Import Flows

Cross-border flows of second-hand EVs are a defining feature of the European fleet transition. Results show that high-income countries with short vehicle lifespans, such as Germany, Belgium, Luxembourg, and the United Kingdom, emerge as the primary exporters. By contrast, lower-income countries in the Baltics and Balkans remain structurally dependent on imports to renew their fleets, consistent with historical trends in the conventional vehicle market.

In 2025, total second-hand EV exports across Europe reach approximately 94000 vehicles, corresponding to 3.25% of annual new registrations. Germany alone accounts for roughly 40% of total exports, followed by the United Kingdom and Belgium. A striking example is Luxembourg, which despite ranking modestly in cumulative EV sales, appears in 2025 as one of the largest exporters representing around 6% of all EU trade, due to its exceptionally high turnover rate. In relative terms, Luxembourg exports approximately 10% of its domestic EV stock in 2025, one of the highest turnover ratios in Europe, despite representing less than 0.6% of total EU sales. This short-term prominence gradually declines as larger markets like Italy and Spain begin exporting in greater numbers after 2035, once their substantial sales volumes mature into second-hand flows. Conversely, Lithuania, Latvia, Bulgaria, and Croatia emerge almost exclusively as net importers. In these markets, imports can exceed 10% of annual new EV registrations, underlining structural dependence on second-hand inflows from wealthier EU states [12].

Figure 1 illustrates these asymmetric flows, with Western Europe acting as a net exporter and Eastern Europe as a net importer, reinforcing socioeconomic divides in EV adoption.

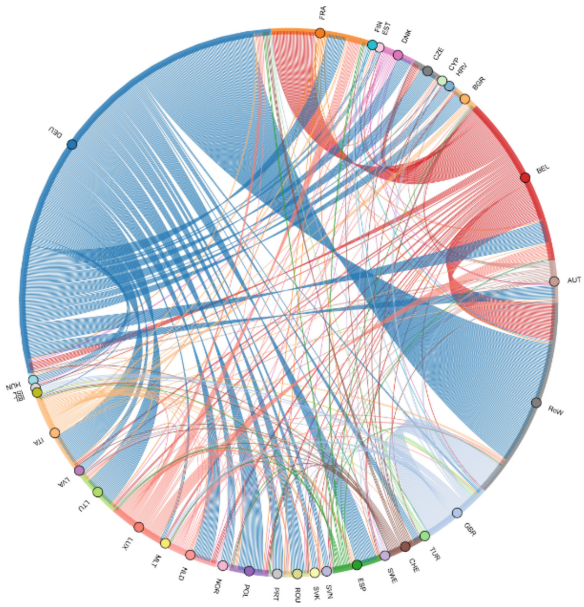


Fig. 1. Chord diagram of EV exports and imports in 2025 under NZE scenario

3.2 National EV Stocks

Integrating sales (inputs), survival probabilities, and trade flows yields the total stock of EVs per country. Under the NZE pathway, the European EV fleet reaches approximately 190 million vehicles by 2045.

Germany reaches approximately 37 million EVs by 2045, followed by United Kingdom (27.2 million), France (26.4 million), and Italy (22.3 million), together accounting for nearly 60% of total European stock. Norway remains an exceptional case with near-total electrification already achieved. Mid-sized countries such as Poland, Spain, and Turkey climb in relative importance by 2045, reflecting their potential for late but rapid uptake.

The role of imports is particularly visible in Baltic and Balkan countries, where inflows from Western Europe significantly boost stock growth despite weaker domestic sales.

Figure 2 shows the cumulative evolution of the fleet across countries, highlighting both the scale of deployment and adoption trajectories trends within Europe.

3.3 Maximum Recovery Potential

Finally, the embedded critical materials in the projected fleet were quantified as a proxy for maximum recovery potential. This metric represents an upper bound of secondary raw material availability in case of full recycling at end-of-life. By 2045, the projected embedded stock reaches approximately: 1.9 Mton of lithium, 5.9 Mton of nickel, 1.15 Mton of cobalt and 2.35 Mton of manganese.

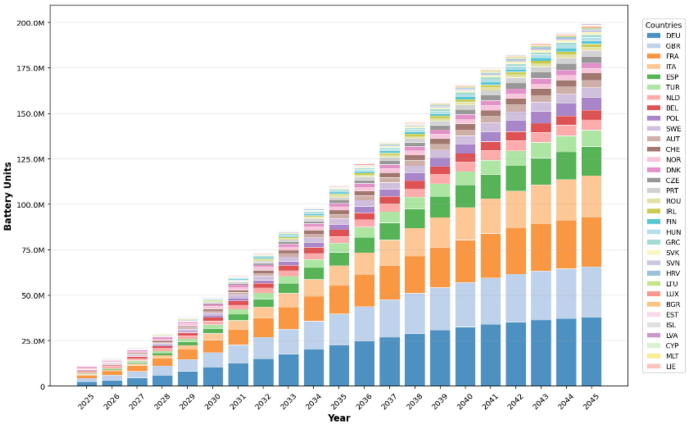
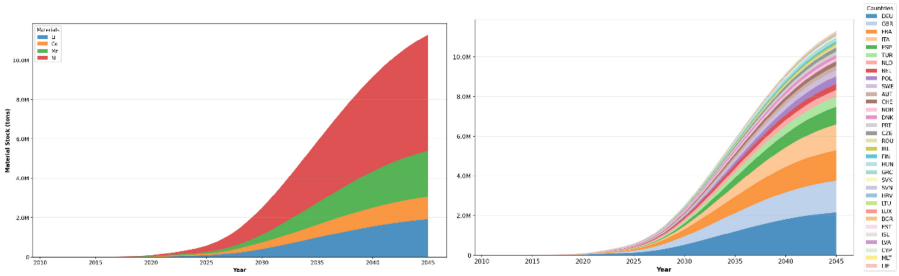


Fig. 2. Projected EV battery stock in units under the NZE scenario

At the aggregate level, nickel emerges as the fastest-growing material, reflecting the dominance of Ni-rich chemistries (NMC622/811, NMCA, NCA). In contrast, cobalt growth remains limited, increasing by 75.1% between 2035–2045, whereas nickel increases by 89.3% over the same period, consistent with industry-wide substitution trends toward cobalt-free chemistries such as LFP and sodium-ion [2]. Lithium and manganese expand steadily in proportion to the fleet, with lithium in particular scaling directly with battery capacity growth.



(a) Projected recovery potential by material. (b) Projected recovery potential by country.

Fig. 3. Maximum recovery potential of embedded critical materials (NZE)

At the country level, Germany alone accounts for approximately 19.1% of total European nickel stock and lithium stock by 2045, followed by the UK and France. However, when normalized by population or expressed as a share of the European total, smaller but fast-growing markets such as Poland and Czechia climb in relative ranking, underlining their intensifying material intensity.

Industry trends underlying these results include: (i) cobalt thrift and substitution (LFP, Na-ion) motivated by cost, ethics, and supply-chain concentration [13]; and (ii)

the broad shift to high-Ni cathodes within NMC/NMCA and NCA systems, which raise specific energy while reducing cobalt intensity [2].

Figure 3a and b highlight both the technological trends driving material substitution and the geographic concentration of embedded stocks within Europe.

4 Conclusion

While several recent studies by the IEA and JRC quantify EV deployment and critical material demand at the aggregate European level, the present framework advances the analysis by explicitly integrating (i) cohort-based stock dynamics with a dual Weibull survival structure separating technological and behavioural effects, (ii) cross-border second-hand redistribution mechanisms capturing intra-European and Europe -Rest of the World trade flows, and (iii) country-level embedded material stock evolution over time. This combination enables a more granular representation of fleet ageing, redistribution asymmetries, and national recovery potential dynamics, extending beyond aggregate flow-based projections.

Overall, the model projects more than 190 million EV batteries embedded in the European fleet by 2045, corresponding to approximately 20 TWh of cumulative battery capacity. Under the NZE pathway, Europe's transition to electric mobility is projected to generate large, embedded stocks of batteries and critical materials within the next two decades. The results point to clear country asymmetries that were previously expected: high-income countries accumulate larger absolute stocks and act as net exporters in the second-hand market, while lower-income countries rely more heavily on imports to electrify their fleets. Because chemistry shares are held common across countries in this baseline, these geographic differences arise primarily from scale and timing (sales volumes, survival, and the sequencing of adoption), which reinforces the internal consistency with the stock and battery-mass metrics.

Interpreting the embedded materials as a maximum theoretical recovery potential (not recovered output) provides a useful upper bound for planning. In practical terms, the pack-level framing connects capacity to total mass handled by logistics, pre-treatment and recycling, while the material-level view highlights where nickel growth and cobalt thrift will shape future feed composition.

These notions aim to guide future European efforts when battery recycling will become a norm and necessary to repurpose the currently growing and evolving landscape of EV batteries.

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References

1. European Alternative Fuels Observatory: Road. https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road. Accessed 30 Oct 2025
2. International Energy Agency: Global EV Outlook 2024. International Energy Agency, Paris (2024). https://www.iea.org/reports/global-ev-outlook-2024. Accessed 30 Oct 2025
3. European Automobile Manufacturers Association: Vehicles on European roads 2024. European Automobile Manufacturers' Association, Brussels (2024). https://www.acea.auto/publication/report-vehicles-on-european-roads/. Accessed 30 Oct 2025
4. Held, M., Rosat, N., Georges, G., Pengg, H., Boulouchos, K.: Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. Eur. Transp. Res. Rev. **13**, 9 (2021). https://doi.org/10.1186/s12544-020-00464-0
5. Xu, C., Dai, Q., Gaines, L., Hu, M.: Quantifying the lifetimes of electric vehicle lithium-ion batteries. Energy Rep. **6**, 200–210 (2020). https://doi.org/10.1016/j.egyr.2020.09.027
6. Kastanaki, E., Giannis, A.: Dynamic estimation of end-of-life electric vehicle batteries in the EU-27 considering reuse, remanufacturing and recycling options. J. Clean. Prod. **393**, 136349 (2023). https://doi.org/10.1016/j.jclepro.2023.136349
7. Hill, N., et al.: Determining the Environmental Impacts of Conventional and Alternatively Fueled Vehicles through LCA. European Commission, DG Climate Action, Brussels (2020)
8. Hill, N., Clarke, D., Blair, L., Menadue, H.: Circular Economy Perspectives for the Management of Batteries Used in Electric Vehicles: Final Project Report. Publications Office of the European Union, Luxembourg (2019). https://doi.org/10.2760/537140
9. International Energy Agency: Global EV Outlook 2022. International Energy Agency, Paris (2022). https://www.iea.org/reports/global-ev-outlook-2022. Accessed 26 Oct 2025
10. International Energy Agency: Trends in batteries. In: Global EV Outlook 2023. International Energy Agency, Paris (2023) https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries. Accessed 30 Oct 2025
11. Houache, M.S.E., Yim, C.-H., Karkar, Z., Abu-Lebdeh, Y.: On the current and future outlook of battery chemistries for electric vehicles—mini review. Batteries. **8**(7), 70 (2022). https://doi.org/10.3390/batteries8070070
12. carVertical: carVertical's market transparency index for 2023. https://www.carvertical.com/en/blog/carverticals-market-transparency-index-for-2023. Accessed 24 Oct 2025
13. International Energy Agency: Global Critical Minerals Outlook 2024. International Energy Agency, Paris. https://www.iea.org/reports/global-critical-minerals-outlook-2024 (2024). Accessed 30 Oct 2025

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eRoadMontBlanc: A Large-Scale Demonstrator of Ground-Level Power Supply for Electric Heavy Trucks

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Abstract. To reduce greenhouse gas emissions from heavy trucks, the development of a network of electric roads is an economically viable solution that reduces the strain on natural resources for batteries. Major investment in the development of this network can only be made once the relevance of electrification technologies has been proven on demonstrators. The ground-level power supply technology using conductive segments on the surface of the pavement can deliver high power with excellent efficiency and is compatible with different types of vehicles, from cars to heavy trucks. A 420 m long demonstrator of this technology was built in late 2024 on the Transpolis site in France. This French test centre is a closed site dedicated to innovation and the development of safe, sustainable vehicles and infrastructure. The aim of this demonstrator is to transfer power of up to 500 kW to light commercial vehicles, coaches and heavy trucks. It was built by Eiffage in collaboration with Alstom and under the management of Université Gustave Eiffel as part of the eRoadMontBlanc research project funded by the French government and the European Union. Several innovative processes were implemented for the construction of the demonstrator and for the monitoring of its operation.

Keywords: Electric Road · Ground-level Power Supply · Electrification

1 Introduction

Europe and France are aiming for carbon neutrality by 2050. The European Union has set ambitious intermediate targets for reducing greenhouse gas emissions, including a 40% reduction in emissions from heavy goods vehicles by 2030 compared to 1990. Decarbonizing road transport, particularly long-distance freight, is essential to achieving these targets. Several solutions exist for that purpose [1], such as biogas, biodiesel, electric-hydrogen, battery electric and the ERS (Electric Road System).

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The principle of ERS is to power vehicles while they are moving using the transport infrastructure. ERS systems allow for a reduction in battery size, particularly if they are designed to mesh a territory, since in this case, batteries are only needed for short distance local services. ERS are particularly relevant for long distances. Even if the analysis of total costs of ownership suggests that ERS heavy-duty vehicles could be slightly more competitive than diesel heavy-duty vehicles [2], the investment in ERS represents significant costs, estimated at several million euros per km of equipped road. There are three main ERS technologies: overhead conductive power supply via catenaries, induction power supply, and ground-level power supply.

The overhead conductive solution is an adaptation of the technology used for railways. It involves the use of catenaries that supply power to vehicles via roof-mounted pantographs. Overhead conductive technology benefits from the maturity and experience gained in the railway sector. It can be implemented without modifying the pavement structure. Several demonstration projects have been conducted since 2010: in Germany with about 30 km of roads equipped [3, 4], on the E16 motorway in Sweden and in the USA [5]. Inductive power is a contactless energy transfer method. The system consists of two main components: transmitter coils embedded in the roadway and receiver coils installed under vehicles. The main advantage of inductive power supply is its low level of intrusion once installed in the pavement and its low impact on infrastructure operations. There is also no physical contact between the vehicle and the power infrastructure, and it can power all types of vehicles. Several demonstrators have been installed: 1 km in Italy for the Arena del Futuro project in 2021 [6], 1.6 km in Detroit (USA) in 2023, 1.5 km in France on the A10 motorway in 2024.The ground-level power supply solution involves conductive segments embedded in the road surface or placed laterally along the track. Several variants exist. There is a two parallel rails system where an articulated arm under the vehicle, equipped with two pads, connects to the rails for power transmission [7]. There is also a single segmented rail system divided into very short segments powered with alternating polarities [8] and a rail in a groove system with a current collector under the vehicle inserted into the groove to capture energy [9, 10]. These solutions can deliver high power with better efficiency compared to the overhead solution thanks to less component heating. It is compatible with various vehicle types, from cars to heavy goods vehicles, and potentially allows for stationery charging. Achievements for ground-level power supply technology include a demonstration track in Hällered near Gothenburg in Sweden built in 2014 for the two parallel rail system and a 2 km demonstrator in 2018 near Arlanda in Sweden for the rail in a groove system.

A report from the French Ministry of Transport, drawn up in 2021, specifies in its recommendations that the ground-level power supply solution seems to be the most suitable for the electrification of the road network, ahead of the catenary solution [2]. Yet, it is not sure what technology will be used in the future. All of the ERS technologies have to be evaluated at the scale of large demonstrations on open roads to evaluate precisely their costs, their construction process and their durability.

To study the ground-level power supply solution with the two parallel lines a consortium was built around the eRoadMontBlanc project. This project is funded by the French government through the BPI France agency and by the EU within the Next Generation - EU framework. The consortium is constituted of French companies and universities:

ATMB (operator of the highway leading to the Mont Blanc tunnel and of the tunnel itself), Alstom, Université Gustave Eiffel, FAAR Pronergy and Greenmot. The project has two phases: the first one consists in the realization of a demonstrator on a test site and the second one is the installation of about 1 km on an open road section. Vehicles will be equipped specifically to conduct tests on the two test sites. This paper describes the preparation and the construction of the demonstrator on the test site of Transpolis (located in the Auvergne-Rhône-Alpes region in France) in the first phase of the project. It was built in 2024 by Eiffage in collaboration with Alstom and under the management of Université Gustave Eiffel.

2 Ground-Level Power Supply Technology with Two Parallel Conductive Segments

2.1 Description of the System

The ERS technology tested in Transpolis is a ground-level power supply system, segmented for greater safety, similar to the technology used for tramways. The system consists of two main parts: the infrastructure and the on-board equipment. The main component of the infrastructure is the power track (Fig. 1): integrated in the pavement, it consists of 11 m long conductive segments (rails), placed end to end. Each segment contains positive and negative conductive bars and a potential barrier for safety. The conductive segments are integrated into rubber insulating elements previously installed in the road. The rubber track elements, but also the rails, have textured surfaces to ensure the grip of the tire on the roadway in case of emergency braking.

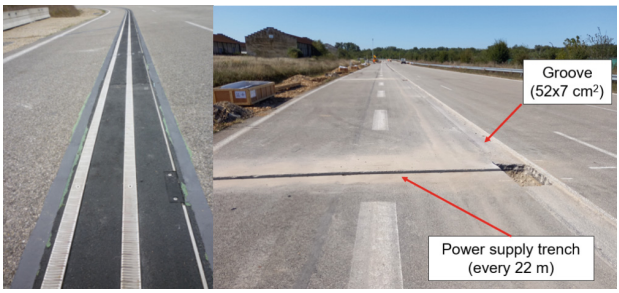


Fig. 1. Rubber track element with conductive segments installed in Transpolis (left) in a groove in the center of the slow lane (right)

The main on-board equipment in the vehicles is a retractable current collector located under the conductive segments. It is equipped with antennas to communicate with the infrastructure. Communication systems allow the infrastructure to power the conductive segments only when the vehicle is just above them and deploy the current collector when no obstacle is detected on the track.

2.2 Development of the Retractable Current Collector

An important part of the eRoadMontBlanc project is the development of the retractable current collector, which enables the vehicles to collect current from the conductive segments. This component has been developed by FAAR-Pronergy and Mersen. This robotized, retractable current collector has a control system that can detect the rail, position the collector on the rail while the vehicle is moving, and retract the collector if an obstacle is detected, or when the vehicle leaves the ERS section. The development of this current collector required building a dedicated test bench, simulating lateral movements of the rail, to validate the detection and positioning system (Fig. 2).

The current collector is equipped with four metal friction pads that slide along the two conductive rails, to enable vehicle charging. Dedicated tests were performed to evaluate the wear of the rails and friction pads in motion. These tests were carried out on the "Grenoble wheel", a test equipment which consists of a 13 m diameter wheel, with a peripheral track on which two rows of ERS-type rails can be fixed (see Fig. 2). The wear tests consisted in testing simultaneously a set of eight friction pads applied to a single ERS rail (i.e. 16 units for the two ERS rails), and to simulate the passage of 5,000,000 of heavy vehicles on the rail, and an operating distance of 50,000 km for the pads, at a speed of 90 km/h.

These tests showed that the wear of the rails was very low (only about 0.1 mm for 5 million load passes), and of several types of friction pads. The service life of the friction pads varied approximately between 10,000 and 20,000 km.

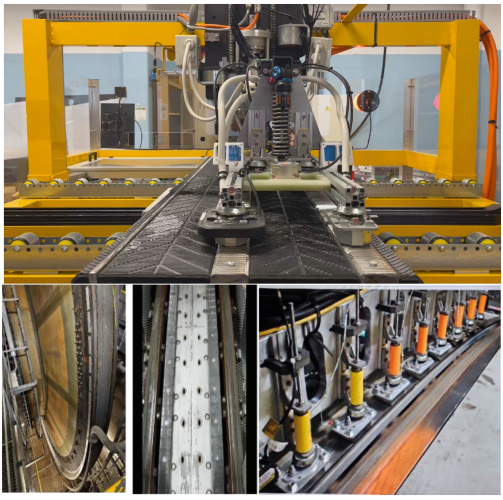


Fig. 2. Tests on the current collector (test bench, top) and on the friction pads (with the Grenoble Wheel, bottom)

2.3 Tests for Road Integration

An important challenge for the deployment of the ground-level power supply with conductive segments technology is to ensure proper integration in the road, ensuring durability and road safety. The integration method consists in milling a trench in the pavement structure and sealing the rubber track elements in the trench with a resin, which can ensure efficient and durable bonding with the pavement layers. To propose a suitable integration method, the studies carried out at Université Gustave Eiffel included first laboratory tests, and the full scale accelerated pavement tests (APT), to validate the resistance to traffic of the ERS road structure.

The objective of the laboratory tests was to select suitable resins for sealing the rubber track elements in the asphalt layers. Three candidate resins, already used for road applications, were selected, and submitted to two types of tests, adapted to the evaluation of the bonding between the asphalt materials, the resins, and the rubber track elements. The first test was a 4-point bending test, carried out on beam specimens made of two materials (asphalt and resin or rubber and resin). These tests made it possible to measure the tensile strength of the interface between the rubber and resin, or between the asphalt and resin, at different temperatures.

The second type of test was a rutting test, based on the principles of the wheel tracking test (standard EN 12697–22). This test consists in submitting a slab of asphalt material to moving wheel loads, at high temperature, and measuring the induced rutting. In this study, the tests were performed on slabs of asphalt material integrating a rubber bar sealed with resin, simulating the rubber track element. Although the wheel tracking test does not simulate exactly pavement loading conditions, it was considered as a practical method to evaluate the resistance to wheel loads of the embedded rubber track element. The modified rutting tests consisted in applying successively to the ERS specimens 20,000 load cycles at three increasing temperatures, 20 °C, 40 °C and 60 °C, and monitoring the rutting during each test phase.

The results of the 4 point bending tests and wheel tracking tests allowed us to select two resins, which presented both a high tensile strength, and a good resistance to rutting under wheel loads, for the following full-scale tests. The third resin was not selected, due to excessive rutting at 60 °C.

To evaluate the resistance to heavy traffic loads of the ERS road structures, full scale APT tests were performed with the FABAC traffic simulator of Université Gustave Eiffel. The FABAC machine consists of four rolling trains driven by a chain-sprocket-electric motor assembly (Fig. 3). The machine can be equipped with single or dual wheels, that roll on the pavement over a length of two meters and then move up into the upper part of the cage. The loading speed can vary between 0.5 and 5 km/h, and the loads between 30 and 75 kN. The distance between consecutive wheels is 2.20 m. Thanks to these closely spaced loads, the FABAC machine has a high loading capacity, of up to 1 million loadings per month. It can also be equipped with a temperature control system, which can apply temperatures varying from 10 °C and 60 °C on the pavement surface.

The FABAC tests were performed on a pavement structure simulating a heavy traffic motorway structure, consisting of 4 asphalt layers, with a total thickness of 25 cm. Three ERS test sections were built on this structure and tested: Sections A and B included conductive track segments sealed in the pavement with the two resins selected following

the laboratory tests. Section C was used to test road maintenance, consisting in milling and renewing the asphalt surface course around the conductive track.

The tests were performed with 65 kN dual wheel loads, and 3 successive loading phases were applied: 200,000 load cycles at ambient temperature (about 15 °C), then 45,000 cycles at 35 °C and finally 10,000 load cycles at 50 °C. The tests confirmed the good performance of the two sections A and B under traffic, with no deterioration of the rails and joints, and only limited rutting of the pavement structures, after the tests at high temperature (maximum rutting of 8 mm on section B). After validating the solutions for road integration, it was decided to build the Transpolis demonstrator, and to test further the two sealing resins.



Fig. 3. FABAC traffic simulator (on the left) and track section A after testing (on the right)

3 Large-Scale Demonstrator of Ground-Level Power Supply ERS Technology

The 420 m demonstrator in Transpolis was built in 2024. The objective of this demonstrator is to transfer power up to 500 kW to light utility vehicles, coaches, and heavy goods vehicles. Two different installation processes of the rubber elements were tested.

3.1 Installation Without Renewing the Surface Layer

The first technique involved a precise grooving of the centre of the slow lane (see Fig. 1), to a width of 52 cm and a depth of 7 cm, allowing the installation of the rubber track elements with an optimal resin thickness. The edges of the trench are chamfered to strengthen the resin's hold. Every 22 m, a transverse supply trench 10 cm wide and 20 cm deep, is created to accommodate the power and communication cables, thus ensuring an efficient connection between the power track and the power boxes on the side of the road.

Once the resin is applied, the rubber element is placed on the milled bottom surface, and metal templates ensure perfect alignment with the pavement surface. This method allows an installation rate of up to 100 m per day. Its main advantage is the economy of construction work because no new asphalt is needed but it requires resin, an expensive

material, to bound the rubber element to the existing pavement. Trenches at the surface of the pavement could also be a threat to the durability of the pavement.

3.2 Installation Renewing the Surface Layer

The second technique involves the complete milling of the wearing course, offering the advantage of making the supply trenches only in the base layer. The rubber element is laid in resin on the milled area, followed by a new asphalt wearing course compacted on both sides of the element, thus covering the supply trenches. This method guarantees excellent uniformity of the wearing course, ensuring better resistance to repeated truck traffic and optimal comfort for road users. To strengthen the adhesion of the asphalt to the rubber element, a commercial bituminous joint was tested, previously evaluated in the laboratories of the Université Gustave Eiffel in comparison with a resin bond. The feedback from the demonstrator shows that the bituminous joint offers a superior finish, confirming its effectiveness in this application. In this section, where asphalt layers were renewed, multiple sensors were installed in the pavement to monitor the deformation and the temperature.

Regardless of the technique chosen, the rails are inserted and screwed into the rubber track elements and then connected to the power supply.

4 Conclusions

The ERS technology for ground-level power supply needed a large-scale demonstrator to develop the installation process and evaluate its durability. It was built in 2024 on a 420 m length on the test site of Transpolis (France) in the first phase of the eRoadMontBlanc project.

Prior to the construction of the demonstrator, dedicated laboratory tests were performed to evaluate the wear of the rails and friction pads in motion, and it was observed to be very low. Laboratory testing and full-scale accelerated pavement testing made it possible to select resins with the best resistance to traffic to be used in the Transpolis demonstrator where their resistance will be evaluated when exposed to weather for multiple years.

Two construction processes were experimented in Transpolis. The first one consists of grooving the existing pavement and placing the rubber track elements with resin. The second one consists in milling entirely the surface layer, placing the rubber track elements in resin on the milled surface and then laying a new asphalt surface layer on both sides of the track. The last technique is more costly but could be more sustainable.

Before tests with heavy trucks, charging tests for light utility vehicles in 2025 proved to be successful. The Transpolis demonstrator will be monitored closely in the next years to evaluate precisely the durability of the ground-level power supply ERS technology.

References

1. DGITM: Système de route électrique (ERS). Groupe de travail n°1. Décarboner le transport routier de marchandise par l'ERS, enjeux et stratégie (2021)
2. DGITM: Système de route électrique (ERS). Groupe de travail n°2. Solutions techniques, potentialités et verrous (2021)
3. Boltze, M.: eHighway – an infrastructure for sustainable road freight transport. In: Ha-Minh, C., Dao, D., Benboudjema, F., Derrible, S., Huynh, D., Tang, A. (eds.) CIGOS 2019, Innovation for Sustainable Infrastructure Lecture Notes in Civil Engineering, vol. 54. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-0802-8_4
4. Gnann, T., et al.: BOLD - Accompanying Research for Overhead Catenary Trucks in Germany. Final report. Öko-Institut, ifeu, Fraunhofer ISI, Berlin, Heidelberg, Karlsruhe (2023)
5. Lehmann, M.: eHighway SoCal - construction of a 1 mile catenary system and develop & demonstrate catenary electric trucks. Final report. (2018)
6. Saldarini, A., et al.: Electric vehicle modelling applied to dynamic wireless charging: case study. IFAC-PapersOnLine. **58**(13), 374–379 (2024). https://doi.org/10.1016/j.ifacol.2024.07.511
7. Hornych, P., Gabet, T., Nguyen, M.L., Lédée, F.A., Duprat, P.: Evaluation of a solution for electric supply of vehicles by the road, at laboratory and full scale. In: Chabot, A., Hornych, P., Harvey, J., Loria-Salazar, L. (eds.) Accelerated Pavement Testing to Transport Infrastructure Innovation Lecture Notes in Civil Engineering, vol. 96. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-55236-7_71
8. Abrahamsson, P.: Electro mechanic design and test of conductive electrical road system - overall system design and protection. Master's thesis, Division of Industrial Electrical Engineering and Automation Faculty of Engineering, Lund University. CODEN: LUTEDX/(TEIE-5349)/1-53/ (2015)
9. Asplund, G.: System and method for electrical feeding of road vehicles. EP 4 031 407 B1 (2024)
10. Asplund, G., Rehman, B.: Conductive feeding of electric vehicles from the road while driving. In: Proceedings of 4th International Electric Drives Production Conference (EDPC), Nuremberg, Germany, pp. 1–9. IEEE (2014). https://doi.org/10.1109/EDPC.2014.6984418

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Adoption of Electric Mobility and Energy Management Technologies: A Case Study in Guimarães, Portugal

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Abstract. The transport sector accounts for about 30% of Europe's emissions, with road transport making up 70% of that total due to widespread use of internal combustion engines. While electric vehicles (EVs) offer zero tailpipe emissions and are being promoted by governments, their impact alone is insufficient, as other sectors - particularly buildings - continue to pollute significantly. Integrating Vehicle-to-Everything (V2X) systems offers a solution by enabling EVs to serve as energy storage units that supply buildings during idle periods, reducing reliance on the grid and lowering overall carbon emissions.

This work evaluates the benefits of a V2X system in Guimarães' city center, focusing on areas with diverse socio-economic and demographic profiles. It characterizes public and private mobility patterns assessing their impact on overall system efficiency. An integrated framework will combine building energy models with mobility data to assess passive and active solutions, including the adoption of electric vehicles in urban mesh. It also considers renewable energy systems for buildings and public energy storage to manage surplus energy, aiming for optimized cross-sector energy use and reduced GHG emissions. The results will pave the way for a wider adoption of EV technologies in the case study that, alongside stationary electrical batteries and energy management systems, will allow for greater reductions in energy consumption and carbon emissions, and improve energy efficiency in both economic sectors, when compared to isolated decarbonization strategies. They will also provide a clear path for users and a guideline for local and national energy agencies and governmental bodies, in implementing financial mechanisms for electric powertrain adoption in urban areas.

Keywords: Urban Mobility · Vehicle-to-Everything Systems · Energy Management Systems · Decarbonization

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1 Introduction

The building and transport sectors are Europe's largest energy consumers and greenhouse gas emitters, together responsible for 71% of energy use and 56% of emissions [1–3]. To fight this the EU promotes energy efficiency through Near Zero Energy policies in buildings [4, 5], and electric drivetrains in the transport sector [6]. Integrate this with Vehicle-to-Everything (V2X) systems enables energy exchanges between EV's and buildings, enhancing grid stability and renewable energy use in building energy consumption [7], by making use of energy stored in EV's batteries during idle periods, and while they are docked in charging stations to feed electrical energy to energy infrastructures nearby, through bi-directional charging systems in charging stations [7, 8]. More particularly, and by implementing Vehicle-to-Building (V2B) systems, the implementation of Home Energy Management Systems (HEMS) and Building Energy Management Systems (BEMS) [9] can be implemented in buildings, exploring the capabilities of the vehicle and ancillary energy systems such as stationary electrical batteries to improve energy efficiency, performance, and usage in buildings [10, 11], by implementing key energy management tasks, such as overseeing energy costs, automating demand response approaches, detecting energy use anomalies, and manage loads and shift energy consumption profiles to higher renewable energy output, while separating energy exchange activities from the electrical grid, to avoid backflow of electrical power, thus eliminating the risk of EV electrical overflow and energy supply problems at neighborhood level [12].

As such, this study focuses on developing parish-level energy strategies such as the ones described previously in five parishes of the city of Guimarães, to assess the energetic and environmental impact of building and vehicle demands in urban setting. It aims to evaluate transition scenarios – from Business-as-Usual to low-carbon urban mobility profiles – and to establish a framework for implementing policies on energy efficiency and sectoral decarbonization. On the building side, this study will cover the implementation of active and passive retrofitting measures in energy performance, when compared with current architectural features of the case study, and considering the implementation of Renewable Energy Systems (Photovoltaic Pannels) in the dwellings. From this analysis, crucial parameters such as the excess photovoltaic energy production will be used to model the mobility side of this paper, by modelling the variables that will determine the feasibility of implementing urban electric mobility products on the urban mesh. This involves applying decision-making algorithms to reduce energy consumption and emissions in both the building and transport sectors, leveraging national regulations on building energy performance, drivetrain standards, mobility surveys, traffic data and considering external factors such as energy markets, renewable energy sources and socio-demographic characteristics. The findings of this study will provide a clear path in decarbonizing the mentioned economic sectors and evaluate the feasibility of mass adoption of electric drivetrains and their impact in overall energy efficiency, consumption, and carbon emissions, with future research to include the impact of stationary energy storage systems and energy management systems, at building and at neighborhood level.

2 Case Study and Methodology

The case study focuses on a BGRI (Base Geográfica de Referenciação de Informação, or in English, Geographic Information Reference Database) area in the city of Guimarães, covering infrastructures from the parishes of Creixomil, Union of Parishes of Oliveira, São Paio and São Sebastião, and Urgezes. These are characterized by having buildings from various types of architecture, from early 20th century to early 21st century construction standards, and with diverse types of usage, from office buildings, shopping and retail, restaurant, and residential, (single and multi-familiar residential households) buildings. This information was introduced in City Energy Analyst [13], an Urban building Energy Modelling tool that allows the user to simulate energy parameters in urban areas, by taking into consideration building stock parameters such as the type of construction, type of use, type of ancillary systems present in the buildings, to accurately simulate energy demands and potentials of entire neighborhoods.

Furthermore, and to achieve this study's goal, the methodology shown in Fig. 1 was applied, incorporating data from National Institute of Statistics [14] (on population bus stops and charging stations) and vehicle fleet data from CTech [15], which outlines Guimarães' mobility characteristics (e.g. number of vehicles, types of drivetrains, etc). These datasets were further compiled and explored using QGIS and Python to provide the inputs to define 4 energy scenarios, according to the Portuguese Legislation on Building's Energy Performance [16], and the expected results of Fig. 2:

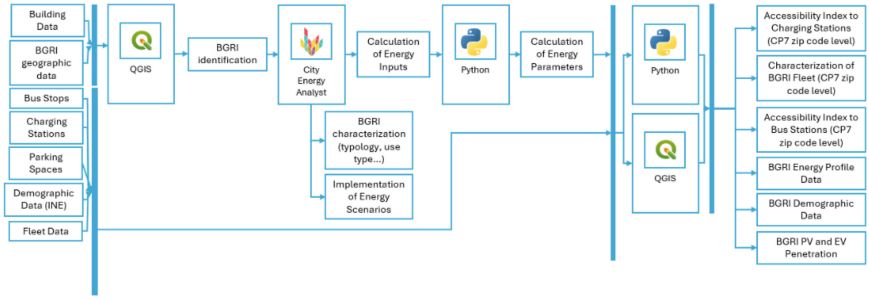


Fig. 1. Case Study Methodology

These outputs are used to compute key transport-related variables in the case study area, assessing their role in reducing energy use and emissions. This includes EV Availability (EV_{use}) (Eq. 1), which measures the number of hours per year that an electric vehicle has enough energy stored in the battery (SOC_{EV}) and that is able to supply energy to a building based on consumption at time t, and Home-to-Vehicle (H2V) interactions (Equation 2), which quantifies the hours when solar excess is available for charging. Additionally, a potential analysis was conducted, considering an Annual Solar Excess limit (Equation 3), whereby one extra EV is assigned to a building if its annual solar surplus exceeds this threshold.

$$\%EV_{use(t)} = \frac{\sum(SOC_{EV}(t) \geq Load(t))}{8760} \tag{1}$$

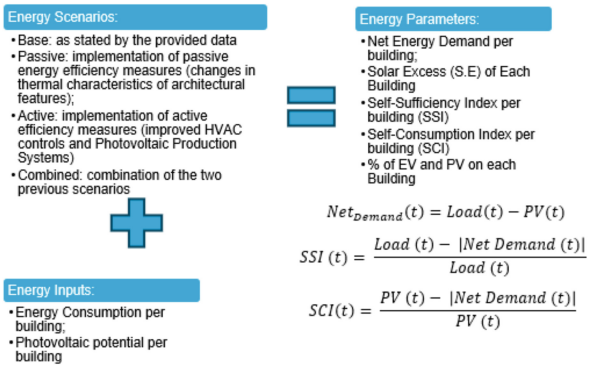


Fig. 2. Energy Inputs and Outputs

$$\%H2V = \frac{nr\ hours\ (EV\ is\ present \& solar_{excess} > 0)}{8760} \tag{2}$$

$$SolarExcess_{limit} = \frac{2 * Trip * EV_{consumption} * 260\ Week\ days}{Occupation} \tag{3}$$

3 Results and Conclusions

By computing all the mentioned variables and equations, Fig. 3 represents the difference in the energy parameters across the mentioned scenarios(Energy Demand in Dark Blue, PV Production in Orange, Net Energy Demand in Green and Solar Excess in Light Blue), where it can be shown that, despite the increase of energy consumption in ACTIVE and COMBINED scenarios, (due to the addition of ancillary systems), solar production alone is insufficient to meet total annual energy demand across the whole case study. This holds true despite observed and promising energy values in PV Production, leading to higher Solar Excess and Net Demand values, when the overall values are analyzed. Moreover, and another indicator of the feasibility of the algorithm is the Self-Sufficiency and Self-Consumption Indexes, ranging from an average of 20 to 24% for the SSI and from 33 to 34% for the SCI across all scenarios, indicating a positive impact of PV penetration. Additionally, and despite the increase in energy consumption, the implementation of PV panels induces energy savings and carbon emissions reductions across all scenarios, and with positive solar excess, these carbon savings are even more relevant (Table 1).

The observed parameters, especially the PV production registered, supports the adoption of electric transport technologies across the case study. By using real ownership data from the National Institute of Statistics [14], EV availability ranges between 23 and 24% across all scenarios, showing that, despite the existence of electric transports in the analysis, energy exchange activities only cover around 23% of the whole year-analysis, relating to around 2000 h/year (roughly 84 days). In addition, H2V interactions are even more reduced, only accounting for 9 to 11% of total Ev Availability time (around 8 full days). Even when Solar Excess thresholds are considered, as stated in Equation 3,

Table 1. Building Energy and Emissions Analysis

	ACTIVE		BASE		COMBINED		PASSIVE	
Parameter	**Energy Indicator (GWh/year)**	**Carbon Impact (ton-CO_2/year)**	**Energy Indicator (GWh/year)**	**Carbon Impact (ton-CO_2/year)**	**Energy Indicator (GWh/year)**	**Carbon Impact (ton-CO_2/year)**	**Energy Indicator (GWh/year)**	**Carbon Impact (ton-CO_2/year)**
Energy Demand	71.00	8094.44	56.74	6468.23	69.01	7866.95	52.74	6012.84
Energy Demand Compared to BASE	+14.26	+1626.21	–	–	+12.27	+1398.72	−4	−455.39
Net Energy Demand	54.55	6218.56	40.28	4591.72	52.55	5990.13	36.28	4135.83
Solar Excess	5.30	−604.30	6.05	−689.64	5.25	−598.34	6.08	−693.64
Savings	**Energy Indicator (GWh)**	**Carbon Impact (ton-CO_2)**	**Energy Indicator (GWh)**	**Carbon Impact (ton-CO_2)**	**Energy Indicator (GWh)**	**Carbon Impact (ton-CO_2)**	**Energy Indicator (GWh)**	**Carbon Impact (ton-CO_2)**
Without Solar Excess	−16.45 GWh	−1875.88 tonCO_2	−16.46 GWh	−1876.51 tonCO_2	−16.46 GWh	−1876.82 tonCO_2	−16.46 GWh	−1875.88 tonCO_2
With Solar Excess	−21.75 GWh	−2480.18 tonCO_2	−22.51 GWh	−2566.05 tonCO_2	−21.71 GWh	2475.16 tonCO_2	−22.54 GWh	2569.52 tonCO_2

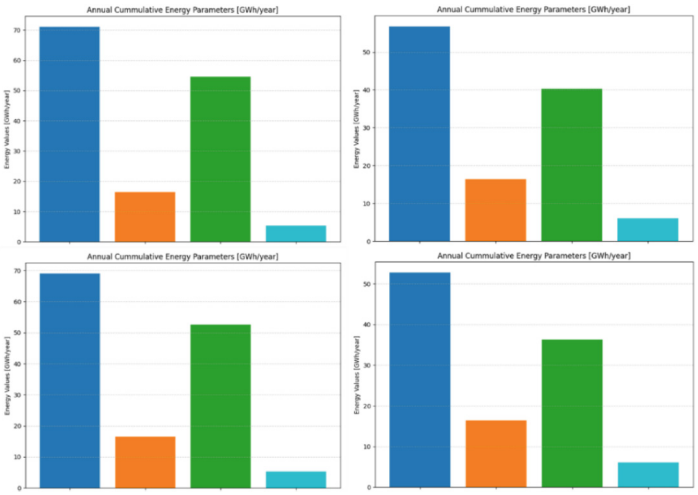


Fig. 3. Annual Cumulative Energy Parameters (ACTIVE, BASE, COMBINED, PASSIVE, from top to bottom, left to right), in GWh

the potential for these interactions stay relatively the same, ranging from 8 to 10%. Such results can be backed by demographic statistics, that confirm the case study geolocation as a densely populated one, resulting in reduced solar excess thresholds, and, consequently, induce low H2V figures.

However, if we analyze the difference in buildings covered by EVs, the results change drastically: for initial H2V values, there were only 123 buildings out of 561 that had these types of interactions, with 10% of the time being related to H2V activities. If the building count is filtered for buildings that register substantial values, the number of

buildings on the analysis drops to 85 in the worst-case scenario (ACTIVE) and to 90 in the best-case scenario (BASE and PASSIVE). In these situations, H2V interactions rise to 14%. And an even greater result is verified when considered H2V potentials, related to the solar excess threshold. For this variable, the original building count is the total case study's sample (561). When filtered, this value decreases to 238 in the worse scenario (ACTIVE) and to 257 in the best scenario (BASE). And the H2V potential increases too, registering 23% as the percentage of hours in a year that these interactions occur.

Although the results are encouraging, further underlying potential resides in this analysis. Future work will explore the integration of Energy Storage Systems, both at the building and at the neighborhood level, that can improve the efficiency of the system and increase the number of interactions of electric drivetrains and dwellings, due to the ability to store excess solar energy during low-occupancy periods. Also, the implementation of Building Energy Management Systems can enhance the use of Renewables, both at the building and the vehicle level, by redirecting energy flows to proprietary energy systems to further augment overall energy efficiency, both in the building and transport sector. This strategy, conciliated with the coupling of energy markets, will allow both users and governmental agencies to achieve economic benefits, by enabling this system to manipulate the energy flow regarding energy prices, while minting the efficiency of the system, helping reduce grid dependency and carbon emissions associated with it.

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References

1. European Commission: Communication From the Commission to the European Parliament, the European Council, The Council, The European Economic and Social Committee and the Committee of the Regions-The European Green Deal (2019). https://eur-lex.europa.eu/resource.html?format=PDF&uri=cellar%3Ab828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02%2FDOC_1. Accessed 11 May 2026
2. van Heerden, R., et al.: Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050. Nat. Energy. **10**(3), 380–394 (2025). https://doi.org/10.1038/s41560-025-01703-1
3. Abid, H., Kany, M.S., Mathiesen, B.V., Næss, P., Elle, M., Maya-Drysdale, D.W.: Quantification of Savings for the European Transport Sector through energy efficient urban planning. J. Sustain. Dev. Energy Water Environ. Syst. **10**(4) (2022). https://doi.org/10.13044/j.sdewes.d10.0426
4. European Parliament, European Council: Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (2010)
5. European Parliament, European Council: Directive (EU) 2018/844 of the European Parliament and of The Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (2018)

6. Danielis, R., Scorrano, M., Giansoldati, M.: Decarbonising transport in Europe: trends, goals, policies and passenger car scenarios. Res. Transp. Econ. **91** (2022). https://doi.org/10.1016/j.retrec.2021.101068
7. İnci, M., Savrun, M.M., Çelik, Ö.: Integrating electric vehicles as virtual power plants: a comprehensive review on vehicle-to-grid (V2G) concepts, interface topologies, marketing and future prospects. (2022). https://doi.org/10.1016/j.est.2022.105579
8. Islam, S., Iqbal, A., Marzband, M., Khan, I., Al-Wahedi, A.M.A.B.: State-of-the-art vehicle-to-everything mode of operation of electric vehicles and its future perspectives. (2022). https://doi.org/10.1016/j.rser.2022.112574
9. Sihombing, V., Yandri, E., Pramono, K.P., Ariati, R.: Advances in building energy management systems (BEMS): a comprehensive review with bibliometric analysis and future research directions. J. Mechatron. Electr. Power Veh. Technol. **16**(1), 27–41 (2025). https://doi.org/10.55981/j.mev.2025.961
10. Bonilla, D., Samaniego, M.G., Ramos, R., Campbell, H.: Practical and low-cost monitoring tool for building energy management systems using virtual instrumentation. Sustain. Cities Soc. **39**, 155–162 (2018). https://doi.org/10.1016/j.scs.2018.02.009
11. Rehman, M.A., Numan, M., Tahir, H., Rahman, U., Khan, M.W., Iftikhar, M.Z.: A comprehensive overview of vehicle to everything (V2X) technology for sustainable EV adoption. (2023). https://doi.org/10.1016/j.est.2023.109304
12. Monteiro, V., Pinto, J.G., Afonso, J.L.: Operation modes for the electric vehicle in smart grids and smart homes: present and proposed modes. IEEE Trans. Veh. Technol. **65**(3), 1007–1020 (2016). https://doi.org/10.1109/TVT.2015.2481005
13. City Energy Analyst Homepage. https://www.cityenergyanalyst.com. Accessed 11 May 2026
14. Instituto Nacional de Estatística: CENSOS 2021. XVI Recenseamento Geral da População, . VI Recenseamento GerSal da Habitação: Resultados Definitivos. Lisbon (2022)
15. Araujo, G., Santos, L., Leitão, A., Gomes, R.: AD-Based Surrogate Models for Simulation and Optimization of Large Urban Areas, pp. 689–698 (2022). https://doi.org/10.52842/conf.caadria.2022.2.689
16. Direção Geral de Energia e Geologia and ADENE: Manual SCE-Manual Técnico para a Avaliação do Desempenho dos Edifícios (Despacho no 6476-H/2021) (2021)

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Enhancing Battery Diagnostics Using On-Chip Electrochemical Impedance Spectroscopy

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Abstract. Electrochemical impedance spectroscopy (EIS) is a promising non-invasive method that characterizes electrochemical behavior over various time scales. While conventionally utilized in battery design and development, recent efforts attempt to apply EIS in real-time operational environment, i.e. dynamic EIS or DEIS, enabling advanced diagnostics and prognostics. The development of on-chip EIS functionality, which captures impedance data during rest and operation, marks a significant step forward. Unlike conventional BMSs that rely on static tables for current, voltage, and temperature limits, next-generation systems with EIS functionality will be able to dynamically monitor battery health and safety. This is especially important as side reactions result in battery aging and degradation. One critical degradation mechanism is lithium plating, which may occur during fast charging at low temperatures. The on-chip EIS can detect these phenomena by monitoring changes in the real part of the impedance and, in particular, its time derivative at specific frequencies. The objective of the paper is to demonstrate the applicability of a custom-designed PCB incorporating the commercially available DNB1168 IC to perform EIS measurements and detect early-stage lithium plating in battery systems.

Keywords: Battery diagnostics · EIS · Lithium plating · SoH

1 Introduction

Batteries have become a major focus of research in recent years, driven by their increasingly critical role in a wide range of applications. While initially used in low-power devices, such as portable electronics, their use has rapidly expanded to high-energy applications, including electric vehicles (EVs) and large-scale energy storage systems (ESS). Among the various battery technologies, lithium-ion batteries (LIBs) have emerged as the most prominent, due to their high energy density and compact form factor. However, as electrochemical systems, LIBs are subject to environmental sensitivity, inevitable

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aging, and thermal safety challenges [1, 2]. Therefore, the safe, reliable, and efficient operation of LIBs depends heavily on advanced BMSs that provide essential functions such as state estimation, energy management, thermal regulation, and fault diagnostics [2, 3]. Despite advances in battery management systems (BMS) hardware and software, ensuring the safety and durability of lithium-ion batteries (LIB) while increasing their performance remains challenging. A notable limitation of current BMS technologies is the lack of integration of electrochemical insights vital for early fault detection and enhanced safety. These insights can be accessed through virtual sensing or in-situ cell measurement. Recent developments have increasingly emphasized the use of Electrochemical impedance spectroscopy (EIS) as a diagnostic method [4], owing to its capability to provide comprehensive insights into internal battery dynamics [5]. This integration has gained significant attention for its potential to advance diagnostic accuracy, improve system reliability, and facilitate the evolution of next-generation BMS technologies [6]. EIS has been widely recognized in the literature for its diagnostic utility in lithium-ion battery systems [7]. Locorotondo et al. [8] applied EIS to evaluate the state of health (SoH) during the battery aging process. Furthermore, Zhang et al. [9] studied the formation of solid electrolyte interface (SEI) layer on the surface of graphite in Li/graphite cells using the EIS.

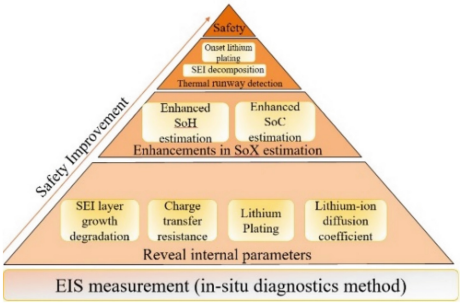


Fig. 1. Framework highlighting the contribution of EIS measurements.

However, detecting impedance changes becomes less reliable as pack complexity increases, highlighting the critical influence of cell packaging and battery design on SoS monitoring. Srinivasan et al. [10] presented a new approach for predicting and preventing thermal runaway in Li-ion batteries using rapid monitoring of impedance phase shift, which is highly sensitive and size independent. Characteristic changes in phase shift appear before and during runaway, enabling early detection via battery management systems. Koleti et al. [11] introduced a method to detect lithium plating by estimating the cell impedance. This technique operates in real time during charging and can be readily integrated into the BMS. Considering prior conducted research and studies, Fig. 1 illustrates how the EIS measurement can positively effect on the safety aspect of the battery system.

2 On-Chip EIS Measurement

EIS demonstrates significant potential for seamless onboard integration and non-invasive real-time analysis, meeting the efficiency and safety requirements of next-generation battery storage systems. However, due to its reliance on a frequency response analyzer (FRA), the implementation of EIS in hybrid electric vehicles, battery electric vehicles, and stationary energy storage systems remains cost-prohibitive [12]. Several studies in the literature have explored the development of cost-effective and efficient monitoring systems that incorporate EIS functionality onboard. Some research efforts concentrate on developing compact solutions for acquiring EIS data, with the potential for online operation, by integrating dedicated hardware implemented through application-specific integrated circuits (ASICs) [13]. In [14] the passive stimulation approach is employed in battery charge balancers which is already integrated into the battery monitoring system. In certain configurations, enabling EIS necessitates a more sophisticated setup of the charge balancer, thereby facilitating comprehensive EIS analysis at the cell-level of the battery pack. On-board EIS measurements can be also achieved through the integration of commercially available components specifically designed for impedance measurements, for example the Analog Devices AD5933, and Analog Device CN0510. All the aforementioned studies and applications necessitate specialized hardware, which is often either expensive or too bulky to be practically integrated into a BMS. In the literature, to the best knowledge of the authors, there is only one published study using on-board EIS chip from Infineon for the detection of Li-plating [15]. In this paper, we integrate a commercially available IC manufactured by DNS (DNB1168) with the objective to detect Li-plating by referencing the results with the laboratory-grade device. The IC functions as a single-cell supervisor capable of measuring voltage and temperature, performing passive balancing, and enabling EIS measurements. The design also takes into account physical constraints and the geometry of the battery cell to facilitate easy implementation and integration into the BMS. The IC performs EIS measurements within a frequency range of 7.5 mHz to 7.8 kHz.

3 Methodology

EIS is a powerful non-invasive technique widely used for characterising electrochemical systems, including Li-ion batteries. The main idea behind the EIS is applying a small potentiostatic or galvanostatic excitation to the device under test in the form of a sinusoidal signal spanning several orders of magnitude in frequency [7], typically from the kilohertz (kHz) to the millihertz (mHz) range. By recording the system response in terms of amplitude and phase shift, an impedance spectrum is obtained, usually represented in a Nyquist plot, which reveals processes in the battery occurring over different characteristic time scales. For purposes such as using the EIS device for detection of the onset of Li-plating occurring at fast charging, the dynamic EIS (DEIS) approach is used. During the DEIS approach, a small alternating-current (AC) perturbation is superimposed on the direct-current (DC) bias [16].

One of the major limitations to fast charging and a significant contributor to reduced battery lifespan is lithium deposition, commonly referred to as lithium plating. Lithium

plating can result from limited ionic transport in the electrolyte, restricted intercalation kinetics at the graphite/electrolyte interface, and solid-state diffusion limitations within graphite particles [14]. In general, the primary conditions that increase the likelihood of lithium plating include low temperatures, high charging currents, and high states of charge (SoC) [17].

4 Experimental Setup

To test and benchmark the capabilities of the DNB 1168 chipset on the battery cell, the following equipment was used: Ivium XP40 potentiostat/galvanostat, Lauda Alpha RA 24 cooling thermostat, and a PC for data acquisition. Figure 2 presents an experimental setup. In addition to the custom-designed PCB, two high-current cables and two voltage measurement cables from Ivium XP40 were connected to the positive and negative terminals of the battery (see Fig. 2(a) and (b)). The Ivium XP40 served as an external charger/load for the battery cell. A thermocouple was placed on the cell surface to monitor the temperature (Fig. 2(c)). Finally, the entire assembly was put in a protective plastic bag and submerged in a cooling thermostat filled with a water-glycol mixture (Fig. 2(d)) to ensure maximum heat transfer during cell operation and, consequently, keep the cell close to the desired temperature. Before starting the measurement (see the test procedure scheme depicted in Fig. 2(e)), a voltage hold of 3.7 V (approx. 50% SoC) was applied to the cell to ensure a consistent starting point and to focus only on the upper part of the SoC range where Li-plating is expected to occur. The cell was then charged with a constant current of 40 A until the cell voltage reached 4.4 V (0.05 V above the upper cutoff voltage specified by the manufacturer), then immediately discharged with the same constant 40 A current until the cell voltage again reached 3.7 V.

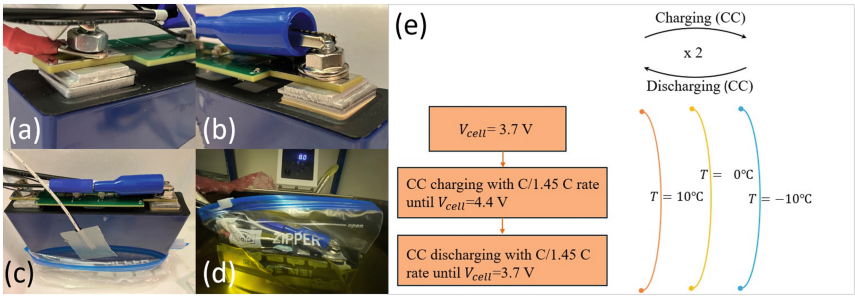


Fig. 2. Experimental setup with DNB 1168 chipset and Ivium XP40 measuring cables. (a) detail of the positive terminal of the battery cell, (b) detail of the negative terminal, (c) full cell detailed measurement setup with thermocouple attached on the cell's surface, (d) cell submerged into water-glycol mixture, (e) test procedure with two times consecutive constant-current (CC) charge/discharge cycles between 3.7 and 4.4 V at C/1.45, performed at three temperatures: 10 °C, 0 °C and − 10 °C.

This corresponds to an approximately C/1.45 rate for the battery cell with 58 Ah nominal capacity. The voltage hold, charge, and discharge cycle was repeated at three

different temperatures, i.e. 10 °C, 0 °C and − 10 °C. The charge/discharge cycles were repeated two times to avoid interference between the Ivium XP40 and DNB 1168 chipset during AC perturbation. First, DEIS was performed with laboratory-grade device Ivium XP40 only for a benchmark where an AC perturbation of 1 A of amplitude and frequency of 10 Hz was superimposed on the 40 A of constant DC bias. Based on [18], 10 Hz represents the characteristic frequency at which the response of the anode kinetics is observed. For the second part of the DEIS measurements, the Ivium XP40 served only as a charger with a constant DC current bias of 40 A. The AC perturbation was handled purely by the DNB 1168 chipset at 9.5 Hz with an amplitude of a few 100 mA depending on the potential difference between the positive and negative battery cell terminals. The following section presents the acquired results from the measurements.

5 Results

This section presents the acquired results from the measurements in which the goal was to provoke a Li-plating phenomenon inside the battery cell, confirm it with the widely adopted method, and finally detect it during the charging with both devices. Fig. 3(a) first shows the charge curves, i.e. the cell potential versus the charge transferred from the initial voltage hold at 3.7 V at three different thermostat temperatures (10 °C, 0 °C and − 10 °C). This figure clearly shows the ever-increasing initial voltage jump at the beginning of the charge, indicating an increase of internal resistance as the temperature decreases. Furthermore, the overpotential required for charging at constant current also increases significantly with lowering the temperature. To complement the charge curves, Fig. 3(b) presents the cell surface temperature during charging at three different thermostat temperatures measured by the thermocouple. It can be seen that even in the liquid-filled thermostat, the surface cell temperature increases rapidly during the initial charge stage and then equilibrates with about 4 to 5° above the surrounding coolant temperature. To check for the occurrence of Li-plating phenomena during the charging at any of the three different temperatures, a widely adopted approach was chosen. Namely, during relaxation or discharge after charging, a distinct signal associated with stripping of deposited Li metal, i.e. the voltage plateau (see references [19, 20]) can be observed. For the untrained eye, the voltage plateau depicted in the plots showing potential versus time or charge might not reveal itself immediately (see Fig. 3)(c). Therefore, it is helpful to plot the derivative of the charge transferred over the cell voltage, that is dQ/dV. This was done in Fig. 3(d). One can immediately notice the difference in the curves at 10 °C and 0 °C and the curve at −10 °C, being the occurrence of the expected voltage plateau at −10 °C. The voltage plateau is associated with the process called Li-stripping [19]. Figure 3(d) therefore confirms the occurrence of the Li-plating during charging.

As Li-plating is, in general, an unwanted and also damaging process in insertion electrodes, the objective is to prevent it. Since detection of Li-stripping is not a suitable method to achieve this objective, we focus on methods that are capable of detecting Li-plating as soon as possible, which means that it should be detected during charging. According to [14] the interfacial impedance of graphite decreases during Li-plating and can be detected using the DEIS approach. Figure 3(e) shows the measured real part of the impedance (R_s) during charging using DEIS approach with Ivium XP40 device and

with DNB 1168 chipset (Fig. 3f) plotted versus cell's potential. As seen in Fig. 3(a) the impedance increases with decreasing temperature. The overall trend shows a decrease in the value of the impedance during the charging as the cell voltage increases. By comparing both figures, it can be seen that the DNB 1168 chipset is capable of replicating DEIS measurements of the laboratory-grade device.

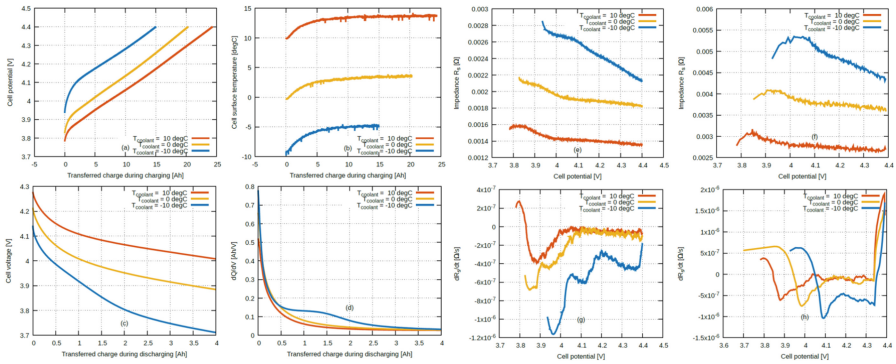


Fig. 3. (a) Charge curves vs. the charge transferred from 3.7 V to 4.4 V with 40 A of charging current at three different thermostat temperatures. (b) cell's surface temperature during charging, (c) cell voltage and (d) calculated derivative of charge over cell voltage (dQ/dV) during the discharge after the 4.4 V was reached, (e) measured real part of the impedance (R_s) during the charging using DEIS approach with Ivium XP40 device and (f) DNB 1168 chipset plotted versus cell's potential, (g) calculated derivative of real part of the impedance over time (dR_s/dt) during the charging using DEIS approach with Ivium XP40 device and (h) DNB 1168 chipset plotted versus cell's potential.

Since no clear evidence of a sudden decrease of impedance is easily discernible from Fig. 3(e) and (f), a derivative of the real part of the impedance over time (dR_s/dt) was calculated from the measurements, which is shown in Fig. 3(g and h). The derivatives were calculated by applying a simple moving average algorithm to the impedance (R_s) measurements to reduce the noisy data. Comparing again the dR_s/dt curves at different temperatures, a notable decrease in these values can be observed from the -10 °C case after the cell potential reached 4.2 V. This phenomenon can be observed with both devices at almost identical cell voltage, which can be (with a certain amount of caution) proclaimed as a detected onset of Li-plating during the charging. To conclude this section with the outlook and applicability of the proposed methodology in a real-time BMS in is important to consider computational constraints of the embedded hardware. The signal processing steps used in this study are computationally efficient and can be executed on the currently available automotive-grade microcontrollers. Compared to the laboratory grade equipment, the low-cost EIS chip provides reduced measurement accuracy but enables easier integration into embedded systems. This trade-off is acceptable for onboard diagnostics, where the objective is not high-precision impedance reconstruction but rather the online detection of characteristic trends associated with undesirable side reactions.

6 Conclusion

This study demonstrates the potential for the integration of EIS into battery management systems (BMS) for real-time monitoring and diagnostics. By introducing the low-cost EIS chip, it becomes possible to measure impedance during the rest and operation of the battery cell and potentially enables detection of the onset of Li-plating during charging. Further investigation is still needed to develop a robust online algorithm capable of adequate processing of the noisy data and predicting the onset of Li-plating and other degradation phenomena with high degree of confidence. However, EIS chips offer an opportunity for the next generation BMS to actively intervene with the aim of preventing unwanted degradation phenomena and consequently improving the battery safety and longevity.

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References

1. Jiang, B., Zhu, J., Wang, X., Wei, X., Shang, W., Dai, H.: A comparative study of different features extracted from electrochemical impedance spectroscopy in state of health estimation for lithium-ion batteries. Appl. Energy. **322**, 119502 (2022)
2. Jung, M.J., Lee, S.-G., Choi, K.-S.: A new diagnostic indicator for lithium-ion batteries via electrochemical impedance spectroscopy: harnessing the highest frequency peak in distribution of relaxation times. J. Power Sources. **611**, 234743 (2024)
3. Rahmani, P. et al.: Driving the future: a comprehensive review of automotive battery management system technologies, and future trends. J. Power Sources. **629**, 235827 (2025)
4. Wu, C., Zhu, C., Ge, Y., Zhao, Y.: A review on fault mechanism and diagnosis approach for li-ion batteries. J. Nanomater. **2015**, 631263 (2015)
5. Mele, I., Zelič, K., Firm, M., Moškon, J., Gaberšček, M., Katrašnik, T.: Enhanced porous electrode theory based electrochemical model for higher fidelity modelling and deciphering of the EIS spectra. J. Electrochem. Soc. **171**, 080537 (2024)
6. Li, Y. et al.: Capacity estimation of lithium-ion battery through interpretation of electrochemical impedance spectroscopy combined with machine learning. Measurement. **243**, 116374 (2025)
7. Meddings, N. et al.: Application of electrochemical impedance spectroscopy to commercial Li-ion cells: a review. J. Power Sources. **480**, 228742 (2020)
8. Locorotondo, E., Cultrera, V., Pugi, L., Berzi, L., Pierini, M., Lutzemberger, G.: Development of a battery real-time state of health diagnosis based on fast impedance measurements. J. Energy Storage. **38**, 102566 (2021)
9. Zhang, S.S., Xu, K., Jow, T.R.: EIS study on the formation of solid electrolyte interface in Li-ion battery. Electrochim. Acta. **51**, 1636–1640 (2006)
10. Srinivasan, R., Demirev, P.A., Carkhuff, B.G.: Rapid monitoring of impedance phase shifts in lithium-ion batteries for hazard prevention. J. Power Sources. **405**, 30–36 (2018)

11. Koleti, U.R., Dinh, T.Q., Marco, J.: A new on-line method for lithium plating detection in lithium-ion batteries. J. Power Sources. **451**, 227798 (2020)
12. Mattia, L., Petrone, G., Pirozzi, F., Zamboni, W.: A low-cost approach to on-board electrochemical impedance spectroscopy for a lithium-ion battery. J. Energy Storage. **81**, 110330 (2024)
13. Manfredini, G. et al.: An ASIC-based miniaturized system for online multi-measurand monitoring of lithium-ion batteries. Batteries. **7**, 45 (2021)
14. Koseoglou, M., Tsioumas, E., Ferentinou, D., Jabbour, N., Papagiannis, D., Mademlis, C.: Lithium plating detection using dynamic electrochemical impedance spectroscopy in lithium-ion batteries. J. Power Sources. **512**, 230508 (2021)
15. Straßer, A., Adam, A., Li, J.: In operando detection of lithium plating via electrochemical impedance spectroscopy for automotive batteries. J. Power Sources. **580**, 233366 (2023)
16. Drvarič Talian, S., Kapun, G., Moškon, J., Dominko, R., Gaberšček, M.: Operando impedance spectroscopy with combined dynamic measurements and overvoltage analysis in lithium metal batteries. Nat. Commun. **16**, 2030 (2025)
17. Weiss, M. et al.: Fast charging of lithium-ion batteries: a review of materials aspects. Adv. Energy Mater. **11**, 2101126 (2021)
18. Katzer, F., Rüther, T., Plank, C., Roth, F., Danzer, M.A.: Analyses of polarisation effects and operando detection of lithium deposition in experimental half- and commercial full-cells. Electrochim. Acta. **436**, 141401 (2022)
19. Yang, X.-G., Ge, S., Liu, T., Leng, Y., Wang, C.-Y.: A look into the voltage plateau signal for detection and quantification of lithium plating in lithium-ion cells. J. Power Sources. **395**, 251–261 (2018)
20. Janakiraman, U., Garrick, T.R., Fortier, M.E.: Lithium plating detection methods in Li-ion batteries. J. Electrochem. Soc. **167**, 160552 (2020)

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Leveraging the Business Canvas Modell for the Hungarian Biomethane Industry

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Abstract. The global biogas and biomethane sectors are experiencing significant growth, driven by rising environmental concerns, international decarbonisation goals, and the broader transition to renewable energy sources. These developments have positioned these subsectors of the alternative fuel industry as the targets of strategic investment opportunities for multinational companies pursuing sustainable business models. Our paper seeks to identify and assess some of the critical factors that influence successful entry into the biogas and biomethane production markets, using the Business Model Canvas (BMC) as an analytical framework. Through a comprehensive, multidimensional approach, our research explores key partners, core activities, customer segments and value proposition characteristics of the application of BMC in the transport sector. Special emphasis is placed on aligning company capabilities with national energy strategies, including potential partnerships, and economic feasibility of the alternative fuel projects. Our study's findings contribute to the growing number of publications on sustainable business strategies and the dynamics of renewable energy markets of alternative fuels. Furthermore, our research provides practical insights for industry practitioners, innovators, and policymakers involved in strategic decision-making within the biofuel sector. By leveraging the BMC model, this study offers the Hungarian use case for the rapidly evolving biogas and biomethane production industry.

Keywords: Decarbonisation · Alternative Fuels · Biogas and Biomethane · Market Entry Strategy · Business Model Canvas (BMC)

1 Introduction

The global energy landscape is undergoing rapid transformation, driven by the dual imperatives of climate change mitigation, energy security and long-term fossil fuel dependency. Among these, biogas and its upgraded form, biomethane, have emerged as promising alternatives because of their versatility, scalability, and compatibility with existing infrastructure [1]. This trend is also driven by the European Union's REPowerEU initiative, which has set an ambitious target of producing 35 billion cubic meters

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(bcm) of biomethane annually by 2030 [2]. According to the European Biogas Association (EBA) [3], the previously described goal is supported by a €27 billion investment plan aimed at accelerating infrastructure development, technological innovation, and regulatory harmonization across member states.

Biomethane is an energy source that can be injected directly into the natural gas grid or used in transport or industrial processes [4]. This position positions biomethane as a key enabler of circular economy principles, as it transforms waste streams into valuable energy and fertilizer outputs [5, 6].

Hence, Hungary, in alignment with EU directives and its own National Energy and Climate Plan [7] has initiated a strategic push to expand its biogas and biomethane capacities. The country aims to triple its biogas production by 2030, reaching 600 million cubic meters annually, with 184 million cubic meters designated for biomethane conversion (see Fig. 1). This ambition is backed by robust policy instruments, including the METÁR brown premium subsidy and a €100 million nonrefundable CAPEX grant scheme under the Jedlik Ányos Energy Program [8].

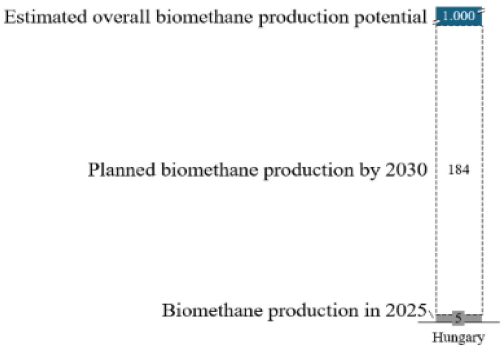


Fig. 1. Current, planned and estimated biomethane production in Hungary in million m^3. Source: Own edition based on the Schönherr [8], Budapest Business Journal [9] and European Commission [10] datasets.

Despite these promising developments, the biomethane industry faces several challenges, including high production costs, regulatory uncertainty, and market fragmentation. In this context, strategic tools such as the Business Model Canvas (BMC) offer valuable frameworks for navigating the complexities of market entry and long-term viability.

This paper aims to bridge the gap between theoretical frameworks and practical implementation by applying the BMC to the Hungarian biomethane industry. Through a multidimensional analysis, it seeks to provide actionable insights for industry practitioners, policymakers, and innovators engaged in the transition to renewable energy in terms of the transportation sector. By mapping these interdependencies through the BMC, stakeholders can better align their value propositions, revenue models, and operational strategies, thereby enhancing the feasibility and scalability of biomethane ventures.

2 Materials and Methods

The BMC is a strategic framework that visualizes how organizations create, deliver, and capture value. It consists of nine interrelated components that span the customer, infrastructure, and financial domains. The implemented BMC model consists of the following segments: Key partners; Key activities; Value proposition; Customer relationships; Customer segments; Key resources; Distribution channels; Cost structure; Revenue streams. Originally developed by Osterwalder and Pigneur [11], the BMC provides a structured approach to visualizing and analyzing business models. Its adaptability has made it a popular tool in various industries, including renewable energy [12]. However, Joyce and Paquin [13] suggested that traditional BMC frameworks may require modification to fully capture the unique dynamics of energy enterprises, particularly those operating under public interest mandates and sustainability constraints.

Supplementary insights were drawn from scientific publications and biogas project documentation. The findings of the analysis of the abovementioned reports have been put into the context of key related Hungarian energy policies, laws and market studies to highlight policy and market dynamics.

3 Application of the Business Model Canvas

As the BMC implements a well-structured approach for companies to examine potential market entry, evaluating the general approach in light of market specifics is particularly worthwhile. This also plays a key role in emerging markets. The following subchapters summarize the BMC sections with Hungarian biomethane-specific characteristics.

3.1 Key Partners

In Hungary's biomethane transport sector, key partners include agricultural cooperatives, bio-CNG/LNG technology providers, fuel distributors, grid operators, and the Ministry of Energy as regulatory authority. Strategical investors also play a pivotal role in the ecosystem, as partnerships support infrastructure development, enhance long-term agreements, and align with national transportational decarbonisation goals [15].

3.2 Key Activities

The core activities in the Hungarian biomethane business model include feedstock procurement, biogas production, upgrading, grid injection, and certification. Activities might also include Renewable Support Scheme System (METÁR) brown premium participation, residue valorization, and infrastructure development under the Jedlik Ányos Program [16; 17].

3.3 Value Proposition

Biomethane offers carbon-neutral energy, enhances energy security, esteems agricultural waste, and supports rural development in Hungary. Furthermore, it enables

grid-compatible green gas, contributes to climate targets, and qualifies for METÁR subsidies and Guarantees of Origin trading [18]. With respect to its transportation usage, biomethane offers reliable GHG emission mitigation potential and reduces the dependence on fossil fuels by promoting sustainable economic solutions [19].

3.4 Customer Relationships

The effective use of biomethane in the Hungarian transport market relies on the cultivation of durable, cooperative ties with industrial users, transport operators, municipalities, and green certificate purchasers. These connections foster regulatory coherence, ensure demand stability, and support long-term market growth. Trust, transparency, and certification frameworks are key enablers of these relationships [20].

3.5 Customer Segment

As the Hungarian biogas-biomethane market is currently in the early development phase, key customer groups differ from those in mature countries. The comprehensive demand for renewable gases includes gas traders, grid operators, industrial users, and, in the future, possible CNG/biomethane transport companies and firms purchasing green certificates for compliance alignment.

3.6 Key Resources

Essential resources in Hungary's biomethane sector mostly rely on feedstock availability, technological infrastructure for production and upgrading, skilled human resources, financial capital, and regulatory permits. Given the CAPEX-heavy nature of the industry, strategic proximity to gas grid infrastructure enhances injection feasibility and market access. These assets underpin operational efficiency and scalability and overall ensure a viable and long-term market presence [21].

3.7 Distribution Channels

Biomethane could reach the market within Hungary through grid injection into the national gas system, CNG filling stations for transport use or through Guarantees of Origin traded on the G-REX trading platform. Direct bilateral contracts with industrial consumers and municipalities could also serve as key commercial channels [20; 22].

3.8 Cost Structure

Hungarian biomethane projects face high CAPEX needs for plant construction, upgrading units and grid connections. OPEX costs include those associated with feedstock procurement, maintenance, energy use and wastewater treatment. Logistics and compliance costs also apply. Public grants such as the Jedlik Ányos Program help offset investment burdens [2; 23]. In transport applications, biomethane deployment entails additional expenditures for expanding fueling infrastructure, fleet renewal, and long-distance distribution logistics, which can constrain market penetration.

3.9 Revenue Streams

Hungarian biomethane producers could earn income from gas sales via grid injection, CNG distribution, and certification traded on the G-REX platform. Additional revenues stem from METÁR brown premiums, CAPEX subsidies (e.g., Jedlik Ányos Program), and avoided compliance costs. In addition to the revenue streams mentioned above, biogas through CHP configurations also offers electricity and heat sales opportunities. [20; 22]. In the transport segment, further income opportunities may arise from long-term fuel supply contracts with captive CNG/LNG fleets, particularly in heavy-duty road transport and public bus operations seeking to reduce GHG-related exposure.

3.10 Overall Results

In Hungary's biomethane sector, the application of the BMC can facilitate strategic alignment between company capabilities and national energy objectives. It enables stakeholders to identify critical success factors, assess economic feasibility, and explore potential partnerships. Moreover, by incorporating environmental accountability and stakeholder impact into the model, as proposed by Dobrowolski and Sułkowski [24], the BMC can evolve into a more holistic tool for sustainable business development. Within the segments of the BMC model, the key importance of segments are the Value propositions, Key resources, Key activities and Key partnerships segments (see Fig. 2), as they are considered to be the most important factors for investors to understand the biogas-biomethane value chain regarding transportational en-use by describing the market in general. However, after the key aspects mentioned above are understood, the remaining categories of the BMC model should be customized.

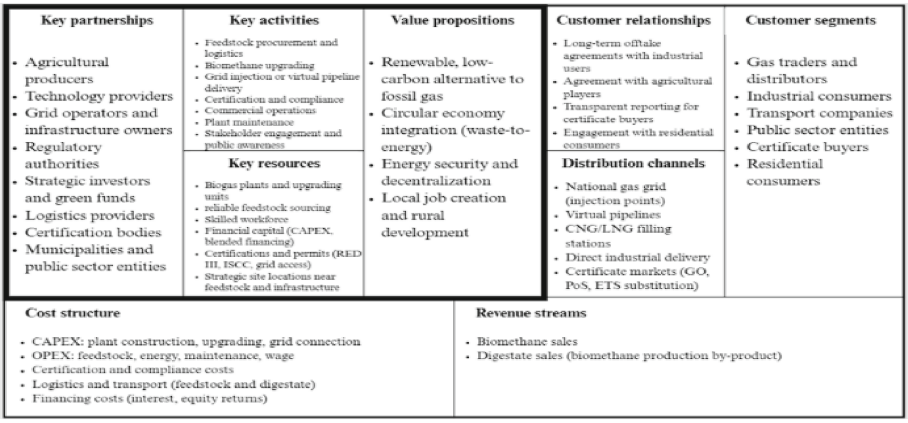


Fig. 2. The biomethane Business Model Canvas. Source: Own edition based on Osterwalder & Pigneur [11] BMC methodology.

4 Discussion and Conclusion

4.1 Strategic Implications and Limitations

Although its strategic targets and market forecast are beyond those of other European countries [3; 25; 26], Hungary's biomethane approach is still ambitious, as outlined in the 2024 National Biogas and Biomethane Action Plan, emphasizes centralized, large-scale production and aims to reduce agricultural greenhouse gas (GHG) emissions while promoting circular waste management.

Its strategic considerations include the following:

- High feedstock potential: Animal manure is expected to supply 55% of the demand, with the remainder being from agricultural and food processing byproducts [14].
- Favouring larger schemes, which align with the business case for biomethane production, with a goal of having 100 biogas plants operational by the end of the decade [14].
- Limited infrastructure maturity, with only two operational biomethane plants as of 2024, and significant investment needed to reach national targets.

Early-phase mover advantage, as entering a relatively underdeveloped market allows early entrants to influence standards and secure lasting contracts. Therefore, Hungary may offer strategic success by securing feedstock partnerships, navigating permitting processes, and leveraging compliance value through certificate trading and Emission Trading System (ETS) substitution.

4.2 Conclusion

This study applied the Business Model Canvas (BMC) framework to the Hungarian biomethane industry, offering a structured analysis of its strategic components focusing on transport sector applications. The findings underscore that the Hungarian biomethane industry, aligned with EU directives and national strategies, is aiming to significantly increase production capacity by 2030, supported by policy instruments and investment schemes.

Despite its promising agricultural feedstock potential, the sector faces challenges, including high CAPEX, regulatory complexity, and limited operational scale. However, early market entrants may benefit from shaping standards and securing long-term contracts. To ensure this, emphasis is placed on four BMC segments-value propositions, key resources, key activities, and key partnerships-which are critical for investors and stakeholders in understanding the early development of the biogas-biomethane value chain, especially for the transport segment.

Notably, as the Hungarian biogas-biomethane market is rapidly evolving, any current analysis is only a snapshot that may not fully reflect future developments. Despite the abovementioned data limitations and regulatory fluidity, we believe that our research offers a valuable starting point for new market participants seeking structured insights. Future research should explore financial models, lifecycle emissions, and regional deployment strategies to further support market development and policy refinement.

References

1. European Biogas Association (EBA).: Activity Report 2024. EBA. Accessed 1 Jul 2025. https://www.europeanbiogas.eu/eba-activity-report-2024/
2. European Commission. REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131 Accessed 3 Mar 2026.
3. European Biogas Association. Biomethane Investment Outlook. (2025a). EBA-Biomethane-Investment-Outlook_2025.pdf
4. Nevzorova, T., Kutcherov, V.: Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review. Energ. Strat. Rev. **26** (2019). https://doi.org/10.1016/j.esr.2019.100414
5. D'Adamo, I., Ribichini, M., Tsagarakis, K.P.: Biomethane as an energy resource for achieving sustainable production: economic assessments and policy implications. Sustainable Prod. Consumption. **35**, 13–27 (2023). https://doi.org/10.1016/j.spc.2022.10.014
6. Lindfors, A., Feiz, R., Eklund, M., Ammenberg, J.: Assessing the potential, performance and feasibility of urban solutions: methodological considerations and learnings from biogas solutions. Sustainability. **11**(14) (2019). https://doi.org/10.3390/su11143756
7. European Commission. Hungary - Final Updated NECP 2021–2030. (2024). https://commission.europa.eu/publications/hungary-final-updated-necp-2021-2030-submitted-2024_en
8. Schönherr Rechtsanwälte GmbH.: Hungary's strategic push for biogas and biomethane – key developments and opportunities for producers. https://www.schoenherr.eu/content/hungarys-strategic-push-for-biogas-and-biomethane-key-developments-and-opportunities-for-producers Accessed 3 Mar 2026
9. Budapest Business Journal. https://bbj.hu/economy/energy/green-energy/hungary-set-to-triple-biogas-production-to-annual-600-mln-cubic-meters-by-2030/ Accessed 1 Sep 2025
10. European Commission. BIOMETHANE FICHE – Hungary. https://circabc.europa.eu/ui/group/8f5f9424-a7ef-4dbf-b914-1af1d12ff5d2/library/97d2cee9-5f3c-4684-8d11-501f3e4790cb/details?download=true. Accessed 3 Mar 2026
11. Osterwalder, A., Pigneur, Y.: Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. Wiley, (2010). https://www.researchgate.net/publication/236650466_Business_Model_Generation_A_Handbook_for_Visionaries_Game_Changers_and_Challengers
12. Reim, W., Parida, V., Sjödin, D.: Circular business models for the bio-economy: a review and new directions for future research. Sustainability. **11**(9), 2558 (2019). https://doi.org/10.3390/su11092558
13. Joyce, A., Paquin, R.L.: The triple layered business model canvas: a tool to design more sustainable business models. J. Clean. Prod. **135**, 1474–1486 (2016). https://doi.org/10.1016/j.jclepro.2016.06.067
14. Hungarian Energy Ministry. Hungary's Plans to Encourage Biogas, Biomethane Production. Budapest Biogas Summit. Budapest. (2025). https://budapestbiogassummit.hu/downloads/2025/Viktor-Horvath%2D%2DDeputy-State-Secretary%2D%2DMinistry-of-Energy%2D%2DHungary.pdf
15. European Biogas Association. Biogases: beyond energy – Transport. https://www.europeanbiogas.eu/wpcontent/uploads/2023/06/EBA_Campaign_FS3_Digital.pdf. Accessed 3 Mar 2026
16. Bioenergy Times. https://bioenergytimes.com/hungary-launches-e100-million-scheme-to-boost-biogas-and-biomethane-production/. Accessed 2 Sep 2025
17. Kinstellar. New opportunities in biogas and biomethane production in Hungary. https://www.kinstellar.com/news-and-insights/detail/3273/new-opportunities-in-biogas-and-biomethane-production-in-hungary. Accessed 2 Sep 2025.

18. CEEnergy News. https://ceenergynews.com/bioenergy/biogas-support-scheme-soon-hungary/. Accessed 2 Sep 2025.
19. Oehmichen, K., Majer, S., Thrän, D.: Biomethane from manure, agricultural residues and biowaste—GHG mitigation potential from residue-based biomethane in the European transport sector. Sustainability. **13**(24), 14007 (2021). https://doi.org/10.3390/su132414007
20. IEA Bioenergy. Biomethane –Factors for a Successful Sector Development. (2021). https://www.ieabioenergy.com/wp-content/uploads/2022/03/IEA-Bioenergy-Renewable-Gas-Intertask-WP1-Synthesis-report_2021.pdf
21. Scarlat, N., Dallemand, J.F., Fahl, F.: Biogas: developments and perspectives in Europe. Renew. Energy. **129**, 457–472 (2018)
22. Garay, R., Kozak, A., Nyárs, L., Radóczné, K.T.: The potential for the production and use of biomass-based energy sources in Hungary. Stud. Agric. Econ. **114**, 1–9 (2012) http://repo.aki.gov.hu/2208/1/The_potential_for_the_production_and_use_of_biomass-based_energy_sources_in_Hungary.pdf
23. Magyar Energetikai és Közmű- szabályozási Hivatal [MEKH]. Alternatív szakpolitikai intézkedések az energiahatékonyság szolgálatában. https://enhat.mekh.hu/alternativ-szakpolitikai-intezkedesek. Accessed 15 Sep 2025
24. Dobrowolski, Z., Sułkowski, L.: Business model canvas and energy enterprises. Energies. **14**(21), 1–10 (2021). https://doi.org/10.3390/en14217198
25. Nagy, D., Princz-Jakovics, T.: Biogáz-politikák és szabályozási keretek: a közlekedési célú biometán használat összehasonlító elemzése a Visegrádi Négyek országainak körében. XV. Nemzetközi Közlekedéstudományi Konferencia. Széchenyi István Egyetem. Győr., 12–13 (2025b)
26. Nagy, D., Princz-Jakovics, T.: Biogas regulatory frameworks in Europe: comparative analysis of biomethane usage in transport. Energy Rep. **13**, 6397–6410 (2025a). https://doi.org/10.1016/j.egyr.2025.05.035

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Operational Environmental Performance of a PV-Assisted Heavy-Duty Battery-Electric Truck: Insights from the ESCALATE Project

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Abstract. Freight transport decarbonisation is essential to achieving climate neutrality targets, particularly for energy-intensive refrigerated heavy-duty vehicle (HDV) operations. Vehicle-integrated photovoltaics (VIPV) offer the potential to partially offset electricity demand and enhance energy autonomy. This study presents an operational environmental performance of a refrigerated battery-electric truck equipped with rooftop photovoltaic (PV) panels, developed within the ESCALATE project. Route-specific simulations for Germany and the United Kingdom were conducted under Base (grid-only) and Offset (PV-assisted) scenarios using the Environmental Footprint 3.0 method. Annual PV yields of 1640 kWh (DE) and 1550 kWh (UK) displaced less than 0.5% of total electricity demand, avoiding 619 and 380 kg CO_2-eq/year, respectively. Although roof-only PV remains limited under current constraints, results demonstrate feasibility and highlight the importance of grid mix and system configuration, providing insight into VIPV's role in freight decarbonisation.

Keywords: Life cycle assessment · Vehicle-integrated photovoltaics · Heavy-duty vehicles · Freight decarbonization

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1 Introduction

Freight transport decarbonisation is critical for achieving the European Union's 2050 climate neutrality target. Heavy-duty vehicles (HDVs), representing less than 2% of the vehicle fleet, account for more than 25% of road transport greenhouse gas (GHG) emissions and over 6% of total EU GHG emissions [1]. The EU has introduced increasingly stringent CO_2 emission standards, mandating a 45% reduction by 2030 and 90% by 2040 relative to 2019 levels [2], to accelerate zero-emission vehicle adoption.

Among ZEV options, battery-electric trucks (BETs) have attracted increasing attention in recent years. However, their uptake remains limited outside China, which accounted for more than 80% of the 90,000 electric truck sales globally in 2024 [3]. Market barriers include limited driving range, dependency on carbon-intensive electricity grids, and significant auxiliary energy demands in refrigerated freight operations.

To enhance energy autonomy and reduce upstream emissions, vehicle-integrated photovoltaics (VIPVs) have emerged as a complementary technology. Onboard photovoltaic (PV) systems can extend the driving range of electric vehicles by 5–15% in shuttle-type applications and by up to 30–100% for light-duty passenger vehicles under private urban duty cycles, as demonstrated by simulation-based analyses [4]. Previous studies have investigated the integration of photovoltaic systems in transport applications, demonstrating their potential to reduce energy demand and extend driving range, particularly in light-duty vehicles and controlled duty cycles [5, 6]; however, empirical evidence for HDV applications remains limited. This study evaluates a well-to-wheel (WTW) operational environmental assessment of Pilot 4, a refrigerated heavy-duty battery-electric truck with rooftop PV panels, developed within the Horizon Europe ESCALATE project.

2 Methodology

2.1 Goal and Scope Definition

This study follows the ISO 14040/14044 framework and focuses on the operational phase. The case study vehicle, referred to as Pilot 4, is a 40-t refrigerated battery-electric truck equipped with rooftop copper indium gallium selenide (CIGS) PV panels installed on the trailer roof. The objective is to evaluate the environmental contribution of rooftop PV generation under real-route-based simulated conditions, with emphasis on electricity-related impacts.

The system boundary includes grid electricity supply in Germany (DE) and the United Kingdom (UK) and vehicle energy use for traction and auxiliaries, including refrigeration, HVAC, and onboard systems. PV electricity was treated as an avoided burden, offsetting the equivalent average national grid electricity. Non-electricity life cycle stages such as vehicle manufacturing, infrastructure, maintenance, end-of-life (EoL) treatment, and non-exhaust emissions (tire, brake, and road wear) are excluded but represented schematically in the system diagram to facilitate future integration. Figure 1 illustrates the operational boundary, including grid charging, PV generation, and auxiliary loads. The functional unit is defined as one kilometer of vehicle operation, covering all electricity demand for propulsion and auxiliaries under the assessed duty cycle scenarios.

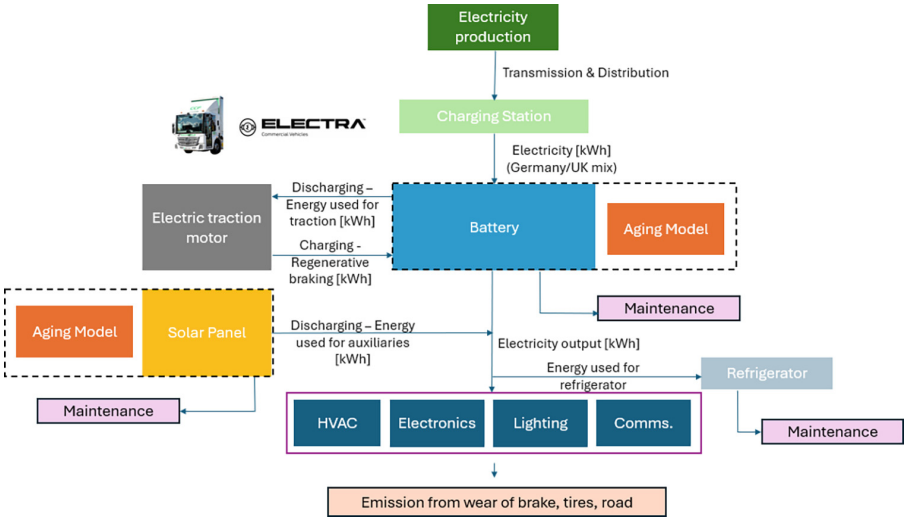


Fig. 1. Schematic representation of energy flows.

2.2 Vehicle Description and Operational Data

Pilot 4 is powered by a modular lithium-ion battery system with a total capacity of approximately 1000 kWh, coupled with Accelera 17Xe e-axles to ensure efficient traction. Table 1 summarises the key technical specifications and operational assumptions. Energy performance values were derived from route-based simulations reflecting real-world duty cycles.

Table 1. Route characteristics and energy consumption.

Parameter	Value/Description	Energy consumption (kWh/100 km)
Routes	Flensburg–Karlsruhe (780 km round trip, long haul)	172.94
	Dundee–Southampton (760 km round trip, regional)	168.86

To quantify operational energy demand, the total vehicle energy consumption was defined as shown in Eq. 1:

$$Evehicle = Etraction + Eaux + Erefrigeration - Eregen - Epv \quad (1)$$

where E*traction* is the propulsion energy demand, E*aux* includes HVAC, lighting, and electronics, E*refrigeration* represents the cooling load, E*regen* is energy recovered through regenerative braking, and E*pv* is the contribution of rooftop PV panels. The instantaneous traction power was expressed in Eq. 2:

$$Ptraction(t) = (Froll + Faero + Fslope + m \times a(t)) \times v(t) \quad (2)$$

where m is the vehicle mass (kg), v (t) is the instantaneous velocity ($m.s^{-1}$), and a(t) is the instantaneous acceleration ($m.s^{-2}$). The resistive forces were defined in Eqs. 3 , 4 and 5:

$$Froll = Cr \times m \times g \tag{3}$$

$$Faero = \frac{1}{2}\rho \times Cd \times Af \times v(t)^2 \tag{4}$$

$$Fslope = m \times g \times \sin\theta \tag{5}$$

where Cr is the rolling resistance coefficient (−), g is the gravitational acceleration (9.81 $m.s^{-2}$), ρ is the air density ($kg.m^{-3}$), Cd is the aerodynamic drag coefficient (−), Af is the frontal area (m^2), and θ is the road slope angle (rad). Finally, the specific energy consumption (SEC) was calculated in kWh per 100 km as shown in Eq. 6:

$$Es = \frac{\int \frac{1}{3600\times1000} \times P(t)dt}{Rd\,(t)} \times 100 \tag{6}$$

where the numerator represents the total traction energy demand integrated over the driving cycle (expressed in kilowatt-hour (kWh) with 1 Wh = 3600 J), and Rd. (t) is the total distance travelled (km). Multiplying by 100 scales the results to the conventional unit of kWh/100 km.

The vehicle's energy management system offers three operational modes: standard, energy saving, and critical reserve. In the present study, all route-based simulations were conducted in Standard mode, representing a balanced trade-off between dynamic performance and auxiliary demand. It should be noted that activating the Energy Saving mode could have further reduced electricity consumption, while potentially limiting certain vehicle performance parameters. This operational choice was maintained consistently to ensure comparability across scenarios.

2.3 Scenario Framework

Two operational scenarios were modelled to evaluate the environmental impact contribution. In the Base Case, all electricity demand is supplied by the national grid, whereas in the Offset Case, a share is displaced by rooftop PV generation. Both scenarios assume identical operational conditions to ensure comparability.

For Pilot 4, a roof-only VIPV configuration was considered. Annual PV yields were estimated at 1640 kWh for DE and 1550 kWh for the UK [7, 8]. These correspond to net grid consumptions of 396,295 kWh and 466,868 kWh, respectively, for annual driving distances of 230,100 km and 277,400 km. Total operational energy demand was 397,935 kWh (DE) and 468,418 kWh (UK). National electricity mixes for 2024 were applied using modified Ecoinvent v3.8 datasets (Table 2) [9].

Table 2. National electricity generation mix in 2024 (% share by source).

Source	UK	DE
Coal	0.82	21.88
Natural Gas	29.92	16.60
Wind	29.96	27.98
Solar	5.53	14.89
Bioenergy	14.02	9.63
Hydropower	1.96	4.91
Nuclear	14.51	–
Other	3.28	4.11

2.4 Impact Assessment

Environmental impacts were modelled in SimaPro v9.5 using Environmental Footprint 3.0 midpoint indicators, focusing on climate change, freshwater eutrophication, fossil resource use, and ionising radiation. Annual impacts were calculated for each country and scenario, then expressed per kilometre to derive impact intensities. This ensured comparability across routes and conditions, while normalisation was applied to assess the relative significance of impact categories.

3 Results and Discussion

3.1 Climate Change Impacts across Scenarios

Figure 2 illustrates the climate change impacts across scenarios. The estimated annual impacts of Pilot 4 were 150,228 kg CO_2-eq in Germany and 114,934 kg CO_2-eq in the UK under the Base Case. Integration of rooftop PV resulted in annual GHG savings of 619 kg CO_2-Eq (0.41%) in Germany and 380 kg CO_2-Eq (0.33%) in the UK.

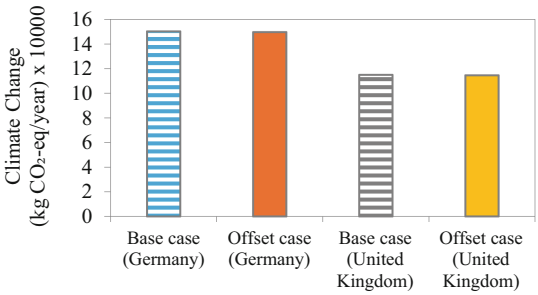


Fig. 2. Annual climate change impacts (kg CO_2-eq/year) of Pilot 4 under scenarios.

When expressed per kilometre, the impacts were 0.653 kg CO_2-eq/km in Germany and 0.414 kg CO_2-eq/km in the UK under the Base Case, declining slightly to 0.650 kg CO_2-eq/km and 0.413 kg CO_2-eq/km in the Offset Case. The lower carbon intensity of the UK electricity grid, supported by a 44% share of renewable and nuclear generation, resulted in lower per-kilometre emissions overall. However, higher annual mileage and total electricity demand in the UK reduced the gap in absolute emissions between the two countries. In contrast, Germany's continued reliance on coal contributed to higher overall emissions (Table 2). The differences between Base and Offset scenarios, though numerically small, are consistent with expectations for roof-only VIPV configuration in HDVs, where surface area and module efficiency constrain potential contributions.

3.2 Broader Environmental Trade-Offs

Beyond climate change, additional midpoint categories were evaluated to capture broader environmental trade-offs associated with operating Pilot 4. Figure 3a presents normalised results across categories, indicating that freshwater eutrophication is the dominant impact, followed by fossil resource use.

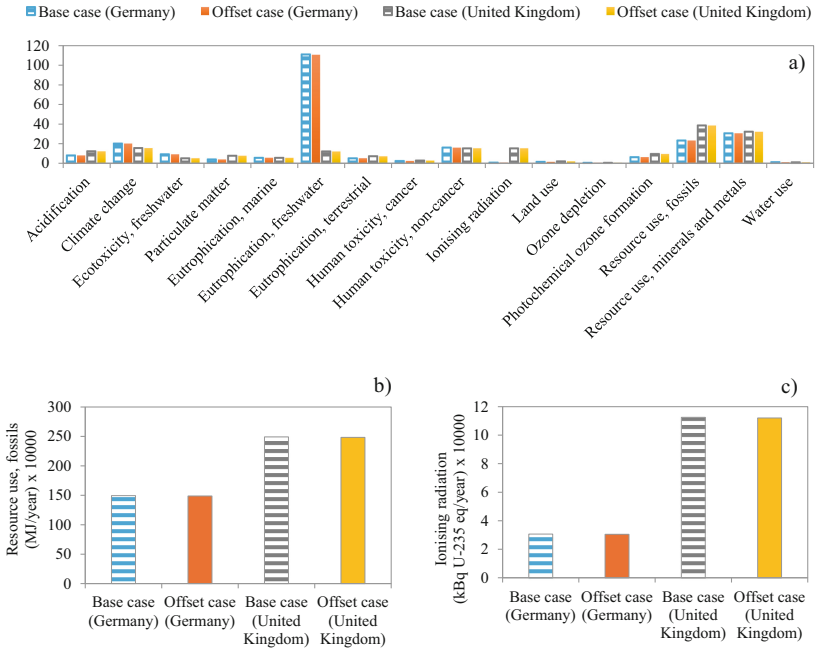


Fig. 3. Environmental impact comparison across four operational scenarios. (a) Normalised midpoint results (Pt); (b) Characterised results for resource use, fossils; (c) Characterised results for ionising radiation.

Fossil resource use and ionising radiation are further examined through characterised results in Fig. 3 b–c. Fossil resource depletion was most pronounced in the UK,

where the Base Case exceeded 2,49 million MJ/year, compared to 1,49 million MJ/year in DE (Fig. 3b). Despite the UK's lower carbon intensity, over 30% of its electricity remains fossil-based, predominantly from natural gas (29.9%), which drives this result. PV reduced fossil resource use by 15,158 MJ in Germany and 22,246 MJ in the UK. Ionising radiation impacts were substantially higher in the UK, at 63,345 kBq U-235 eq/year in the Base Case, compared to only 1,399 kBq U-235 eq/year in Germany (Fig. 3c). This difference stems from the UK's 14.5% nuclear share. PV-induced changes were again negligible (<0.5%), underscoring the limited role of rooftop PV in influencing nuclear-related burdens. Other impact categories, including particulate matter formation, human toxicity, and acidification, showed limited variation between scenarios, with reductions consistently below 1%.

This highlights trade-offs in transition strategies and aligns with studies emphasising vehicle-integrated PV for reducing grid dependency [5, 10]. However, roof-only systems offer limited benefits due to surface and efficiency constraints, while higher-efficiency modules, advanced energy management, and multi-surface integration could provide greater mitigation potential [5, 11]. Such innovations, currently more common in passenger EVs, may also extend to HDVs. Yamaguchi et al. [6] showed that increasing PV efficiency from 20% to 30% using tandem III–V/Si architectures could significantly extend solar driving range. Translating these advances to HDVs may require curved-surface integration and intelligent routing systems.

4 Conclusions

The integration of rooftop PV modules, despite constraints such as limited surface area and moderate efficiency, displaced approximately 0.3–0.5% of annual electricity demand of Pilot 4. Relative benefits were greater in Germany, where coal remain prominent in the electricity mix, underscoring the contextual value of onboard renewable solutions. Although the absolute mitigation achieved by the current configuration is modest, the results confirm its technical feasibility and strategic relevance as a complementary measure in zero-emission logistics.

This operational-phase assessment establishes a foundation for future cradle-to-grave analyses within the ESCALATE project, including battery, vehicle, and PV manufacturing as well as EoL processes. While the inclusion of PV manufacturing may offset some of the benefits in low-carbon contexts, the overall balance is expected to remain favourable in regions with more carbon-intensive grids. At a fleet scale, even small per-vehicle savings could accumulate into meaningful reductions, particularly in high-mileage freight operations.

It should be noted that this study did not include explicit uncertainty or sensitivity analyses. Future studies may address parameter variability (e.g., electricity mix, mileage, and PV efficiency), alternative PV configurations, fleet-level applications, and prospective electricity scenarios to assess the robustness, scalability, and long-term sustainability of PV-assisted heavy-duty transport.

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References

1. European Commission: Heavy-duty vehicles – CO_2 emission standards and decarbonisation policies. Directorate-General for Climate Action. https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/heavy-duty-vehicles_en. Accessed 6 Sept 2025
2. European Commission: Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019: Setting CO_2 emission performance standards for new heavy-duty vehicles and amending directive 2007/46/EC and regulations (EC) no 595/2009 and (EU) 2018/956, as amended in 2024 under the fit for 55 package. Off. J. Eur. Union L. **198**, 202–240 (2019) https://eur-lex.europa.eu. Accessed 6 Sept 2025
3. IEA: Global EV Outlook 2025: Trends in Electric Vehicle Markets, Charging Infrastructure and Policy. International Energy Agency, Paris. https://www.iea.org/reports/global-ev-outlook-2025. Accessed 6 Sept 2025
4. Sagaria, S., Duarte, G., Neves, D., Baptista, P.: Photovoltaic integrated electric vehicles: assessment of synergies between solar energy, vehicle types and usage patterns. J. Clean. Prod. **348**, 131402 (2022). https://doi.org/10.1016/j.jclepro.2022.131402
5. Li, T.T. et al.: Integrating solar-powered electric vehicles into sustainable energy systems. Nat. Rev. Electr. Eng. **2**, 467–479 (2025). https://doi.org/10.1038/s44287-025-00181-7
6. Yamaguchi, M., Masuda, T., Araki, K., Ota, Y., Nishioka, K.: Impact and recent approaches of high-efficiency solar cell modules for PV-powered vehicles. Jpn. J. Appl. Phys. **61**(SC), SC0802 (2022). https://doi.org/10.35848/1347-4065/ac461b
7. ESCALATE: Powering European Union net zero future by escalating zero emission HDVs and logistic intelligence – Project homepage, demos & pilots description. https://www.escalate-eu.com/problem-statement-vision/. Accessed 25 Apr 2025
8. Ehrenberger, G., Alberer, D., Strobl, S., et al.: Life cycle assessment of zero-emission heavy-duty vehicles: analysis of the ESCALATE project pilots. In: 38th International Electric Vehicle Symposium and Exhibition (EVS38), Göteborg, Sweden (2025)
9. Ember: Electricity mix–Our World in Data, https://ourworldindata.org/electricity-mix. Accessed 6 Sept 2025
10. Popa, D.M., Popa, D., Tabacu, S.: Heavy-duty vehicles with solar panels as a regenerative power source. In: IOP Conference Series: Materials Science and Engineering, vol. 1311, p. 012032. IOP Publishing (2024). https://doi.org/10.1088/1757-899X/1311/1/012032
11. IEA PVPS: State-of-the-art and expected benefits of VIPV–Executive summary update 2025. https://iea-pvps.org/wp-content/uploads/2025/06/2025-Task-Updates-final.pdf. Accessed 6 Sept 2025

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Advanced Photovoltaic Technologies for Sustainable on Board Railways Services

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Abstract. The integration of photovoltaic (PV) technologies on railway rolling stock has gained increasing attention as part of the broader transition toward sustainable and energy-efficient transport systems. While conventional on-board PV installations have primarily targeted auxiliary loads rather than traction, recent advances in module efficiency, flexibility, and integration approaches open new perspectives for their application.

This paper reviews the transition from early amorphous silicon projects to modern crystalline, CdTe, and CIS technologies, including emerging perovskite tandem cells. A feasibility study of the ETR 1000 high-speed train auxiliary compressed-air system indicates that modern crystalline modules outperform legacy baselines by factors of 2.8–3.9, while perovskite tandems could increase yields by a further 20–35%. These results demonstrate that on-board PV, supported by Building Attached and Building Integrated Photovoltaics integration strategies, is a viable solution for meeting auxiliary energy demands in both retrofitted and next-generation train designs.

Keywords: Sustainable Railways · Decarbonization · Photovoltaic · Perovskite · Back-Contact Technology

1 Introduction

The transport sector is responsible of the 29% of the GreenHouse Gas (GHG) emissions in Europe. In particular, its GHG emissions increased by 6.7% from 1990 to 2023 [2]. The vast majority of these emissions were produced by road transport (72%), marine transport (14%), and aviation (13%), whereas railway resulted to be the more sustainable transport (0.3% of total GHG), despite carrying 8.1% of passengers and 16.6% of freight within the EU. Thus, in the context of the European Green Deal and of the Net Zero Emissions by 2050 Scenario (net zero CO_2 emissions by 2050 for the global energy sector), railways play a crucial role in the decarbonization of the transportation in Europe. The

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International Union of Railways (UIC) articulated the UIC Low Carbon Rail Transport Challenge targets to guide the railway sector climate action by 2030 and provide a long-term vision extending to 2050.

In this paper a study about the use of Photovoltaic (PV) energy to integrate the powering system of trains is presented. The aim is to highlight how the adoption of PV energy solutions to power on-board systems is suitable to reduce the energy expenditure simply recovering energy freely available on the environment. In perspective this technology evolution could exalt the role of railway as green mass transport mode, for both passengers and freight.

The study is focused on on-board installation. Indeed, the integration of solar energy to encompass the huge energy need of railway and sustain its greening process is a well consolidated solution, including PV plants managed by railway operators, installations near and on the roofs of stations and along the tracks. [14]. However, track-side PV installations are increasingly hindered by environmental fouling, particularly sand and dust accumulation in arid regions [9,27], where solar energy could be highly available due to the high radiation, and vandalism and theft. On the counter side, on-board installation mitigates these drawbacks, becoming more feasible thanks to the advent of more lightweight and flexible PV modules, suitable to adapt to the roof of convoys. In particular, the most innovative PV technologies, such as Perovskite or Back-Contact, enables to improve the estimations previously elaborated [21].

The paper is organized as follows: Sect. 2 briefly summarizes the current use of photovoltaic energy on board trains, Sect. 3 illustrates the feasibility study about advanced PV technologies to cover on-board systems needs, and Sect. 4 draws some conclusions.

2 State of the Art

The integration of photovoltaic technology into the railway sector has been explored at different scales, from fixed infrastructure to roof-mounted systems on rolling stock. Early efforts were directed toward large-scale infrastructure projects. A well-known example is the PV tunnel along 3.6 km of the Antwerp-Amsterdam high-speed line (2011), where 16,000 monocrystalline modules generate about 3.2 GWh annually for traction, signaling, and station services [6]. Research on on-board systems began with small-scale demonstrators, to take into account the constraints of roof curvature, motion, and vibration typical of rolling stock. The EU LIFE programme PVTrain project [5], launched by Trenitalia, installed PV modules on locomotives, passenger, and freight cars, mainly to recharge on-board batteries and supply auxiliary services. Although it proved technically viable and environmentally beneficial, the use of triple-junction amorphous silicon modules limited efficiency and added significant weight. Another early example is the Vili tourist train in Hungary, where a 10 m^2 PV array fully meets the modest energy demand [7].

More recently, field deployments have been conducted on passenger coaches. Since 2017, Indian Railways has tested Diesel Electric Multiple Unit coaches

fitted with approximately 4.5 kWp of rooftop PV, primarily for auxiliary loads such as fans and lighting [8]. Experimental studies highlighted the practical role of roof PV in reducing diesel consumption while confirming its limitations for traction, confirmed but similar trials on the Kalka–Shimla and Jodhpur divisions. Instead, in the Byron Bay Solar Train in Australia, 6.5 kWp of curved PV modules on carriage roofs, combined with a 30 kW station array and lithium-ion batteries, supports both auxiliary systems and traction in the specific context of a short heritage shuttle [1].

Recent research has focused on optimizing performance under real operational conditions. Darvishpour et al. [11] analyzed rooftop PV integration on Milan commuter lines, comparing different Maximum Power Point Tracking (MPPT) methods showing that controller choice has a measurable impact under variable irradiance and shading. Similar advances have been reported for panel-level optimizers and micro-inverters designed to mitigate partial shading in moving vehicles [23]. In parallel, developments in module technology are extending applicability: flexible thin-film devices have been proposed for curved surfaces [28], while lightweight photovoltaic films have been demonstrated for commuter trains [24]. These materials reduce weight, adapt to irregular geometries, and offer improved low-light performance, although their adoption is still constrained by railway fire safety and vibration standards (EN 45545). Further enhancements are expected from combining PV with advanced storage systems such as lithium iron phosphate batteries and super-capacitors, which improve supply continuity and reliability under fluctuating generation [19].

Literature suggests that train-roof PV systems, typically yielding 3–6 kWp per coach, are optimal for offsetting auxiliary loads. Although traction requirements exceed current capacities, ongoing advancements in materials, power electronics, and storage position on-board PV as a viable complement to sustainable railway operations.

3 Advanced Photovoltaic Technologies On-Board Trains

This section evaluates the integration of cutting-edge PV technologies for on-board auxiliary services, assessing their potential impact on the future evolution of railway energy systems. In particular, the feasibility of the use of advanced PV technologies (Metal halide Perovskite and Back-Contact technology) for the provisioning of the auxiliary services energy needs is evaluated.

3.1 Metal Halide Perovskite Technology

Metal halide Perovskite Solar Cells (PSCs) [18] represent a leading emerging photovoltaic technology. The main important features of perovskite are its high conversion efficiency that has reached 25.5% (with a theoretical maximum efficiency of over 43%, 29% reached in 2023 [17]), overcoming the record efficiency of Copper Indium Gallium Selenium (CIGS) solar cells and approaching that of

crystalline-Si solar cells [13], low production cost, ease of processability, flexibility, semi-transparency, thin-film, light-weight. Despite concerns regarding environmental stability (UV and humidity), durability, and lead toxicity, recent research has significantly enhanced material resilience and mitigated leakage risks [25,26].

Perovskite-silicon tandem cells represent the leading edge of PSC technology, leveraging tunable perovskite layers to broaden spectral absorption beyond silicon standard range. Recent implementations [3,16] have successfully passed IEC 6121 durability testing, validating an operational lifespan of at least 25 years. Furthermore, recently flexible perovskite solar cells, obtained printing perovskite thinner than a micron on flexible PET foils [22], enable lightweight Building Applied (BAPV) and Building Integrated Photovoltaics (BIPV) for diverse surfaces, including railway rooftops. Additionally, semi-transparent variants can be laminated into glass for application on windows and facades [4].

3.2 Back-Contact Technology

Commercially available Back-Contact technology optimizes efficiency by situating all electrical contacts on the rear of the panel via a conductive sheet [12]. This architecture replaces traditional welding with fully interconnected electrodes, reducing mechanical stress and the prevalence of micro-cracks. By eliminating front-side ribbons, shading is reduced by 3%, enhancing photon absorption [20]. Additionally, Metal Wrap Through (MWT) technology improves light trapping and electron capture, boosting performance under low-irradiance conditions and achieving conversion efficiencies of up to 27.81% [10].

3.3 Feasibility Study

To assess the potential of advanced photovoltaic technologies in real railway applications, a case study is considered. The reference load is the compressed air production system, which is essential for several on-board utilities, including braking (emergency, service, parking and holding), suspension, and air-conditioning. As a representative train, the ETR 1000 high-speed unit is selected, a fixed composition trainset consisting of eight driving carriages and four carrying carriages. Based on the analysis reported in [15], the daily electrical energy consumed by the compressor system along a commercial route is summarized in Table 1.

In [5], the performance of onboard photovoltaic installations was evaluated by comparing the PVTrain project (early 2000s, based on amorphous silicon) with modern crystalline, CdTe, and CIS technologies. Here, the feasibility study is extended by considering Metal halide perovskites (PSC) and Back-Contact crystalline silicon cells. The aim is to quantify their potential contribution to the auxiliary energy needs of high-speed trains.

Methodology. The comparison is based on two factors: (i) the *installed capacity* achievable on the roof of a coach (as derived in Section B), and (ii) the *technology multiplier*, i.e., the expected energy gain relative to standard crystalline

Table 1. Daily energy consumption of the ETR 1000 compressor system [15].

Consumed energy	[kWh]
Total daily consumption	123.1
Pre-service (night)	20.4
Start of commercial service	7.0
Five and a half hours of operation	32.0

silicon modules under the same conditions. While geometry and mounting constraints determine the installed capacity (e.g., 3.75 kWp for a passenger coach roof, compared to 1.36 kWp in PVTrain), the technology multiplier accounts for differences in conversion efficiency and spectral response (e.g., +10.4% for CIS, +11.5% for CdTe, +20–35% for perovskite tandem devices, and +3–8% for back-contact cells).

Table 2. Relative energy production gains by PV technology, normalized to the PVTrain baseline (a-Si modules). Passenger car values assume curved roof (tiles), freight car values assume flat roof (framed modules).

Technology	Capacity factor vs. PVTrain	Technology multiplier	Overall gain (passenger car)	Overall gain (freight car)
PVTrain a-Si (baseline)	1.00	1.00	1.00	1.00
Crystalline (today)	2.76	1.00	2.76	2.87–3.91
CIS	2.76	1.104	3.05	3.17–4.31
CdTe	2.76	1.115	3.08	3.20–4.36
Back-contact	2.76	1.05	2.90	3.01–4.11
Perovskite (tandem, mid)	2.76	1.25	3.45	3.59–4.89
(tandem, high)	2.76	1.35	3.73	3.87–5.28

The relative gains of different photovoltaic technologies are visualized in Fig. 1, which highlights the higher potential of tandem perovskite cells, especially in freight car configuration.

Results. Table 2 reports the relative production factors compared to PVTrain. For passenger coaches, replacing the original amorphous silicon installation with modern crystalline technology already increases the annual energy by a factor of 2.76. Applying CIS or CdTe modules yields an additional 10–11% improvement, while back-contact technology offers a more modest gain of about 5%. In contrast, tandem perovskite modules could provide a substantial boost, with expected improvements of 25% in the conservative case and up to 35% in favorable scenarios. Overall, passenger coaches could achieve factors of 3.0–3.7 compared to PVTrain.

For freight cars, where the roof surface allows installation of larger framed modules, the geometric factor alone leads to a 2.9–3.9× increase over PVTrain. CIS and CdTe extend this to 3.2–4.4×, back-contact to 3.0–4.1×, and perovskite to 3.6–4.9× (up to 5.3× in the most optimistic case).

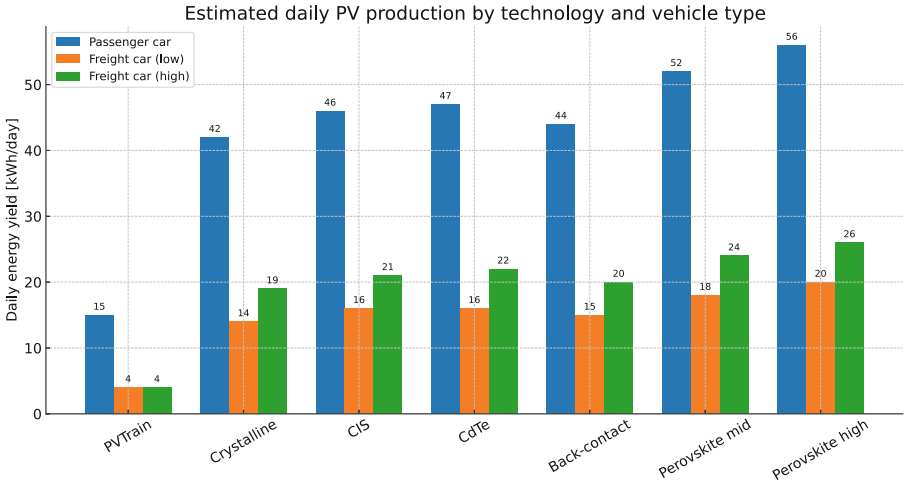


Fig. 1. Different technologies comparison.

Implications for Auxiliary Loads. Returning to the ETR 1000 compressor case (123.1 kWh/day), these results indicate that modern crystalline technology could already cover a significant share of the daily energy needs through roof-mounted arrays. CIS and CdTe modules provide incremental gains, while perovskite tandem modules, if their durability issues are fully resolved, would enable the most substantial leap, potentially covering an additional 20–35% of the load compared to crystalline silicon alone. Back-contact modules, although less transformative in terms of absolute yield, offer valuable improvements in mechanical robustness and resilience under partial shading, which are critical factors for the harsh operating environment of rolling stock.

4 Conclusions

This paper has investigated the role of advanced photovoltaic technologies for on-board railway applications, with a specific focus on auxiliary energy services. Starting from early experiences such as the PVTrain project, which relied on amorphous silicon modules with limited efficiency, the study has highlighted the substantial progress enabled by current crystalline silicon solutions and the additional improvements offered by thin-film and emerging technologies.

The feasibility analysis, carried out on the compressed air system of the ETR 1000 high-speed train, has quantified the potential energy contribution of different PV options. Results show that replacing amorphous silicon with modern crystalline modules increases the energy yield by a factor of 2.8–3.9, corresponding to about 42 kWh/day per passenger car and 14–19 kWh/day per freight car. This translates into roughly one third of the compressor's daily demand being covered by roof-mounted PV. CIS and CdTe modules provide incremental

gains (+10–11%), while back-contact silicon offers robust but modest improvements (+5%), particularly under partial shading conditions. The most significant advances are expected from perovskite tandem devices, which could deliver 52–56 kWh/day per passenger car and 18–26 kWh/day per freight car, covering up to 46% and 21% of the compressor load, respectively.

Beyond the purely quantitative results, the discussion has emphasized the importance of integration strategies. Building Attached/Applied Photovoltaics offer a pragmatic pathway for retrofitting existing fleets with flexible or lightweight modules, while Building Integrated Photovoltaics enable deeper integration, including semi-transparent solutions embedded into windows or structural roof laminates. These approaches broaden the available surface area for solar harvesting and support the long-term vision of fully integrated solar-powered rolling stock.

In conclusion, while traction requirements remain far beyond the reach of current PV technologies, on-board solar energy represents a viable and increasingly effective solution for covering auxiliary loads. The combination of higher-efficiency modules, innovative form factors, and optimized integration strategies can substantially reduce fuel consumption and grid dependence, thereby reinforcing the contribution of railways to sustainable mobility. Future research should focus on long-term stability and safety of perovskite technologies, the optimization of hybrid PV-storage architectures, and the standardization of BAPV/BIPV solutions tailored to the railway sector. Furthermore, the analysis will focus on the estimation of the PV production, including energy storage or in-grid integration, payback periods, installation and maintenance costs.

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References

1. Byron bay solar train. https://byronbaytrain.com.au
2. European environmental agency transport emissions. www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobilitysystems/climate?activeTab=249511af-f0b6-4f4e-b698-cc9ce7431c63
3. Oxford pv. https://www.oxfordpv.com/
4. Perovskite building integrated photovoltaics. sauletech.com/bipv/
5. PhotoVoltaic Train (PVTrain) project. http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2061

6. Solar-powered rail vehicle ready for service. http://www.railjournal.com/index.php/rolling-stock/solar-powered-rail-vehicle-ready-for-service.html
7. Vili solar-powered tourist train. International Railway Journal
8. Indian railways rooftop solar demu coaches. Press Information Bureau, Government of India (2017). https://pib.gov.in/PressReleasePage.aspx?PRID=1496828
9. Alsahli, A.,Alsulmi, M.: Automatic detection of sand fouling levels in railway tracks using supervised machine learning: a case study from Saudi Arabian railway. Arab. J. Sci. Eng. **48** (2023). https://doi.org/10.1007/s13369-022-07243-0
10. https://static.longi.com/Back_Contact_BC_Solar_Technology_Development_White_Paper_ff1a12170f.pdf
11. Darvishpour, A., Rossi, F., Bianchi, M.: Integration of rooftop solar PV on trains: comparative analysis of MPPT methods for auxiliary power supply of locomotives in Milan. Electronics **13**(17), 3537 (2024)
12. Gorai, P., et al.: A search for new back contacts for CDTE solar cells. Sci. Adv. (2023)
13. Green, M., Unlop, E., Hohl Ebinger, J., Yoshita, M., Kopidakis, N.: Solar cell efficiency tables. Prog. Photovoltaics, pp. 3–15 (2021)
14. Jia, L., Ma, J., Cheng, P., Liu, Y.: A perspective on solar energy-powered road and rail transportation in china. CSEE J. Power Energy Syst. **6**(4) (2020)
15. Matteo, L.T.: Energy analysis and optimization of the compressed air generation system on high-speed trains: the case of the Frecciarossa 1000. Master's thesis, Politecnico di Torino (2022)
16. Microquanta.com/en//v2/pc/product
17. Www.telegraph.co.uk/business/2024/01/30/oxford-pv-university-spinoutbreakthrough-solar-panel-tech/
18. News.oregonstate.edu/news/crystal-structure-discovered-almost-200-years-agocould-hold-key-solar-cell-revolution
19. Rossi, G., Bianchi, A., Verdi, L.: Hybrid PV storage systems for European railway applications: Performance assessment and sustainability analysis. Appl. Energy **356**, 122604 (2024)
20. Rudolph, D., et al.: Improvement of solder interconnections applied on back contact solar cells with low-temperature copper paste busbars. Sol. En. Mater. Sol. Cel. **264**, 112603 (2024)
21. Ruscelli, A.L., Cecchetti, G., Castoldi, P.: Energy harvesting for on-board railway systems. In: 5th IEEE MT-ITS, pp. 397–402 (2017)
22. Sauletech.com/wp-content/uploads/2025/01/Product-Catalog-Saule.pdf
23. Wang, H., Li, S., Dong, F.: Panel-level power optimization for mobile PV systems: application to railway vehicles. IEEE Trans. Transp. Electrif. **9**(2), 2210–2220 (2023)
24. Yamada, T., Nishimura, K., Takahashi, M.: Lightweight photovoltaic films for transport applications: case study on commuter trains. J. Clean. Prod. **356**, 131849 (2022). https://doi.org/10.1016/j.jclepro.2022.131849
25. Yoo, J.J., Shin, S.S., Seo, J.: Toward efficient perovskite solar cells: progress, strategies, and perspectives. ACS Energy Lett. **7** (2022)
26. Zhang, H., Ji, X., Yao, H., Fan, Q., Yu, B., Li, J.: Review on efficiency improvement effort of perovskite solar cell. Solar Energy **233**, 421–434 (2022)
27. Zhang, J., Li, X., Wang, J., Qiao, L.: CFD–dem simulation of dust deposition on solar panels for desert railways. Appl. Sci. **13** (2023)
28. Zhao, Y., Zhang, L., Liu, H.: Flexible thin-film PV applications for curved railway surfaces. Renew. Energy **170**, 1123–1134 (2021)

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Performance and Emission Assessment of Biofuels in Marine Vessel Engines

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Abstract. The maritime sector is under growing pressure to reduce greenhouse gas emissions and transition toward sustainable energy sources. This study investigates the feasibility of using biofuels as a cleaner alternative to conventional marine diesel in medium-sized vessels. Through controlled engine trials, real-world vessel testing program and in conformity with applicable rules from classification society Bureau Veritas and French Flag, we evaluated the impact of using B100 biodiesel (100% FAME Biofuel) on their performance, fuel consumption, and emissions profile. Our results show that biofuels can significantly reduce GHG and local pollutants without any modifications to existing marine engines. However, fuel storage handling, cold flow properties, and long-term engine compatibility present operational challenges. Emission measurements indicate a reduction of up to 30% in CO, HC and 80% in particulate emissions with selected biofuel, while maintaining comparable power output and engine efficiency with increased consumption up to 12% due to lower LHV (Low Heating Value) of the biodiesel. However, an increase in nitrogen oxides (NO_n) emissions was consistently observed compared to marine diesel oil (fossil MDO) while still being under the Tier II and Tier III limits. This research provides valuable insights into the operational and environmental impacts of marine biofuels, supporting policy development and industry adoption of low-carbon fuel alternatives in the transition to greener shipping practices.

Keywords: Air emissions · biofuels · shipping · decarbonization

1 Introduction

The shipping industry accounts for roughly 2.5% of global greenhouse gas (GHG) emissions, and with the implementation of the International Maritime Organization's (IMO) MARPOL regulations [1], vessel operators are seeking cleaner alternatives to conventional fuels. Biofuels, specifically FAME (Fatty Acid Methyl Ester) [2], produced from animal fats or used cooking oils, have emerged as a viable candidate, potentially reducing lifecycle GHG emissions while utilizing existing engine infrastructure [3].

This study investigates the real-world performance and emissions of FAME at 100% blend (named B100) compared to low sulfur marine gas oil (LSMGO) on a cruise vessel operated by PONANT EXPLORATIONS GROUP. Using advanced metrology tools and standardized test procedures under real navigation conditions, the project assessed

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engine performance, fuel efficiency, and emissions, including nitrogen oxides (NOx), carbon monoxyde (CO), unburned hydrocarbons (HC), and particulate matter (PM) [4].

This study contributes to filling that gap by offering a detailed, real-world analysis on the performance of marine biofuels in comparison to conventional fuel under varying load and operational conditions.

Beyond the technical motivations, socio-economic factors also drive the urgency of transitioning to renewable marine fuels. The volatility of fossil fuel prices, coupled with international sanctions and supply chain disruptions, has underscored the vulnerability of global shipping to fuel security. Biofuels, particularly those derived from waste and residual feedstocks, offer a pathway toward energy independence and supply diversification.

From a policy standpoint, there is increasing international momentum toward regulating maritime emissions through mechanisms such as global carbon pricing, fuel standard mandates, and lifecycle-based emissions reporting under frameworks led by the International Maritime Organization (IMO) and other multilateral bodies.

2 Methodology

To evaluate the performance and emissions of biofuels in marine engines, a series of controlled tests were performed onboard a PONANT cruise vessel. The campaign included sea trials between Cherbourg and Vigo from September 22 to 29, 2023, using 100% B100 biodiesel FAME and LSMGO as baseline fuel.

The vessel is equipped with four Wärtsilä VAASA 8 L20 medium-speed diesel engines operating in various load regimes (25%, 50%, 75%, 85%). Each engine is connected to a Selective Catalytic Reduction SCR system for NOx emission reduction. Performance and emission measurements were monitored through onboard systems and verified by CERTAM, employing standardized protocols.

A Fourier Transform Infrared (FTIR) spectrometer (Gasmet CX-4000) measured gaseous emissions (NO, NO_2, CO, CO_2, CH_4, NH_3, unburned hydrocabons), with a sensitivity up to ppmV and a time resolution of 1 Hz.

The measure of particulate matters was performed with an ELPI impactor (Electrical Low-Pressure Impactor) using the inertial and aerodynamic properties of the particles and giving a particle size distribution spectrum from 10 nm to 10 μm with a time resolution of 1 Hz.

Regarding the protocol, the Testing followed NTC (Nox Technical Code) standard methodology to ensure repeatability and international comparability. Engine load was monitored via the vessel's integrated automation system, following the load profile, the E2 cycle, required by the NTC for diesel generators. Fuel pump rack position, exhaust gas temperatures and cylinder pressures were recorded, exhaust flow was determined using a pitot tube flowmeter. Measurements were conducted with and without SCR activation to quantify raw and post-treatment NOx emissions [5].

Ambient conditions during the test campaign were logged to account for barometric pressure, humidity, wind speed, and sea state, which can affect both combustion dynamics and exhaust after-treatment. Emissions data underwent outlier filtering and normalization against brake-specific energy consumption. A multivariate regression approach

was employed post hoc to evaluate correlations between fuel type, load, and emissions, controlling for external variability.

FAME B100 biodiesel used in the campaign was derived from used cooking oil (UCO). Fuel samples were also tested. LSMGO was analysed according to ISO 8217 standard while Biodiesel was analysed according to EN14214, assessing density, viscosity, sulfur content, lower heating value (LHV) but also specific component related to FAME degradation such as Acid Number, oxydation stability, water content and microbial contamination. Key properties are compared in the table below [6] (Table 1).

Table 1. LSMGO and B100 characteristics

Parameter	Unit	LSMGO	B100
Ester content	% (m/m)	–	96,7
Density	(kg/m^3)	845.3	883.1
Viscosity	Mm2/s	3.66	4.506
Sulfur Content	(%)	0.073	<0.01
LHV	(MJ/kg)	42.79	37.17
Cetane Number	–	51	52.2
Carbon content	%	86.39	77.16
Hydrogen content	%	13.55	12.29
Oxygen content	%	<0.01	10.55
Emission Factor WtW	(gCO2q/MJ)	90.6	8.21

3 Results and Analysis

Performance and emission data were collected under four engine load conditions for both fuels, with and without SCR activation. Lubrifcation Oil analysis has been performed before and after the use of the biodiesel. A composition analysis of the FAME B100 has been realized at delivery and after 3 months storage to assess the biodiesel degradation with time. Regarding performance, B100 combustion resulted in no significant difference regarding power output and an increase of 12% in fuel consumption (due to lower LHV). Emissions wise, CO and HC were consistently lower for B100 FAME, with reductions up to 30%. particulate matter PM, was also significantly reduced—up to 80%. This is mainly explained by the presence of oxygenates which typically promotes more complete combustion and associated with the absence of aromatics [7].

However, oxygen content of more than 10% in B100 alters flame temperature and increases thermal NOx formation, necessitating tailored combustion and emission control strategies. NOx emissions presented an upward trend with B100 across all loads. Without SCR, B100 NOx levels reached 9,2 g/kWh vs. 8.1 g/kWh for LSMGO. With SCR activated, NOx reductions of 83% (LSMGO) and 72.5% (B100) were observed with NOx levels reaching 2,3 g/kWh for B100 vs. 1,1 for LSMGO, indicating a need

for urea injection optimization to reach the same performance as LSMGO. However, it is important to note that the Tier II and Tier III limits from MARPOL were met, even without any modification of the SCR after-treatment system [8] (Figs. 1, 2 and 3).

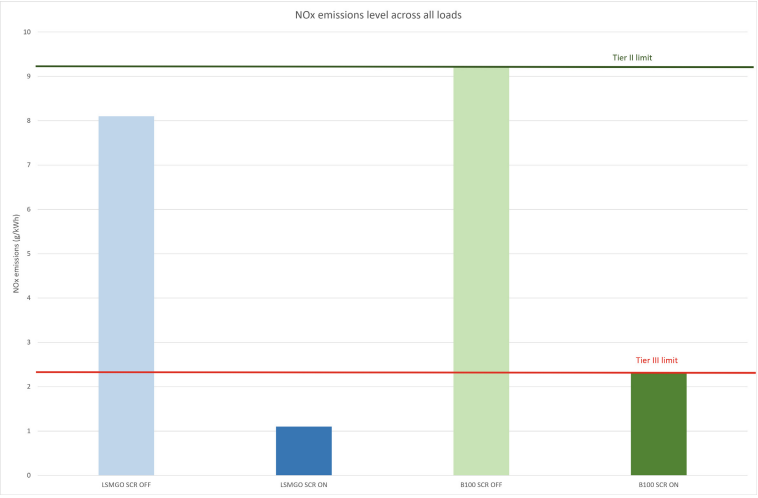


Fig. 1. Comparison of NOx emissions level across all loads for LSMGO and B100 with/without SCR.

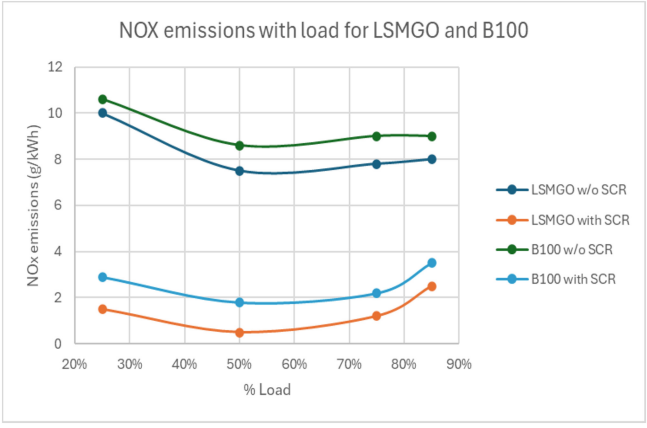


Fig. 2. NOx emissions comparison for both fuels under real operating conditions, with and without the use of SCR

Evaluation of SCR effectiveness on B100 and LSMGO showed that there is some margin to optimize and improve after treatment strategy when using B100.

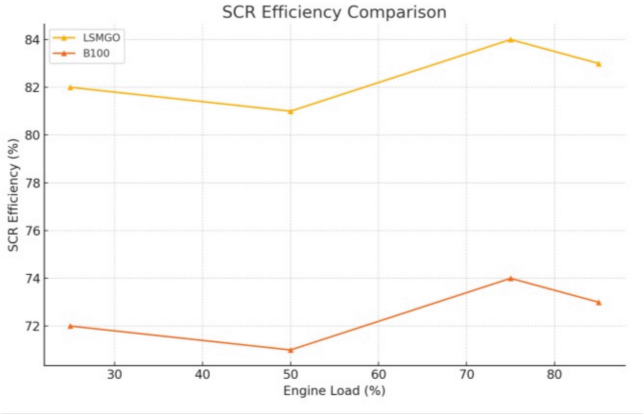


Fig. 3. Comparison of SCR efficiency at varying engine loads for LSMGO and B100

4 Environmental Assessment

To complement operational emissions analysis, an environmental assessment was conducted comparing B100 and LSMGO. The LCA (Lyfe Cycle Assessment) covered feedstock, processing, transport, and combustion. Data were sourced from Ecoinvent v3.7 and the GREET 2020 model developed by Argonne National Laboratory.

4.1 Life Cycle Assessment of Waste-Oil-Derived B100 Using GREET 2020

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model provides a robust framework for estimating life cycle emissions of fuels, including biodiesel (B100). GREET 2020 incorporates updated data on feedstock collection, conversion technologies, fuel transport, and combustion, which makes it well suited for marine biofuel assessment [9].

4.2 System Boundary Definition

- For waste-oil-derived marine biodiesel (B100), the life cycle assessment covers:
- Feedstock stage: collection of used cooking oils and other waste fats.
- Fuel production stage: transesterification into biodiesel and refining.
- Distribution and transport: storage and shipping to marine bunkering facilities.
- Combustion stage: final use in marine engines, producing CO_2, NO_n, SO_n, and PM.
- Because the feedstock is waste-based, cultivation-related burdens such as fertilizer use, irrigation, and indirect land-use change are avoided.

4.3 Key Input Parameters in GREET 2020

- Feedstock availability and collection energy inputs: fuel consumption of collection trucks and pre-treatment operations.
- Processing energy mix: electricity and heat requirements for transesterification, which vary by region and energy source.
- Transport logistics: distances by truck, rail, or ship from processing plants to bunkering facilities.
- Combustion emissions: GREET provides regulated emission factors for CO_2, CH_4, N_2O, NO_n, SO_n, and PM.

4.4 Global Warming Potential (GWP100)

According to GREET 2020, B100 from waste oils achieves up to 85–90% lower life cycle greenhouse gas (GHG) emissions compared with fossil marine fuels such as LSMGO. These reductions are driven largely by the avoided burdens of agricultural production and land-use change. The B100 FAME used in the trials GHG savings are in line with the GREET model, with 91% GHG savings reported in the PoS:

4.5 Air Pollutant Emissions

Marine compression-ignition engine, comparable duty cycle (ISO 8178 E2/E3), no after-treatment. In comparison with the actual measurements done on-board during the tests, the theoretical model from GREET shows good alignment regarding SOx and PM emissions reduction whereas measurements show that NOx emissions may be more important (30 to 90%) than in the theorical environmental assessment. As for BC, it was not evaluated during the trials. Abbreviations: LSMGO = Low-sulfur marine gas oil; B100 = neat biodiesel; BC = black carbon; PM = particulate matter; EGR = exhaust gas recirculation; SCR = selective catalytic reduction (Table 2).

Table 2. Air pollutant emissions of LSMGO Vs B100 (waste oils) from theoretical GREET model

Pollutant	Metric	LSMGO (baseline)	B100 (waste oils)	Δ vs. LSMGO	Basis/comment
SO_x (as SO_2)	g per kg fuel	~2.0	~0.02	−99%	Stoichiometric from fuel S: $SO_2 \approx 2 \times$ S_mass. LSMGO at 0.10 wt% S; B100 ≤10 ppm S.
PM (mass)	% change vs. baseline	–	–	−40%	Lower soot & sulfate due to near-zero S and ~10–11 wt% O in fuel; strongest at medium–high load.

(*continued*)

Table 2. (*continued*)

Pollutant	Metric	LSMGO (baseline)	B100 (waste oils)	Δ vs. LSMGO	Basis/comment
Black carbon (BC)	% change vs. baseline	–	–	to −60%	Typical reductions in elemental carbon fraction;
NO_x	% change vs. baseline	–	–	−50% to − 80%	engine/load dependent.

5 Economic Feasibility

Fuel pricing scenarios modeled over a 10-year horizon show that while B100 currently carries a 20–30% cost premium over LSMGO, the differential is narrowing due to carbon pricing, biofuel subsidies, and improving production efficiency. When factoring in potential savings from carbon taxes or ETS credits, the net present cost gap may fall below 10%. Additional costs include maintenance, cold flow management, and potential SCR system optimization, but these are offset by regulatory compliance avoidance penalties and reputational benefits. Sensitivity analyses indicate that break-even can be achieved when CO_2 prices exceed €100/ton, or when biofuel mandates cover 20% or more of marine fuel usage. Fuel hedging strategies and supply contracts with vertically integrated bio-refineries could improve price stability for fleet operators adopting B100 at scale [10].

6 Discussion and Conclusions

The adoption of biofuels in marine engines is both a technical and operational challenge. This study demonstrates that while B100 offers considerable reductions in GHG emissions but also on CO, HC and particulate emissions, while staying under the Tier II and III limits regarding Nox emissions. Engine load was observed as a dominant factor influencing NOx production. At lower loads (25%), B100 showed disproportionately higher NOx increases relative to LSMGO due to incomplete combustion and insufficient SCR activation temperature. At high load (85%), SCR systems reached optimal conversion efficiency, though B100 still maintained higher baseline NOx concentrations. Fuel consumption analysis revealed B100 required 8–12% more mass flow to achieve equivalent power output across load points, though energy efficiency per MJ remained comparable.

This investigation validates the use of B100 biofuel as a near-drop-in alternative to LSMGO for marine vessels. The environmental benefits—most notably reductions in GHG emissions but also CO, HC, and particulate matter—position B100 as a promising candidate for decarbonizing maritime transport. However, increased NOx emissions and challenges related to SCR system optimization, fuel logistics, and cold weather operations must be addressed. Future studies should explore long-term engine durability,

full lifecycle emissions, and closed-loop SCR control. With appropriate modifications to onboard systems, biofuels can play a key role in meeting international maritime emission targets. Other operational challenges include microbial growth risk in storage tanks (B100 is hygroscopic), filter clogging from polymerization products, and fuel tank cleaning frequency. These maintenance burdens must be factored into total cost of ownership analyses when considering long-term use of biofuels. Nonetheless, the test campaign shows that, with technical refinements and updated onboard procedures, biofuel integration is technically viable and environmentally preferable. Finally, biofuels have demonstrated their effectiveness to drastically reduce GHG emissions and be used as a drop-in solution, but the question around their scalability makes it crucial to combine their use to other solutions, such as energy consumption reduction measures and use of renewable energies (Wind or solar), in order to achieve long term decarbonation targets.

References

1. International Maritime Organization: Fourth IMO Greenhouse Gas Study 2020. IMO Publishing, London (2020)
2. International Energy Agency: Renewables 2023: Analysis and Forecast to 2028. IEA Publications, Paris (2023)
3. Knothe, G.: Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel Process. Technol. **86**(10), 1059–1070 (2005). https://doi.org/10.1016/j.fuproc.2004.11.002
4. Lapuerta, M., Armas, O., Rodríguez-Fernández, J.: Effect of biodiesel fuels on diesel engine emissions. Prog. Energy Combust. Sci. **34**(2), 198–223 (2008). https://doi.org/10.1016/j.pecs.2007.07.001
5. Veritas, B.: Biofuels in Shipping – Technical and Operational Guidance. Bureau Veritas Marine & Offshore, Paris (2022)
6. DNV: Maritime Forecast to 2050 – Energy Transition Outlook 2023. DNV, Høvik (2023)
7. Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B.P.: The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. **21**(9), 1218–1230 (2016)
8. Wang, M., et al.: GREET 2020: Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model. Argonne National Laboratory, Lemont, IL (2020)
9. Rakopoulos, C.D., et al.: Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or biodiesels. Renew. Energy. **36**(3), 1931–1944 (2011)
10. IPCC: Climate Change 2023: Synthesis Report. IPCC, Geneva (2023)

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Battery and Fuel-Cell Electric Vehicle Powertrain Simulation Platform for Heavy-Duty Long-Haul Freight Transport

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Abstract. In the Horizon EU project ZEFES, an important objective is to improve modular heavy-duty (HD) battery electric vehicles and fuel-cell electric vehicles designs by developing and exploiting a design and optimization simulation framework for HD zero emissions vehicle (ZEV) powertrain solutions, focusing on right-sizing of the vehicles' powertrain components, while considering total cost of ownership (TCO) implications and satisfying cross-border European long-haul freight transport missions with payload carriage maximization. This research investigates and presents the feasibility study and results for new flexible vehicle concepts allowing up to 100% payload capacity with HD-ZEV long-haul vehicles. The development of the trucks' models and their integration in an overall online/web-based optimization and design tool, together with detailed simulation capabilities and TCO calculations, is discussed. Moreover, realistic European long-haul missions are simulated and analyzed, where some typical trajectories exceeding 750 km are discussed in detail, including the recharging and refueling of the vehicles along the various mission routes. For the hybrid fuel cell technology, the impact of the energy management strategy and the choice of the battery operation strategy (charge sustaining or depleting) has a significant impact on hardware selection as well as energy and thermal management and cost.

Keywords: Battery Electric Vehicle · Fuel Cell Electric Vehicle · Heavy-Duty Vehicle · Long-haul Freight Transport · Zero Emission Vehicle

1 Introduction

In this paper, the feasibility study of using zero-emission powertrains of Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV) for long-haul heady-duty truck applications are investigated. One of the expected outcomes is the demonstration of highly efficient, long-haul Heavy-Duty Vehicle (HDV) powertrains for truck-trailer combinations, capable of 750 km range without recharging or re-fueling whilst carrying a minimum of 35 tons of payload under operational conditions comparable to the

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VECTO long-haul mission profile. Flexible and modular vehicle configurations for both BEVs and FCEVs are defined and optimized for all proposed HDVs to cover long-haul freight transport missions. This has benefits in terms of scale and time-to-market for new models. The modular configuration allows for scalable truck architectures to be defined based on scenario requirements, through combinations of various powertrain modules. Modules include the rigid truck unit that is a tractor with a permanently connected trailer; a trailer that is a standard shipping container placed on wheels; a dolly that connects two trailers with each other, or a rigid truck unit with a trailer; the electric version of the dolly or the trailer that has a traction unit powering the wheels of that module and an added battery in the module as energy supply to the propulsion system; and finally the e-trailer that is a trailer that has a refrigeration system installed for the cargo and an added battery in the module as energy supply to the refrigeration unit.

The goal is to enhance the vehicle design optimization tool/framework to make it suitable for HD zero emissions vehicles (ZEV) to optimize the vehicle powertrain components with the right sizes, considering the interaction with the charging/re-fueling and energy infrastructure for long-haul trucks. Such digital platforms are increasingly used as a means towards zero emission transition by supporting net-zero initiatives and promoting ZEVs [1]. This framework considers the modularity and standardization of components to be used in different vehicles or applications, covering the need for price reduction. Digital modular platforms for the drivetrain of EVs are innovative solutions that are cost-effective, efficient, and easily reconfigurable and address the shortcoming of full-scale vehicle testbeds that are expensive, bulky, dissipative, and not easily reconfigurable or movable, making scaled modular testbeds more attractive, especially for education and research institutes [2]. The tool helps to make the optimized configuration of a vehicle for each mission profile given or the standardized VECTO long-haul cycle. This is applicable for the architecture definition, the sizing of components and the vehicle management systems. The baselines used for the optimization are based on the definition of the ZEFES demonstrators, which means that the parametrization of the vehicle configurations is based on real use-cases. This gives a better representation of reality. Currently, ZEVs are an increasingly diverse field defined by multiple vehicle categories and this poses challenges with current modular powertrain architectures; thus, the powertrain being considered should also be flexible and modular to integrate different energy sources such as battery, fuel cell, and PV [3] using different topologies to distribute weight [4, 5].

This article consists of the following: Sect. 2 describes the online multi-architecture simulation platform and TCO calculation tool used to simulate the modular powertrain of ZEVs, Sect. 3 describes the various scenarios that were analyzed, including the different truck configurations, driving profiles, and use cases, and the methodology to determine the optimal powertrain configuration for different scenarios, Sect. 4 presents the optimization results and analysis of the simulations, and finally Sect. 5 concludes this paper.

2 Description of the Simulation Tool

The simulation platform represents an energy flow and longitudinal dynamics vehicle model that is governed by physical equations and parametrization of the components in the model [4]. The simulation platform aims to represent the same physical phenomena that can be simulated in specific licensed market software but with the difference that all the possible vehicle and component architectures are already pre-implemented and the user or machine that communicates with the platform only needs to choose the parametrization to execute. This difference is a breakthrough in comparison to market software that requires manual actuation for most of the architecture modifications and aims to make a difference in terms of automatic vehicle optimization, given different scenarios and requirements.

The flexibility that the vehicle model provides to platform users is the main highlight of the ZEFES model in comparison to commonly used compiled models with fixed parameters. This flexibility is required to perform vehicle topology optimization and permit correlation with the different demonstrators of the project [5]. The flexibility of the model can be split into different levels of parametrization options: a) road train architecture, which defines flexible combinations of modules, such as tractor, semi-trailer, dolly and trailer, b) module architecture, which defines the passive or active nature of each module in terms of power delivery, c) powertrain architecture, which defines the traction system in each module, including front/rear/all-wheel drive, the transmission, and the energy source, d) component architecture, which defines the level of fidelity of each component, including low fidelity empirical models or high fidelity physics based models, e) component sizing, which defines the parametric sizes of powertrain variables, including rated power, capacity etc., and f) control system, which defines the possibility to simulate different control strategies of the vehicle control units to control the regeneration strategy, split power control between fuel cell and battery, traction split between front and rear, power limitations and different communication schemes between the control units.

The platform additionally includes a TCO calculation tool for ZEVs. The formulation was based on a deep literature review to define cost contributions as state-of-the-art. The cost-contributions were adapted to the ZEFES logistic use-case and validated through workshops with logistic and OEM stakeholders of the project. The formulation for the TCO calculation with the references used for it can be found in [4]. This formulation was fed with reference values obtained from literature review [6–9]. For the usage of this platform, a web-based solution described in [4, 5] is used, that allows the users to access the tool and parametrically tune the desired combinations of vehicle architecture and mission profiles, perform the simulation in a cloud-based environment and retrieve the results from the web tool, thus providing an installation-free solution, making its use more accessible for different stakeholders. The parameter-defined vehicles and routes are given in JSON format for the architecture and in text format for vectorized multidimensional n-D parameters, all subdivided in different files for components, modules and assemblies for each vehicle and testcase.

3 Proposed Methodology

The simulation tool described in Sect. 2 was used to simulate the energy requirements for different configurations of long-haul heavy-duty trucks across various standard driving scenarios to enable proper sizing of the powertrain components and minimize the vehicle TCO. The various vehicle configurations listed in Table 1 are some of those considered for optimization. These chosen configurations allow research into how the different module types (standard vs. battery & electric vs. battery & refrigerated) affect overall vehicle energy requirements. To ensure appropriate comparisons in the energy requirement between the vehicles, the total traction system power and the total energy storage capacity are approximately similar even though they may be distributed among tractor, dolly, and trailers. Furthermore, comparisons are made using kWh/ton-km or €/ton-km to normalize with respect to weight of vehicle and distance travelled, enabling comparison of vehicles with different masses; thus, the effects on energy requirements are due to the driving cycle (urban vs. highway), the season, and the vehicle configuration. The vehicles were simulated using various VECTO driving cycles, including urban delivery, regional delivery, and long-haul [6]. The driving cycles, which include the velocity and the elevation profile, were repeated to reach the target distance of 750 km. Finally, the seasonal effects on the energy requirements were investigated comparing between summer and winter.

Figure 1 shows the implementation of the optimization strategy using the simulation tool, including different objective functions. The optimization process serves two purposes, one is to properly size the powertrain according to the requirements of the scenario, and the other is to minimize the TCO. The simulation tool resides in the cloud with a built-in automation process that can be programmed to run multiple simulations via input data transmitted as JSON files. On the other hand, the optimization algorithm runs on the local PC and communicates, during each iteration, the different configurations of powertrain parameter values using multiple JSON files, with each JSON file indicating one specific combination of configurable values. The sizing optimization loop employs improved Simple Optimization (iSOPT), which is an effective meta-heuristic algorithm used for rapid solving of multi-objective optimization problems [10]. The iSOPT optimization algorithm generates 4 parameter combinations per iteration, thus each vehicle and use-case requires 4 JSON files in every iteration. Finally, as there are 4 vehicles being compared, a total of 16 JSON files representing the vehicles (4 combinations x 4 vehicles) and 6 JSON files representing the use-cases (3 driving cycles x 2 seasons) are zipped and uploaded into the simulation tool. Thus, the simulation tool simulates a total of 96 simulations (16 vehicles x 6 scenarios) per iteration. The optimization is configured with the population space, which is the set of powertrain configurations ordered according to the descending generated score representing how appropriately the vehicle configuration fulfils the desired objectives in a given scenario; the lower and upper bounds, which define the feasible range for each component's sizing within the powertrain, ensuring that the configurations stay within practical limits; and the number of iterations, which represents the current generation count and determines when the recursion stops.

In the optimization loop, the TCO, given as €/ton-km, is considered as the objective function to be minimized. Therefore, the optimization problem formulation is expressed

Table 1. The different combinations of modular powertrain configurations of the long-haul heavy-duty trucks analyzed using the simulation tool

Module	BEV #1	BEV #2	BEV #3	FCEV
Tractor	Mass: 8000 kg ESS: 498kWh EDU: 348 kW	Mass: 7625 kg ESS: 398kWh EDU: 301 kW	Mass: 24875 kg ESS: 598kWh EDU: 403 kW	Mass: 25875 kg ESS: 698kWh EDU: 451 kW Fuel Cell: 80 kW H2 Tank: 100 kg
First Trailer	Mass: 20000 kg ESS: N/A EDU: N/A	Mass: 21000 kg ESS: 117kWh EDU; 50 kW	N/A	N/A
Dolly	Mass: 2500 kg ESS: N/A EDU: N/A	Mass: 3500 kg ESS: 117kWh EDU: 50 kW	Mass: 3500 kg ESS: 151kWh EDU: 50 kW	Mass: 2500 kg ESS: N/A EDU: N/A
Second Trailer	Mass: 22000 kg ESS: 251kWh EDU: 100 kW	Mass: 21000 kg ESS: 117kWh EDU: 50 kW	Mass: 20000 kg ESS: N/A EDU: N/A	Mass: 21250 kg ESS: 51kWh EDU: N/A e-load: 10 kW
GCVW (kg)	52500	53125	48375	49625
Payload (kg)	36000	36000	34500	34500

in Eqs. 1 to 5.

$$\min_{cbat[kWh],pem[kW]} \{TCO\} \tag{1}$$

$$TCO = I + \sum_{i=1\ to\ N} OPEX_i\text{--}P \tag{2}$$

$$P = \left(V_p\text{--}V_i\right)^* r_r/100 \tag{3}$$

$$I = V_p\text{--}V_i + T_p \tag{4}$$

$$OPEX_i = X_i + T_o + R + M + I_c + W + L_i \tag{5}$$

Where I is the investment, $OPEX_i$ is the yearly operational expenses from $i = 1,2, \ldots$ N years of life of the vehicle and P is the resale value. The optimization is also subjected to constraints consisting of the following vehicle performance requirements:

- Maximum speed >80 kph
- Driving range > 750 km
- Minimum slope of >10%
- Minimum state of charge >20%

While the search algorithm binds the inputs to the given ranges, the constraints bind the outputs and violation of these constraints incurs a penalty in the optimization score that dismisses a given configuration in future iterations.

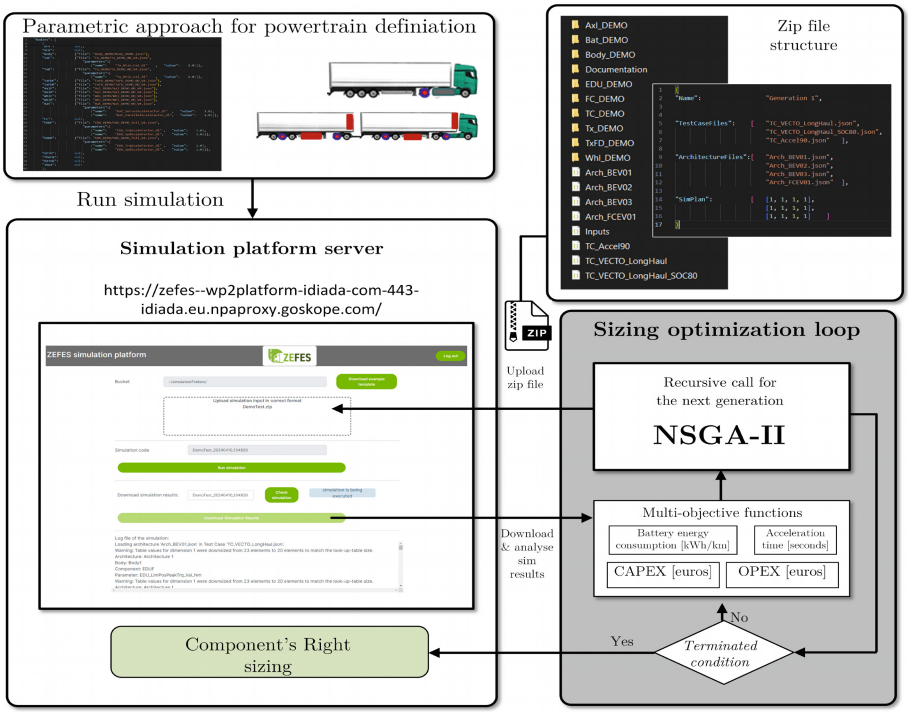


Fig. 1. Powertrain optimization flowchart.

4 Optimization Results

The results of the simulation for the optimized configuration on the VECTO long-haul driving cycle for the ZEVs are presented in Fig. 2. It shows energy breakdown between the various modules based on the truck configuration, which are described in detail in Table 1. The figure shows the breakdown pattern for the energy sources, i.e. battery and FC, present in the different truck modules. The energy breakdown follows a similar pattern for the energy sinks, i.e. the EDU and Auxiliary; thus, only the sources breakdown is presented in Fig. 2. Since these are the results of the optimization, the battery maintains an SoC greater than 20% after driving for 750 km, as per the scenario requirements. Table 2 shows the final configuration of the BEVs and FCEV based on the scenario with the highest energy requirement: the VECTO long-haul driving cycle. The results show that in FCEVs, the H2 provides a major portion of the energy supply; thus, the battery size in FCEV can be reduced as seen in Table 2. Furthermore, results show that the rigid tractor configurations (BEV3 and FCEV), required less battery capacity and EDU power to fulfil the scenario, because a rigid tractor results in smaller GCVW, compared to a semi-trailer, for the same payload.

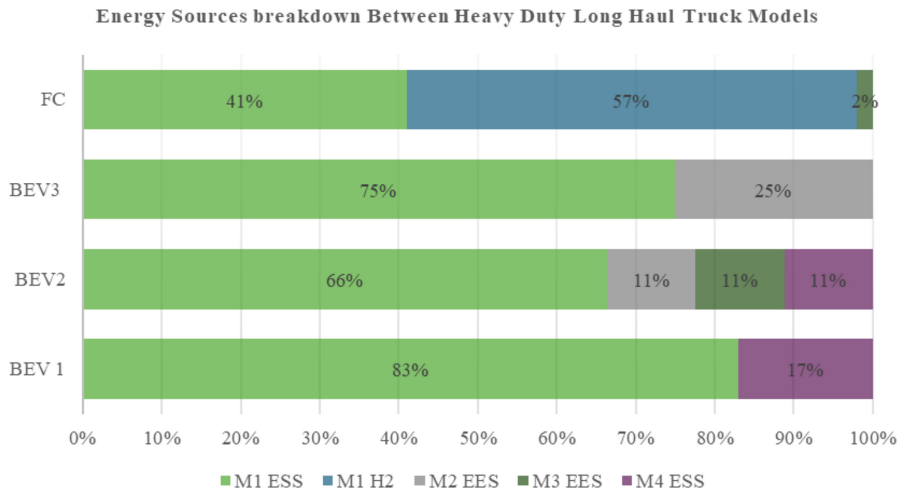


Fig. 2. Comparison of the breakdown of the energy sources between BEVs and FCEVs.

Table 2. Optimization results for the ZEVs with 100% payload and depot charging for the scenario with highest energy consumption

Parameter	Unit	BEV #1	BEV #2	BEV #3	FCEV
Baseline ESS capacity	kWh	749	749	749	749
Optimized ESS capacity	kWh	1149	1124	999	668
Baseline EDU power	kW	448	451	453	451
Optimized EDU power	kW	700	650	600	550
FC power	kW	–	–	–	200
H2 tank	kg	–	–	–	57
Battery energy use	kWh/ton-km	0.0426	0.0416	0.0386	0.0258
Powertrain efficiency	%	82	82	82	<50
TCO	€/ton-km	0.0311	0.0310	0.0301	0.575

5 Conclusion

A modular multi-architecture simulation tool was utilized to simulate a variety of powertrain configurations for HD-ZEVs for long-haul applications. The tool was used within a recursive optimization process to properly size different BEV and FCEV truck configurations for different use-cases of driving scenarios. Based on the worst-case energy requirements, the optimization determined the energy storage capacity, FC system power and the required traction power that fulfil the operational constraints. The findings of this feasibility study suggest that for the long-haul logistic scenarios evaluated, in terms

of economic viability, BEVs are favored over FCEVs in terms of energy efficiency and TCO mainly due to the hydrogen costs, despite FCEVs being more energy and power dense compared to BEVs. Furthermore, analysis showed that the rigid tractor combinations were more energy efficient and cost effective compared to the semi-trailer options for the same payload options.

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References

1. Ning, C.Y.: Digital platforms in zero emission vehicle transition: a stakeholder engagement and policy strategy for the UK's net-zero future, sustainable. Futures. **10**, 100682 (2025). https://doi.org/10.1016/j.sftr.2025.100682
2. Kardasz, M.R., Kazerani, M.: Design and experimental evaluation of a scaled modular testbed platform for the drivetrain of electric vehicles. Vehicles. **5**(1), 830–845 (2023). https://doi.org/10.3390/vehicles5030045
3. Stumpp, M., Kuznik, A., Beidl, C.: Modular hybrid powertrain. In: Kulzer, A.C., Reuss, H.C., Wagner, A. (eds.) 23rd International Stuttgarter Symposium (ISSYM). Springer Vieweg, Wiesbaden (2023). https://doi.org/10.1007/978-3-658-42048-2_21
4. Roche, M., Esteban, R., de Lima, D.A., Barrio, R., Plana, J.: Zero emission flexible vehicle platform with modular powertrains serving the long-haul freight eco system (ZEFES) - vehicle simulation platforms (deliverable D2.1). Horizon Europe Program. Grant Agreement, 101095856 (2024)
5. Tran, D. et al.: Zero emission flexible vehicle platform with modular powertrains serving the long-haul freight eco system (ZEFES) - design optimization tool and right powertrain components' sizing (deliverable D2.2). Horizon Europe Program. Grant Agreement, 101095856 (2024)
6. VECTO Wiki.: https://code.europa.eu/groups/vecto/wikis/home. Accessed 30 Sept 2025
7. Basma, H., Saboori, A., Rodríguez, F.: Total cost of ownership for tractor-trailers in Europe: battery electric versus diesel [white paper]. In: International Council on Clean Transportation (2021)
8. Anculle, E., Bubna, P., Kuhn, M.: E-Truck Virtual Teardown Study.: Final Report,. Ricardo PLC (2021)
9. Schroten, A. et al.: Transport taxes and charges in Europe: an overview study of economic internalization measures applied in Europe. Publications Office of the European Union (2019). https://doi.org/10.2832/416737
10. Scaman, K., Santos, L.D., Barlier, M., Colin, I.: A simple and efficient smoothing method for faster optimization and local exploration. In: 34th Conference on Neural Information Processing Systems (NeurIPS), Vancouver, Canada (2020)

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An Overview of Reliability and Fault Challenges in Active Balancing Circuits for EV Applications

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Abstract. The reliability of active balancing circuits is critical to ensure safe, efficient, and long-term operation of electric vehicles. Passive balancing is widely adopted by automotive original equipment manufacturers (OEMs), as active balancing still faces challenges for a broader implementation. However, active balancing strategies can reduce unnecessary operational safety margins and improve battery utilization by enabling more efficient energy extraction from module capacity. At the same time, active balancing strategies are also susceptible to faults, posing reliability concerns that must be adequately addressed. This paper provides an overview of key reliability concerns and fault diagnosis in active balancing circuits. Building on existing research activities, the paper explores condition monitoring, prognostics and health management of critical components and measurement devices. It also outlines key fault scenarios, offering a high-level perspective on current active balancing vulnerabilities. By synthesizing these insights, the paper aims to equip researchers and OEMs with a clear understanding of the reliability and diagnostic challenges associated with adopting active balancing in BMS architectures.

Keywords: active balancing circuit · battery management system · electric vehicle · fault detection and diagnosis · reliability

1 Role of Active Balancing Circuits in EV Applications

Electric vehicles (EVs) comprise traction, charging, energy storage, and auxiliary subsystems. Multiple electrochemical energy storage options exist, but lithium-ion remains dominant thanks to its energy density, low self-discharge, and lifetime advantages [1]. To meet EV voltage and current requirements, cells are connected in series and/or parallel. Inevitable dispersion of parameters like internal resistance and self-discharge causes voltage/state of charge (SoC) variations during charge and discharge [2]. Battery cell equalization is thus mandatory

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to maintain consistency and mitigate risks of overcharge or overdischarge [3]. Equalization is implemented either as passive (dissipative) or as active (energy-transfer) balancing. Passive approaches are simple, low-cost, and modular, but produce heat losses and slower equalization, while active methods redistribute charge with higher efficiency at the expense of additional components and control complexity [3].

Table 1. Reliability characteristics of key power electronic components.

Component	Failure metric	Key dependence	Mechanism
Power semicon.	Model-based λ, lifetime N_f	T_J, ΔT_J, current, t_{on} [9]	Bond wire & solder fatigue [10]
Diodes/ transistors	$\lambda = \lambda_0 \cdot \pi_T \cdot \pi_S$ [11]	Temp., elec. stress, mission prof. [11,12]	Intrinsic & wear-out [12]
Capacitors	Model-based (wear-out) [12]	Temp., volt., ripple [11,12]	Dielectric/ electrolyte aging [12]
Inductors	0.2–0.6 FIT [12]	Temp., therm. cycl. [12]	80% open/20% short [12]
Transformers	1.5–3 FIT [12]	Temp., load cycl. [12]	Insulation degraded [12]

λ = failure rate (failures/time), λ_0 = base rate (nom. cond.), FIT = failures in time, π_T = temperature factor, π_S = electrical stress factor, T_J = junction temperature, ΔT_J = junction temp. swing, t_{on} = device on-time, N_f = no. of cycles to failure

Emerging wide-bandgap (WBG) devices, such as gallium nitride (GaN) and silicon carbide (SiC), enable higher switching frequencies with lower switching and conduction losses compared to silicon. This not only improves power density, an attractive feature for the compact design of active balancing circuits (ABCs) [4], but also enhances thermal conductivity, allowing more efficient heat dissipation. Their higher switching frequencies facilitate further integration at the module and sub-module levels. These methods, along with their merits and limitations, equalization speed, control complexity, and efficiency are extensively discussed in [3,5].

This review follows a structured, theme-based approach, where the literature is selected based on relevance to reliability, fault mechanisms, and diagnostic methods in active balancing circuits and related power electronic systems.

2 Reliability Methodologies, Prognostics, and System-Level Considerations

This section reviews reliability considerations for ABCs under realistic EV mission profiles, covering operating stresses, Physics-of-Failure (PoF)/Design-for-Reliability (DfR) design methodologies, and prognostics and health management (PHM)-based monitoring and remaining-useful-life (RUL) estimation.

2.1 Operating Stresses in Active Balancing Circuits

Automotive electronics must achieve long service life under temperature cycling, humidity, and vibration [6]. Field data show that power electronic converters are often the weakest links in long-term service availability [7]. At the converter

level, semiconductors and capacitors are statistically the most failure-prone components [8]. Table 1 summarizes typical reliability characteristics, failure metrics, and dominant degradation mechanisms of key power electronic components, based on reliability standards and physics-of-failure studies.

ABCs exhibit similar failure drivers but operate with long duty cycles due to SoC imbalance. They typically operate at 50–500 kHz using MOSFETs, magnetics, and capacitors, with stress governed by mission profiles [13]. WBG devices improve efficiency but increase dv/dt and common-mode stress [4]. Environmental factors such as condensation, vibration, and contamination accelerate insulation degradation and interconnect fatigue [14].

2.2 Reliability Engineering Methodologies

Handbook-based approaches inadequately capture wear-out, motivating Physics-of-Failure (PoF) and Design-for-Reliability (DfR) methods [15]. In ABCs, PoF modeling typically resolves into: 1) Transformer insulation life vs. temperature and dv/dt; 2) Capacitor ESR growth vs. I_{rms} and ΔV; 3) MOSFET parameter drift (e.g., $R_{\text{DS(on)}}$) vs. T_j; 4) Gate-driver lifetime under common-mode transients. DfR applies mission profiles to validate robustness and define design margins [7,15].

Reliability prediction uses IEC/FIDES-based models and mission profiles to estimate component lifetime [16]. Monte-Carlo analysis captures parameter dispersion, while partial-discharge (PD) data are critical for insulation modeling in isolated equalizers [17]. These approaches define a reliability budget linking equalization performance to lifetime margins [18]. Mission-profile-based design maps operating conditions to stress metrics such as junction temperature, capacitor current, and electric field, which are evaluated using PoF models and electro-thermal co-simulation [15,18].

For an equalizer, a reliability budget links equalization performance to lifetime margins by limiting capacitor ESR growth to maintain balancing current, ensuring insulation operates below PD inception, providing sufficient margins for MOSFET and driver stress under worst-case dv/dt, and accounting for interconnect thermo-mechanical fatigue.

Field evidence that semiconductors and capacitors dominate converter failures motivates these allocations [8]. Reliability targets are verified using B_{10} metrics and accelerated life testing (ALT) [15,18].

2.3 Prognostics and Health Management (PHM)

PHM detects and predicts degradation before functional failure. Key indicators include on-state voltage, thermal resistance, and parameter drift in semiconductors [19]. For passives, ESR growth, capacitance loss, and PDIV variation are established precursors [20]. At the ABC level, divergence between commanded and measured balancing current, magnetizing-current drift, DCR-based inductor temperature, and isolation/driver faults are practical signals to monitor.

PHM requires synchronized telemetry of electrical, thermal, and control signals to capture degradation trends [21]. Furthermore, remaining useful life (RUL) is estimated using physics-based and statistical models [21], with practical policies including ESR-based derating and $R_{DS(on)}$ trend tracking. In addition, data-driven methods enable multi-fault detection when sufficient training data are available, while AI-based approaches have demonstrated high accuracy in balancing circuits [22] (Fig. 1).

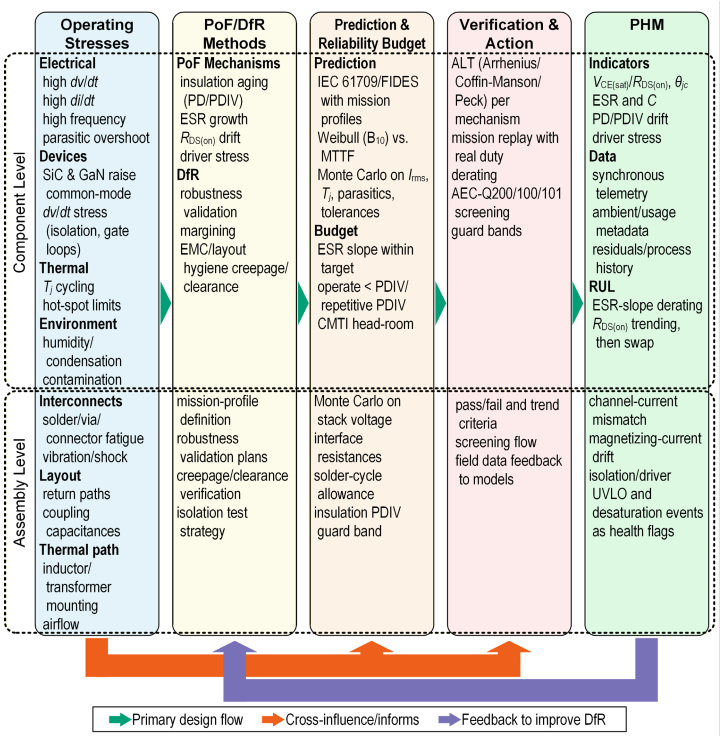


Fig. 1. Reliability workflow map of active balancing circuits (ABCs).

3 Fault Occurrences and Associated Challenges in ABCs

This section highlights the associated challenges of battery equalization circuits, particularly in terms of fault vulnerability. Building on reliability concerns, the focus is now on specific fault mechanisms.

3.1 Fault Types and Underlying Failure Mechanisms

ABCs include power semiconductors, diodes, capacitors, and magnetics elements, along with gate drivers and measurement hardware. From a system-level perspective, failures span hardware (wear-out and random), software, and human factors, as shown in Fig. 2a [16]. There are different failure modes with different failure mechanisms in semiconductors, shown by Fig. 2b. In the semiconductor stage, the dominant observable modes are open-circuit faults (OCFs), with the switch permanently off, and short-circuit faults (SCFs), with the switch permanently on. SCFs are catastrophic events caused by over-current and are typically mitigated by fast driver protection [24]. In contrast, OCFs interrupt energy transfer and, if left undiagnosed, can lead to secondary stress and imbalance [24]. For instance, an OCF in a dual active bridge-based ABC reduces the transferable power, which increases the balancing time and delays SoC equalization [25].

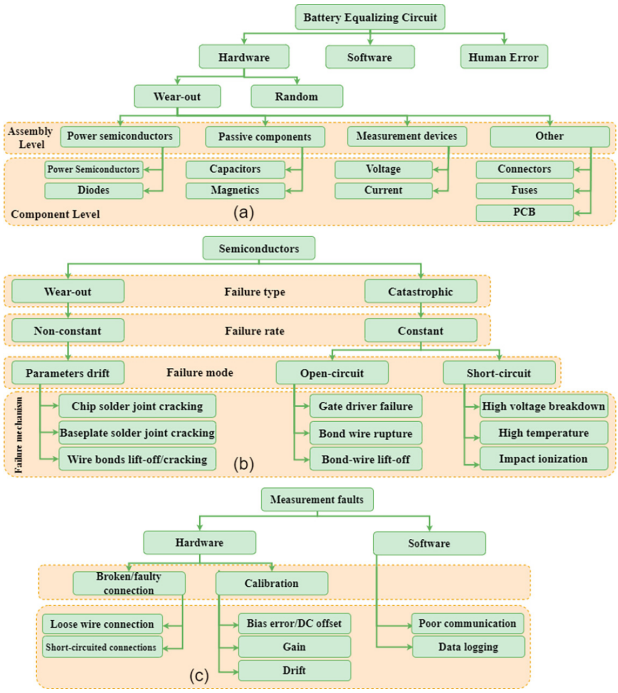


Fig. 2. Overview of possible failures: (a) in a battery equalization circuit (b) in power devices [23] (c) in measurement devices.

Measurement faults include offset, gain error, drift, open/short, and communication or logging faults [26,27]. As measurements directly feed control, undetected errors can create over/under-voltage and thermal excursions and impair equalization over lifetime. Figure 2c presents an attempt to categorize different faults related to measurement devices.

Beneath those fault classes sit the mechanisms that accumulate during service, like thermal-cycling fatigue in bond wires and solder, delamination at die-attach/base interfaces, parameter drift at elevated T_j (e.g., $V_{\mathrm{CE(sat)}}$, $R_{\mathrm{DS(on)}}$), and overstress events (like avalanche, latch-up, and high di/dt) that contribute towards SCFs [9,10,19,28]. For capacitors, electrolytics exhibit ESR rise and C loss, films are susceptible to humidity-assisted partial discharge, and multilayer ceramic capacitors (MLCCs) may crack and short under board flex or vibration. Check [20] for reviews, [17] for HF/PWM PD, and [29] for MLCC failures.

3.2 Importance of Fault Diagnosis and Current Diagnostic Techniques

Fault occurrence in ABCs can cause improper system operation, trigger a secondary chain of failures, and pose safety hazards to battery cells. Therefore, fault diagnosis (FD) within an ABC system is crucial. Three diagnosis methods are:
1) Model-based approach monitors residuals between plant model and measurements. However, it requires accurate modeling, deep system knowledge, and faces added challenges from parasitics, harmonics, and component aging modeling [24,30].
2) Hardware-based supervision adds sensors and dedicated analog/digital/FPGA logic. It reduces the modeling burden, but increases the considerations of bill of materials and overall volume [24,31].
3) Data-driven approaches learn patterns directly from telemetry, reducing modeling effort but relying on data coverage and computation [32].

In a representative ABC study, a convolutional neural network distinguished switch OCFs, sensor faults such as voltage stuck, balancing algorithm defects, and PCB damage with 95.31% experimental accuracy [22].

4 Research Gaps and Outlook

Despite advances in power electronics reliability, active balancing remains underexplored from a reliability, FD, and fault-tolerance perspective. Here, several gaps stand out as:

1) Lack of standardized reliability testing specific to equalizers: ALTs for low-power, high-frequency ABCs are absent. 2) Incomplete PoF models for WBG devices: long-term reliability under humidity and vibration is not fully characterized. 3) Integration of AI and digital twins into PHM: while promising, AI-based prognostics require high-quality data, which are scarce for balancing circuits. 4) Interaction of multiple stressors: combined effect models are lacking. 5) Implementation of DfR at BMS conception and the design of reliability-aware control algorithms considering the most crucial components of the ABCs. 6) Challenges in real-time FD implementation: proposed methods for diagnosing component faults are computationally intensive, which limit their deployment. They should be optimized for fast and low computation EV BMS embedded system usage.

7) Weak FD–control integration: lack of unified framework linking diagnosis to balancing control.

Addressing these gaps will not only strengthen balancing system robustness but also contribute to sustainable, safe, and resilient electromobility.

5 Conclusion

We reviewed reliability and possible faults related to ABCs, connecting operating stresses to mechanisms and then to design-time (PoF/DfR) and run-time (PHM) assurance. The overview highlights the central role of semiconductors and other components and the importance of insulation and isolation design under high-frequency and high dv/dt. Priority research includes equalizer specific ALT, validated WBG PoF models, multi-stressor interaction studies, and scalable diagnostic or PHM pipelines integrated with balancing control. These steps will allow ABCs to realize their reliability potential while containing risk across diverse EV mission profiles. This paper is part of a broader review of different fault types and diagnosis methods in BMS.

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References

1. Sugumaran, G., Amutha Prabha, N.: A comprehensive review of various topologies and control techniques for DC-DC converter-based lithium-ion battery charge equalization. Int. Trans. Electr. Energy Syst. 2023(1). https://doi.org/10.1155/2023/3648488. Transitioning to physics–of–failure as a reliability driver in power electronic3648488 (2023)
2. Izadi, Y., Beiranvand, R.: A comprehensive review of battery and supercapacitor cells voltage-equalizer circuits. IEEE Trans. Power Electron. **38**(12), 15671–15692 (2023). https://doi.org/10.1109/TPEL.2023.3310574
3. Zhao, Z., Hu, H., He, Z., Iu, H.H.C., Davari, P., Blaabjerg, F.: Power electronics-based safety enhancement technologies for lithium-ion batteries: an overview from battery management perspective. IEEE Trans. Power Electron. **38**(7), 8922–8955 (2023). https://doi.org/10.1109/TPEL.2023.3265278
4. Chaudhary, O.S., Denaï, M., Refaat, S.S., Pissanidis, G.: Technology and applications of wide bandgap semiconductor materials: current state and future trends. Energies **16**(18), 6689 (2023). https://doi.org/10.3390/en16186689
5. Rahmani, P., et al.: Driving the future: a comprehensive review of automotive battery management system technologies, and future trends. J. Power Sources **629**, 235827 (2025). https://doi.org/10.1016/j.jpowsour.2024.235827

6. Blaabjerg, F., Wang, H., Vernica, I., Liu, B., Davari, P.: Reliability of power electronic systems for EV/HEV applications. Proc. IEEE **109**(6), 1060–1076 (2020). https://doi.org/10.1109/JPROC.2020.3031041
7. Wang, H., et al.: Toward reliable power electronics: challenges, design tools, and opportunities. IEEE Ind. Electron. Mag. **7**(2), 17–26 (2013). https://doi.org/10.1109/MIE.2013.2252958
8. Yang, S., Bryant, A., Mawby, P., Xiang, D., Ran, L., Tavner, P.: An industry-based survey of reliability in power electronic converters. IEEE Trans. Ind. Appl. **47**(3), 1441–1451 (2011). https://doi.org/10.1109/TIA.2011.2124436
9. Bayerer, R., Herrmann, T., Licht, T., Lutz, J., Feller, M.: Model for power cycling lifetime of IGBT modules - various factors influencing lifetime. In: 5th International Conference on Integrated Power Electronics Systems, pp. 1–6 (2008)
10. Ciappa, M.: Selected failure mechanisms of modern power modules. Microelectron. Reliab. **42**(4), 653–667 (2002). https://doi.org/10.1016/S0026-2714(02)00042-2
11. Electric components – Reliability — Reference conditions for failure rates and stress models for conversion. International Standard IEC 61709, IEC, Geneva, Switzerland (2017)
12. Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment. Technical report IEC/TR 62380:2004(E), IEC, Geneva, Switzerland (2004)
13. Khan, N., Ooi, C.A., Alturki, A., Amir, M., Alharbi, T.: A critical review of battery cell balancing techniques, optimal design, converter topologies, and performance evaluation for optimizing storage system in electric vehicles. Energy Rep. **11**, 4999–5032 (2024). https://doi.org/10.1016/j.egyr.2024.04.041
14. Rahimpour, S., Husev, O., Vinnikov, D., Kurdkandi, N.V., Tarzamni, H.: Fault management techniques to enhance the reliability of power electronic converters: an overview. IEEE Access **11**, 13432–13446 (2023). https://doi.org/10.1109/ACCESS.2023.3242918
15. Wang, H., et al.: Transitioning to physics-of-failure as a reliability driver in power electronics. IEEE J. Emerg. Sel. Top. Power Electron. **2**(1), 97–114 (2014). https://doi.org/10.1109/JESTPE.2013.2290282
16. Peyghami, S., Wang, Z., Blaabjerg, F.: Reliability modeling of power electronic converters: a general approach. In: 2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL), pp. 1–7. IEEE (2019). https://doi.org/10.1109/COMPEL.2019.8769685
17. Guo, Z., Huang, A.Q., Hebner, R.E., Montanari, G.C., Feng, X.: Characterization of partial discharges in high-frequency transformer under PWM pulses. IEEE Trans. Power Electron. **37**(9), 11199–11208 (2022). https://doi.org/10.1109/TPEL.2022.3169747
18. Wang, H., Blaabjerg, F.: Power electronics reliability: state of the art and outlook. IEEE J. Emerg. Sel. Topics Power Electron. **9**(6), 6476–6493 (2021). https://doi.org/10.1109/JESTPE.2020.3037161
19. Oh, H., Han, B., McCluskey, P., Han, C., Youn, B.D.: Reliability of capacitors for DC-link applications in power electronic converters–an overview. IEEE Trans. Power Electron. **30**(5), 2413–2426 (2015). https://doi.org/10.1109/TIA.2014.2308357
20. Wang, H., Blaabjerg, F.: Reliability of capacitors for DC-link applications in power electronic converters–an overview. IEEE Trans. Ind. Appl. **50**(5), 3569–3578 (2014). https://doi.org/10.1109/TIA.2014.2308357

21. Degrenne, N., Ewanchuk, J., David, E., Boldyrjew, R., Mollov, S.: A review of prognostics and health management for power semiconductor modules. In: Annual Conference of the PHM Society, vol. 7 (2015). https://doi.org/10.36001/phmconf.2015.v7i1.2763
22. Kim, K.T., Lee, H.J., Park, J.H., Bere, G., Ochoa, J.J., Kim, T.: Artificial intelligence-based hardware fault detection for battery balancing circuits. In: 2021 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1387–1392. IEEE (2021). https://doi.org/10.1109/ECCE47101.2021.9595404
23. Bakeer, A., Chub, A., Vinnikov, D.: Study of MOSFET post-fault operation in fault-tolerant DC-DC converters. In: 2022 IEEE 7th International Energy Conference (ENERGYCON), pp. 1–5. IEEE (2022). https://doi.org/10.1109/ENERGYCON53164.2022.9830216
24. Kumar, G.K., Elangovan, D.: Review on fault-diagnosis and fault-tolerance for DC-DC converters. IET Power Electron. **13**(1), 1–13 (2020). https://doi.org/10.1049/iet-pel.2019.0672
25. Amani, D., Peña, R.A., Verbrugge, B., Chakraborty, S., Hegazy, O.: A fault-tolerant dual active bridge architecture with enhanced SoC balancing control. In: 2025 14th International Symposium on Advanced Topics in Electrical Engineering (ATEE), pp. 1–6. IEEE (2025). https://doi.org/10.1109/ATEE66006.2025.11299877
26. Sharma, A.B., Golubchik, L., Govindan, R.: Sensor faults: detection methods and prevalence in real-world datasets. ACM Trans. Sens. Netw. (TOSN) **6**(3), 1–39 (2010). https://doi.org/10.1145/1754414.175441
27. Li, D., Wang, Y., Wang, J., Wang, C., Duan, Y.: Recent advances in sensor fault diagnosis: a review. Sens. Actuators, A Phys. **309**, 111990 (2020). https://doi.org/10.1016/j.sna.2020.111990
28. Ciappa, M.: Lifetime prediction on the base of mission profiles. Microelectron. Reliab. **45**(9–11), 1293–1298 (2005). https://doi.org/10.1016/j.microrel.2005.07.060
29. Teverovsky, A.: Cracking problems in low-voltage chip ceramic capacitors. Technical report TN65668. NASA Electronic Parts and Packaging (NEPP) (2018)
30. Poon, J., Jain, P., Konstantakopoulos, I.C., Spanos, C., Panda, S.K., Sanders, S.R.: Model-based fault detection and identification for switching power converters. IEEE Trans. Power Electron. **32**(2), 1419–1430 (2016). https://doi.org/10.1109/TPEL.2016.2541342
31. Khan, S.S., Wen, H.: A comprehensive review of fault diagnosis and tolerant control in DC-DC converters for DC microgrids. IEEE Access **9**, 80100–80127 (2021). https://doi.org/10.1109/ACCESS.2021.3083721
32. Kim, S.H., Yoo, D.Y., An, S.W., Park, Y.S., Lee, J.W., Lee, K.B.: Fault detection method using a convolution neural network for hybrid active neutral-point clamped inverters. IEEE Access **8**, 140632–140642 (2020). https://doi.org/10.1109/ACCESS.2020.3011730

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Electrofuels in Aviation: The Role of eSAF in Decarbonizing Flight

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Abstract. Aviation is a critical component of global transport but presents significant challenges for decarbonization due to high energy density requirements and operational constraints. Sustainable Aviation Fuels (SAFs) derived from biomass offer near-term mitigation but face limitations in feedstock availability and environmental impacts. Electrofuels (eSAFs), synthetic hydrocarbons produced from renewable electricity and captured CO_2, provide a drop-in alternative with potential for near-net-zero lifecycle emissions and scalable production independent of land use. This paper reviews the technical pathways for eSAF production, including hydrogen generation, CO_2 acquisition, and synthesis via Fischer–Tropsch and methanol-to-jet processes. Comparative analysis with biomass SAFs highlights differences in sustainability, lifecycle emissions, economics, and scalability. Policy frameworks and market instruments critical to deployment are surveyed. Additionally, the paper examines non-CO_2 climate impacts, including contrail formation and NO_x emissions, and assesses the potential of eSAFs to mitigate these effects. The findings indicate that eSAFs can contribute substantially to aviation decarbonization, contingent on low-carbon electricity supply, technology improvements, and supportive policy environments.

Keywords: Electrofuels · eSAF · Aviation · Decarbonization · Power-to-Liquid

1 Introduction

Aviation is essential to global connectivity but remains one of the most difficult sectors to decarbonise. The need for fuels with very high energy density limits the applicability of batteries for long-haul aircraft, while hydrogen requires major changes in aircraft design and infrastructure. As a result, current decarbonisation strategies focus on operational efficiency improvements and drop-in Sustainable Aviation Fuels (SAFs) compatible with existing fleets [1, 2]. Biomass-based SAFs represent the most mature alternative today and can significantly reduce lifecycle emissions when produced from waste feedstocks. However, their scalability is fundamentally constrained by limited sustainable biomass availability and potential environmental trade-offs such as land-use change and biodiversity loss [3]. Electrofuels (eSAFs) offer an alternative approach by synthesising hydrocarbons from renewable electricity, water, and captured CO_2. Unlike biomass

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pathways, eSAFs are not limited by agricultural land availability and can be produced in regions with abundant renewable energy resources. However, their production is currently energy-intensive and costly, requiring significant improvements in technology and electricity system decarbonisation [4, 5]. This paper examines the production pathways of eSAFs, compares them with biomass-based SAFs, and evaluates their environmental, technical, and policy dimensions, with a particular focus on both CO_2 and non-CO_2 climate effects.

2 Definition and Production Process

Electrofuels are synthetic hydrocarbon fuels produced via the Power-to-Liquid (PtL) pathway using renewable electricity, water, and CO_2. The process consists of three main stages, as shown in Figure 1.

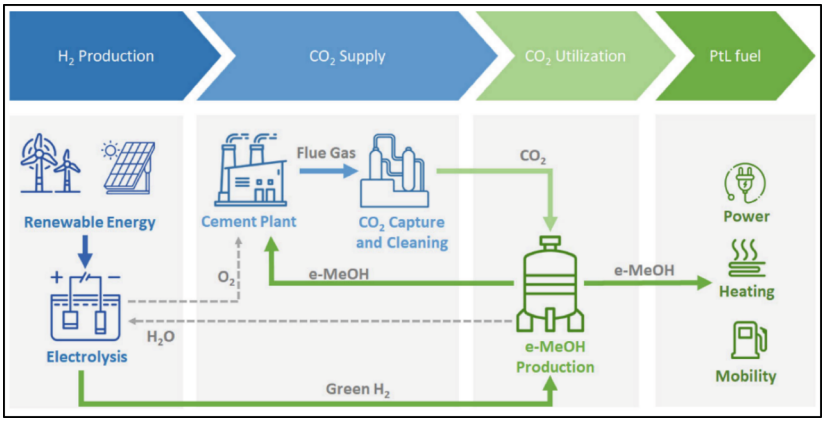


Fig. 1. Power-to-Liquid (PtL) Production Pathway for Electrofuels [6].

2.1 Hydrogen Production

Hydrogen is produced through water electrolysis powered by renewable electricity. The main technologies include alkaline, proton exchange membrane (PEM), and solid oxide electrolysis (SOEC). Alkaline systems are mature and cost-effective, PEM offers operational flexibility, and SOEC provides higher theoretical efficiency but remains in early development stages [7].

2.2 CO_2 Capture

CO_2 is sourced either from industrial point emissions or directly from air via Direct Air Capture (DAC). Point-source capture is currently more energy-efficient, while DAC offers long-term scalability and carbon neutrality potential but remains more expensive and energy-intensive [8].

2.3 Fuel Synthesis

Hydrogen and CO_2 are converted into synthetic jet fuel via Fischer–Tropsch (FT) synthesis or methanol-to-jet pathways. FT is a mature technology producing paraffinic hydrocarbons that are refined into jet fuel, while methanol-based routes offer modularity but higher energy demand. The final product is a synthetic kerosene compatible with existing aviation infrastructure [9, 10]. Key performance factors include electricity source carbon intensity, electrolyser efficiency, and CO_2 capture energy requirements [11].

3 Comparison with Biomass-Based SAFs

3.1 Sustainability and Resource Constraints

Biomass SAFs rely on waste oils, residues, and energy crops. While waste-based pathways are relatively sustainable, total global supply is limited. Large-scale deployment risks indirect land-use change, competition with food production, and biodiversity loss [12]. eSAFs eliminate these constraints by decoupling fuel production from land use, relying instead on renewable electricity and CO_2 availability. This enables deployment in high-renewable regions without agricultural impact [13].

3.2 Lifecycle Emissions

Biomass SAFs can significantly reduce emissions compared to fossil jet fuel, but results vary depending on feedstock type and land-use effects [14]. eSAFs can achieve near net-zero lifecycle emissions when powered by low-carbon electricity and combined with atmospheric or sustainably sourced CO_2, as combustion emissions are offset by captured carbon [15–17] (Fig. 2).

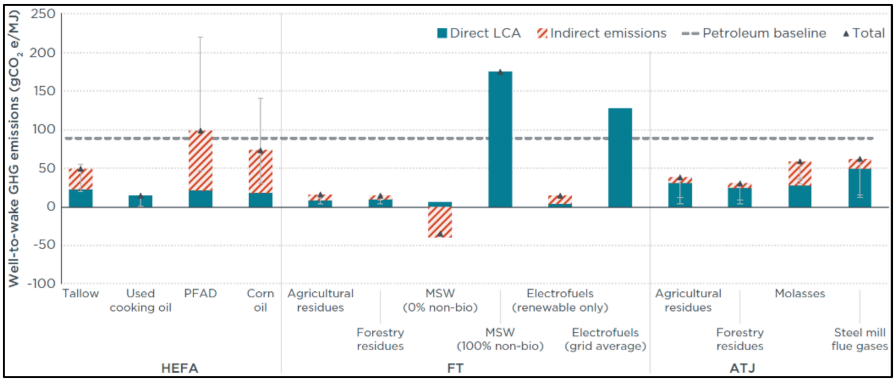


Fig. 2. Well-to-wake GHG emissions [18]. Reproduced under CC BY 4.0.

3.3 Economics and Scalability

Biomass SAFs are currently cheaper and more commercially mature but face long-term supply limitations. eSAFs are significantly more expensive today due to high electricity and capital costs but offer superior long-term scalability. Their future competitiveness depends on declining renewable electricity prices, improved electrolyser efficiency, and scaled CO_2 capture technologies [12].

4 Technical Pathways for eSAF

4.1 Electrolyser Technologies

Alkaline electrolysis is widely deployed but less flexible, PEM offers better dynamic response for variable renewables, and SOEC provides high efficiency potential but remains immature [7, 19].

4.2 Carbon Capture

CO_2 feedstock sources fall into two buckets:

- Point-source capture: Capturing CO_2 from concentrated industrial stacks typically offers lower energy and cost per tonne of CO_2 due to higher concentrations and existing capture infrastructure. Point-source supply is technically simpler, and the captured CO_2 can be used immediately in synthesis. However, reliance on point sources may present limits as industrial decarbonization progresses and emissions decline.
- DAC extracts CO_2 from ambient air and is the most flexible source for achieving a truly circular, economy-wide CO_2 balance. DAC is currently more energy-intensive per tonne of CO_2 captured and more expensive on a per-tonne basis than point-source capture. Future improvements in sorbent materials, process integration and deployment at scale are expected to reduce costs and energy demands [8, 20].

4.3 Synthesis Routes

While Subchapter 2.3 outlines the main synthesis routes, the FT and methanol-to-jet pathways differ notably in their techno-economic characteristics. FT synthesis is a mature, large-scale technology, but it entails high capital costs and complex thermal management. Conversely, methanol-to-jet benefits from established methanol infrastructure and modular deployment potential yet incurs higher energy consumption and catalyst costs due to its multistage conversion. Recent assessments estimate PtL jet fuel production costs at (2.5-4.5 €/*L*), with FT routes are typically 10-20% less expensive than methanol-to-jet owing to higher carbon efficiency [10, 21]. Enhancing catalyst lifetime, process integration, and coupling with renewable hydrogen and DAC systems remains essential to improve overall efficiency and economic viability [22, 23].

4.4 Fuel Specification Compliance

PtL fuels meet aviation fuel standards for energy density, freezing point, and stability, but often require blending due to low aromatic content affecting material compatibility and lubricity. Certification under ASTM D7566 is required prior to deployment [24].

5 Policy Landscape

Deployment of eSAFs depends heavily on policy support. Key instruments include blending mandates, production incentives, carbon pricing mechanisms, and sustainability certification frameworks. Blending mandates ensure demand creation, while subsidies reduce early-stage investment risk.

Carbon pricing improves competitiveness against fossil jet fuel. Robust lifecycle accounting rules are essential to ensure genuine emission reductions [24, 25]. Infrastructure constraints, particularly renewable electricity availability and hydrogen production capacity, remain major bottlenecks for scaling PtL pathways [26].

6 Non-CO_2 Climate Impacts

6.1 Contrail Formation

As shown in Fig. 3 contrails form when water vapour in aircraft exhaust freezes into ice crystals under specific atmospheric conditions, producing radiative forcing effects. Soot particles act as ice nuclei, meaning lower soot emissions from eSAFs can reduce contrail formation intensity and persistence [27].

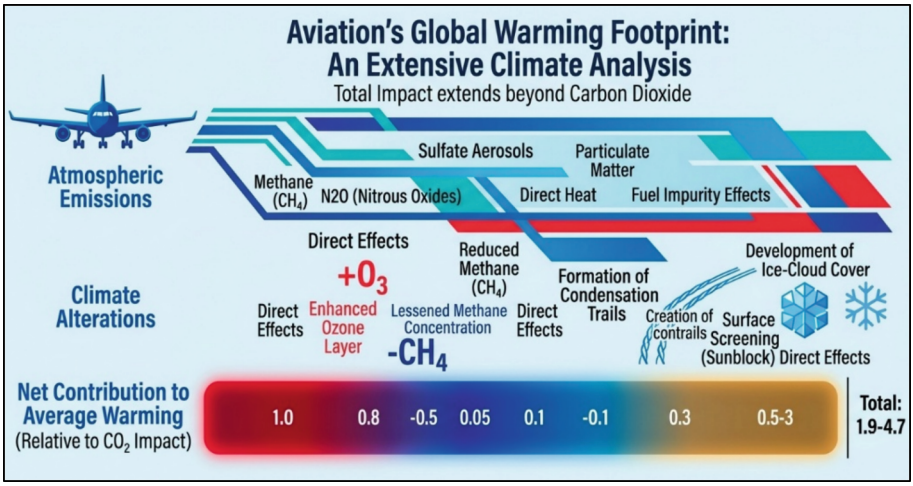


Fig. 3. Effect of Aviation on the Global Climate. Adapted from EESI [28].

6.2 NO_x Emissions

NO_x emissions from jet engines result primarily from high-temperature combustion, and fuel properties can influence their formation through effects on flame temperature, stoichiometry, and mixing. Low-aromatic, low-sulfur synthetic fuels generally burn cleaner and may alter combustion behaviour, but the direction and magnitude of NO_x changes with eSAFs are uncertain and vary by engine design and operating point. Observed effects include slight reductions in smoke and soot, which can shift combustion regimes, and changes in fuel spray and evaporation affecting local stoichiometry and NO_x precursors. Because NO_x impacts ozone on short timescales, even small changes can significantly influence climate forcing, and reductions in soot and contrails may be partly offset by increased NO_x, making trade-offs complex and requiring comprehensive engine and atmospheric chemistry modelling [29–31].

6.3 Net Climate Effects

The potential for eSAFs to reduce non-CO_2 warming, particularly through contrail mitigation, is a key co-benefit beyond CO_2 lifecycle savings, as reduced nvPM emissions can lower contrail optical depths and lifetimes, yielding immediate radiative benefits. However, the magnitude of these effects is uncertain due to nonlinear atmospheric processes and sensitivity to flight altitude, humidity, and meteorology.

Robustly assessing net climate impacts requires controlled engine tests comparing nvPM and NO_x emissions across fuels and operating conditions, in-flight contrail studies under fuel swap scenarios, integrated atmospheric chemistry and climate modelling to quantify radiative forcing and global warming potential, and policy-focused evaluations combining CO_2 and non-CO_2 effects to produce comprehensive climate performance indicators for different SAF pathways [27, 32].

7 Conclusion

Electrofuels represent a promising long-term solution for aviation decarbonisation. They offer compatibility with existing aircraft, scalability independent of land use, and the potential for near-zero lifecycle emissions under renewable energy systems.

Compared to biomass SAFs, eSAFs eliminate feedstock limitations but currently suffer from higher costs and energy requirements. Their viability depends on continued advancements in renewable electricity, hydrogen production, CO_2 capture, and catalytic synthesis technologies.

Non-CO_2 effects such as contrails and NO_x emissions remain critical uncertainties in evaluating total climate impact. Overall, eSAFs are likely to play a central role in aviation decarbonisation, provided strong policy frameworks and infrastructure development are in place.

References

1. Decarbonizing aviation: challenges and levers. D-Carbonize. https://d-carbonize.eu/blog/decarbonization-aviation/ Accessed 20 Oct 2026
2. Alharasees, O., Rohacs, D., Müller, A., Kale, U.: Towards greener skies: evaluating sustainable aviation fuel alternatives. Geoj. Tour. Geosites. **59**, 551–562 (2025)
3. Mansy, A.E., Daniel, S., Fonzeu Monguen, C.K., Wang, H., Osman, A.I., Tian, Z.-Y.: Catalytic production of aviation jet biofuels from biomass: a review. Environ. Chem. Lett. **23**, 419–461 (2025)
4. Wankhede, S., Dixit, J., Sharma, D., Sharma, N.: Comprehensive analysis of electrofuels (e-fuels) as sustainable fuels from renewable electricity: a review. In: Sharma, N., Hespel, C., Panigrahy, S., Singh, P., Agarwal, A.K. (eds.) Sustainable, Scalable and Storable E-Fuels for Decarbonising Transport Sector, pp. 161–190. Springer, Singapore (2025)
5. MacCarley, C.A.: Synthetic and e-fuels. In: MacCarley, C.A. (ed.) Non-Petroleum Automotive Transportation, pp. 351–363. Springer, Cham (2025)
6. Marques, L., Vieira, M., Condeço, J., Sousa, H., Henriques, C., Mateus, M.: Review of power-to-liquid (PtL) technology for renewable methanol (e-MeOH): recent developments, emerging trends and prospects. Energies. **17**, 5589 (2024)
7. Shanian, S., Savadogo, O.: Techno-economic analysis of electrolytic hydrogen production by alkaline and PEM electrolysers using MCDM methods. Discov. Energy. **4**, 23 (2024)
8. Ozkan, M.: Atmospheric alchemy: the energy and cost dynamics of direct air carbon capture. MRS Energy Sustain. **12**, 46–61 (2025)
9. Brübach, L., Wolf, M., Pfeifer, P.: Fischer–Tropsch synthesis. In: Bullerdiek, N., Neuling, U., Kaltschmitt, M. (eds.) Powerfuels: Status and Prospects, pp. 605–645. Springer, Cham (2025)
10. Beiermann, D.: Refining of Fischer–Tropsch products. In: Bullerdiek, N., Neuling, U., Kaltschmitt, M. (eds.) Powerfuels: Status and Prospects, pp. 647–666. Springer, Cham (2025)
11. Batteiger, V., Ebner, K., Moser, L., Penke, C., Portner, B., Sizmann, A.: Power-to-liquid (PtL) kerosene and opportunities to introduce green hydrogen in aviation. In: Bullerdiek, N., Neuling, U., Kaltschmitt, M. (eds.) Powerfuels: Status and Prospects, pp. 849–878. Springer, Cham (2025)
12. Ali, F., et al.: Fueling the future: biomass applications for green and sustainable energy. Discov. Sustain. **5**, 156 (2024)
13. Mukherjee, A., et al.: PtL fuels and biofuels: a dream team? In: Bullerdiek, N., Neuling, U., Kaltschmitt, M. (eds.) Powerfuels: Status and Prospects, pp. 1127–1156. Springer, Cham (2025)
14. Osman, A.I., et al.: Conversion of biomass to biofuels and life cycle assessment: a review. Environ. Chem. Lett. **19**, 4075–4118 (2021)
15. Alharasees, O., Kale, U.: Evaluating criteria for sustainable aviation fuel adoption. In: Sogut, M.Z. (ed.) The Role of Exergy and Energy in Sustainability, pp. 257–268. Springer, Cham (2025)
16. Qasem, N.A.A., et al.: A recent review of aviation fuels and sustainable aviation fuels. J. Therm. Anal. Calorim. **149**, 4287–4312 (2024)
17. Ballal, V., Cavalett, O., Cherubini, F., Watanabe, M.: Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios. Fuel. **338**, 127316 (2023)
18. Assessing the sustainability implications of alternative aviation fuels. International Council on Clean Transportation. https://theicct.org/publication/assessing-the-sustainability-implications-of-alternative-aviation-fuels/. Accessed 19 Apr 2026

19. Laguna-Bercero, M.A., Wang, Y., Zhou, X.-D., Zhu, L.: Fundamentals of solid oxide electrolysis cells (SOEC). In: Laguna-Bercero, M.A. (ed.) High Temperature Electrolysis, pp. 5–34. Springer, Cham (2023)
20. Nisa, M.U., Ishaq, H., Crawford, C.: Electrochemical approaches for CO_2 point source, direct air, and seawater capture. Environ. Sci. Pollut. Res. (2025)
21. Alharasees, O., Kale, U.: Selection of sustainable aviation fuels: an expert-based comparative approach. In: Proceedings, pp. 43–49 (2024)
22. Wang, B., Ting, Z.J., Zhao, M.: Sustainable aviation fuels: key opportunities and challenges. Carbon Capture Sci. Technol. **13**, 100263 (2024)
23. Lapidus, A.L.: Fundamentals of the Fischer–Tropsch synthesis. In: Derouane, E.G., Parmon, V., Lemos, F., Ramôa Ribeiro, F. (eds.) Sustainable Strategies for the Upgrading of Natural Gas, pp. 173–183. Springer, Dordrecht (2005)
24. Pechstein, J., Zschocke, A.: Blending of synthetic kerosene and conventional kerosene. In: Kaltschmitt, M., Neuling, U. (eds.) Biokerosene: Status and Prospects, pp. 665–686. Springer, Berlin, Heidelberg (2018)
25. Prussi, M., Noussan, M., Laveneziana, L., Chiaramonti, D.: The risk of increasing energy demand while pursuing decarbonisation. Transp. Policy. **160**, 154–158 (2025)
26. Meincke, P., Popa, A., Laqua, V.: Analysis of airport infrastructure with regard to sustainable aviation fuels. In: Proceedings, pp. 652–658 (2025)
27. Azar, C., Johansson, D.J.A.: Valuing the non-CO_2 climate impacts of aviation. Clim. Change. **111**, 559–579 (2012)
28. The growth in greenhouse gas emissions from commercial aviation. EESI. https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation. Accessed 19 Apr 2026
29. Investigation of the sooting propensity of aviation fuel mixtures. CEAS Aeronautical Journal. https://link.springer.com/article/10.1007/s13272-020-00482-7. Accessed 19 Apr 2026
30. Wandelt, S., Zhang, Y., Sun, X.: Sustainable aviation fuels: a meta-review. J. Air Transp. Res. Soc. **4**, 100056 (2025)
31. Maroa, S., Inambao, F.: The NO_n formation routes. In: Maroa, S., Inambao, F. (eds.) Biodiesel, Combustion, Performance and Emissions Characteristics, pp. 7–15. Springer, Cham (2020)
32. Al Kazzaz, M.B., Károly, B.: The impact of SAF on reducing NO_n, SO_2, and non-CO_2 emissions. In: Karakoc, T.H., et al. (eds.) Energy and Sustainable Aviation Fuels Solutions, pp. 127–130. Springer, Cham (2025)

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Circular Economy

Novel Lightweight Pultrusion Profiles with Textile Reinforcement for Ultra-Light Frame Structures in Rail and Commercial Vehicles

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Abstract. Innovative lightweight solutions play a crucial role in improving energy consumption of transport systems. However, the weight of vehicles is typically increasing at present, for example due to batteries for hybrid and all-electric drivetrains. A possible lightweight strategy is to reduce the weight of the main load-bearing structure, which is typically a metal frame. Here, substituting metals with high-performance composite materials like carbon fiber reinforced plastics (CFRP) offers a lightweight potential of up to 50%. The predestined technology for cost-efficient production of CFRP profiles is pultrusion, which is predominantly used for simple profile cross-sections with pure unidirectional (UD) reinforcement today. Such UD reinforcements are suited for purely uniaxial loads but not for more complex loading conditions as they occur in real operation. In this work, the pultrusion process is extended to enable the use of multi-axial textile reinforcements as well as the manufacturing of complex cross-sections. For this purpose, active and passive preforming devices have been developed for the wrinkle-free use of non-crimped fabrics (NCF) in pultrusion, partly based on finite element simulations using specially validated material models for textiles. On this basis, first CFRP lightweight pultrusion profiles for rail vehicles were successfully developed, achieving a 30% reduction in weight.

Keywords: Lightweight · Composite · Pultrusion · Rail Vehicles

1 Introduction

The development of innovative and economical lightweight construction solutions plays a key role for the future realization of more energy- and resource-efficient transport systems on land, sea and air. Lowering the structural weight generally leads to significant reduction of energy consumption and subsequently carbon emissions, which is aimed by different programs worldwide like the European Green Deal with a reduction of carbon emissions by 55% until 2030 compared to 1990.

There are various lightweight design approaches to lower structural weight like material lightweight design or shape lightweight design, see e.g [1]. In case of material

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lightweight design, the structural application of endless carbon fiber reinforced plastic (CFRP) with its outstanding specific strength and stiffness usually allows significant mass reductions compared to classic metals of up to 50% in different transport systems like shown for train structures in [2] or [3]. But a major obstacle for wider series application of CFRP often arises from the manufacturing costs of CFRP components, like described in [4].

Here the pultrusion technology offers great opportunities for very cost-efficient production of composite profiles like shown in [5]. Pultrusion is a continuous composite manufacturing process that pulls reinforcement fibers (like carbon fibers) through a resin bath or an injection box for impregnation (if thermoset is used), then through a heated mold section to finally form the profile and cure the resin, see e.g [6]. But the current state-of-art pultrusion technology offers usually unidirectional endless fiber reinforcement in axial direction and very simple hollow or solid cross sections, which limits structural applications mainly to rods with purely axial tensile or compressive loads. In contrast to that, most structural applications in transport systems require the realization of frame structures consisting of profiles with bending, torsion as well as axial tension and compression loads. Furthermore, the limited design space or the required integration of functions like cable channels mostly lead to more complex multi-chamber cross sections with varying wall thicknesses. Today such frame structures like railway car bodies, space frames for cars, chassis for trucks, buses and trailers are mostly made of steel or aluminum profiles like shown in [7].

This paper describes chosen major steps for the further development of pultrusion process to produce CFRP profiles with textile reinforcement in different directions using so-called non-crimp fabrics (NCF) – a standard semi-finished textile material in composite industry e.g. described in [8] – and first structural application of such profiles in load-carrying train structures.

2 Major Challenges for Pultrusion of Complex Profiles with Textile Reinforcement

Advances in pultrusion technology are currently being made in many different areas, for example to improve production quality and efficiency or to reduce manufacturing restrictions in terms of layup and geometry, as shown in [5]. The realization of multiaxial textile reinforcement is mostly based on combination of pultrusion with braiding or winding technology like described in [9] or integration of tailored local textile patches made by tailored fiber placement (TFP) as shown in [10]. Here, the use of commercially available NCF offers an interesting alternative. NCF consists of multiple unidirectionally (UD) reinforced fiber layers with different orientations that are mechanically connected by stitching, knitting or sewing (see Fig. 1). The endless fibers inside NCF have a very low fiber undulation (“waviness”) compared to classic fabrics resulting in very good mechanical in-plane properties.

NCF are two-dimensional (2D) planar semi-finished products on rolls. So, if profiles with complex section geometries are to be manufactured, these textile materials must be formed accordingly. But NCF have a relatively low bending stiffness, which can lead to wrinkling during preforming process, as the material can buckle under compressive

as well as shear forces. In pultrusion direction, a straight fiber alignment is generally ensured, as the fibers are pulled through the mold by a tensile force acting in the 0° direction. However, there is no force acting in transverse direction that could stabilize the NCF material in a straight state in the 90° direction as well. To overcome this major challenge "passive" preforming devices have been developed to ensure a wrinkle-free continuous preforming of the NCF within the feeding section. In addition, novel "active" positioning systems for active alignment of NCF in transverse direction were developed, which act both on the roll with the rolled-up NCF and, subsequently, on the edges of the NCF itself after it has been unwound from the roll. An overview of current continuous preforming technologies for NCF is given in [11].

Another major challenge is the efficient and reliable determination of suited geometries for the NCF preforming devices based on finite element (FE) simulation instead of time-consuming and costly experimental tests. For this purpose, special material models for FE-simulation were investigated which consider the nonlinear behavior of NCF. Moreover, the required material properties of NCF were determined in extensive tests. FE simulations were carried out to model the forming of the NCF, which were validated by accompanying tests.

3 Preforming Devices and Functional Validation Based on Experimental and Simulation Studies

The passive and active preforming devices were developed and tested using a representative U-profile with a width of 50 mm, a flange length of 50.5 mm and a wall thickness of 2.5 mm as a reference. Quadriaxial NCF with areal weights of 800 g/m^2 and 1600 g/m^2 have been used in the tests.

The passive devices are four single preforming tools with designed slot geometries, which continuously form the planar NCF into the shape of the final profile cross section (see conceptual design in Fig. 1). As an alternative passive preforming concept, a single-stage 3D-printed forming tool has been developed and successfully tested, where the NCF is formed in only one step without any preforming tools. For this purpose, preliminary tests and simulations were carried out on the free forming of the textiles from a horizontal- to a U-shape under pulling force without using multiple preforming tools.

In addition, two custom active preforming devices were developed to correct the transverse position of the NCF in the event of displacement, as well as to prevent wrinkling during the forming process by applying an "active" force in the transverse direction (Fig. 1). The first device is the movable storage of the rolled-up NCF material. This allows axial adjustment of the rolls to correct the feed position of the NCF if lateral displacement of the textile occurs or wrinkles begin to form. The second newly developed device are grippers applying lateral tension forces perpendicular to the pultrusion direction to correct the lateral position of the NCF in case of displacements, ensuring a straight fiber alignment in transverse direction. Both active preforming devices are mainly actuated depending on the lateral position of the NCF, which is monitored by a camera-based system measuring the transverse position of the stitching thread at the edge of the NCF.

All passive and active preforming devices have been successfully tested at a custom test stand mimicking the preforming line of a pultrusion machine in a smaller scale based on the example of the described U-profile (see test stand in Fig. 2 (a)).

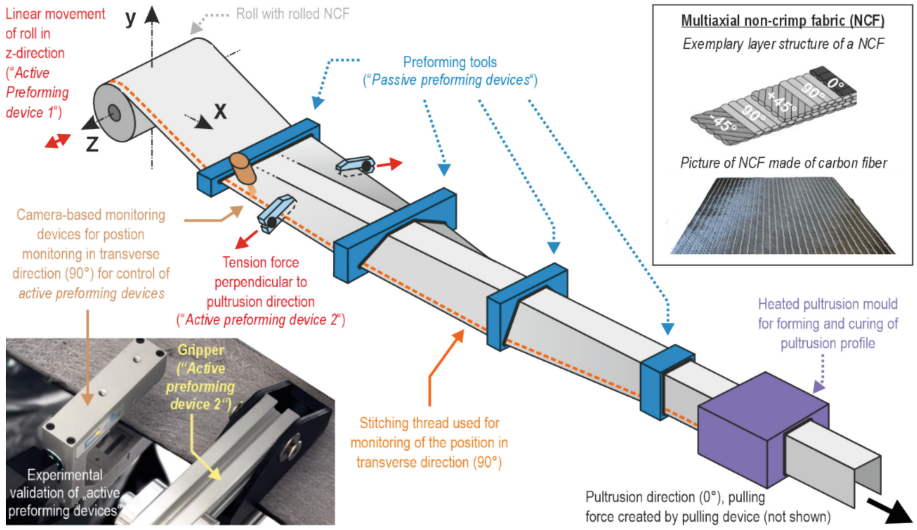


Fig. 1. Basic principle of pultrusion and conceptual illustration of newly developed passive and active preforming devices for non-crimp fabric (NCF).

The test results from those experimental tests were also used for validation of numerical material models as well as approximation models for NCF textiles in FE-simulation as mentioned in Sect. 2. A FE-model was developed to simulate the entire preforming process on the test stand, using the U-profile as reference geometry.

The textile is modeled using 2D shell elements. Two material models have been considered for the fabric material: the model developed by Döbrich et al. [12] as well as the standard fabric material model FABR_A provided by Altair as described in [13]. The preforming tools are modeled with 3D elements as shown in Fig. 2 (a). An appropriate contact was defined between the dies and the textile material. Moreover, a gravity load as well as a tension resistance force in pultrusion direction were applied.

For FE-simulation an explicit solver has been used because of the dynamic process with complex nonlinearities regarding material behavior, geometric changes and boundary conditions.

A comprehensive material characterization determining the highly non-linear NCF material behavior according to material model requirements formed the basis for the preforming simulation. The following main material properties of the considered NCFs with an area weight of 800 and 1600 g/m^2 have been determined: Young's modulus in 1- and 2-direction by tensile strip test according to [14], bending stiffness by cantilever bending test according to [15] and shear modulus and shear locking angle by bias extension test as well as picture frame test like described by Rothe et al. [16]. The shear locking angle is the limit, where the in-plane shear deformation of the 2D NCF becomes significantly restricted mainly due to compression of the fibers against each other and out-of-plane deformation (like wrinkling) becomes more likely. Thus, this angle characterizes the critical point of deformation related to the starting of wrinkling during the textile preforming, see e.g [17].

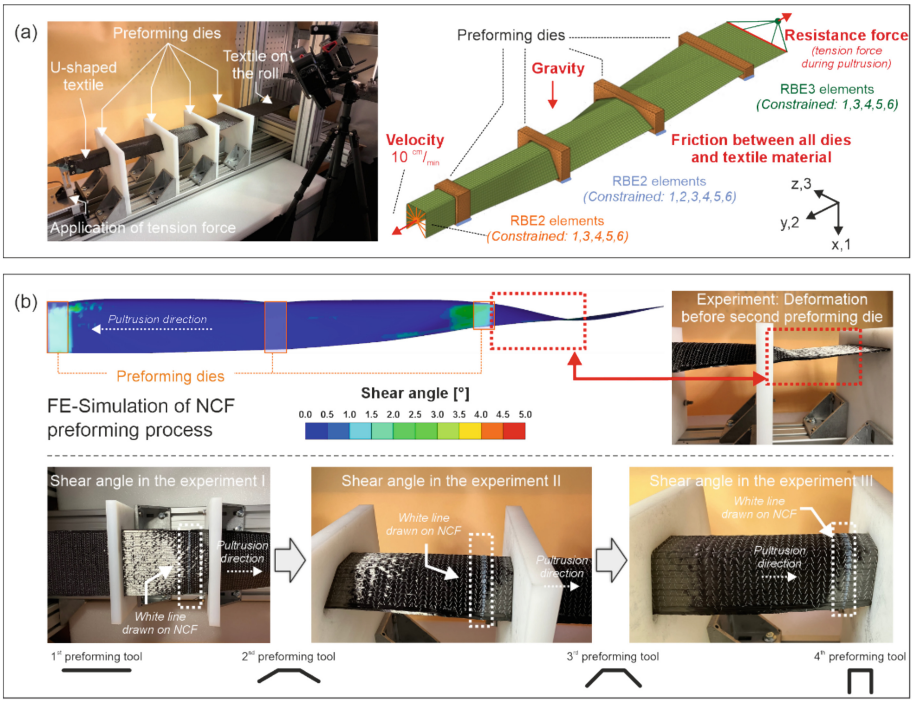


Fig. 2. (a) Preforming test jig: experiment and FE-model; (b) Comparison of experimental and simulation results – deformation and shear angle.

Figure 2 (b) exemplarily shows the unscaled deformed shape of the NCF as well as the shear angle as contour plot in FE-simulation using the material model FABR_A of Altair. The deformation shows a very good correlation; for example, a characteristic wave-shaped deformation occurs between the first and the second preforming tool in the experiment as well as in the simulation. Furthermore, the shear angle in the NCF material in the simulation is not higher than 2.5°, which is much lower than the shear locking angle. For monitoring the shear angle in experiment, a white line was drawn on the fabrics to make potential shear deformation visible. As it can be seen in Fig. 2 (b) the white line remains unaffected while moving through the different preforming dies confirming the very low shear angles observed in the simulation results.

The very good correlation of the results shows that the simulation-based approach to model NCF behavior during the preforming stage of the pultrusion process is a valuable tool for depicting the unique forming behaviors as well as predicting critical wrinkling areas. The computation time management still represents a critical issue and had to be handled by introducing techniques like mass scaling to balance simulation stability and time efficiency without compromising the simulation results.

4 Conclusion

The conducted research on active and passive preforming devices for continuous preforming as well as on preforming simulation of NCF allowed a substantial step forward to serial application of NCF for pultrusion of profiles with complex sections. The developed preforming devices make it possible to use NCF without wrinkling and with reduced fiber undulation in the pultrusion process. The proposed approach for FE-simulation of preforming NCF under unidirectional tension in pultrusion process was successfully validated by experiments. Thus, the simulation-supported approach can be used for designing complex preforming tools for NCF instead of conducting costly and time-consuming test series.

Those results formed the basis for successful realization of a new generation of ultralight CFRP pultrusion profiles with multi-chamber cross sections, which are used for structural components in rolling stock industry. Exemplary structural CFRP-profiles with NCF reinforcement are shown in Fig. 3 (a).

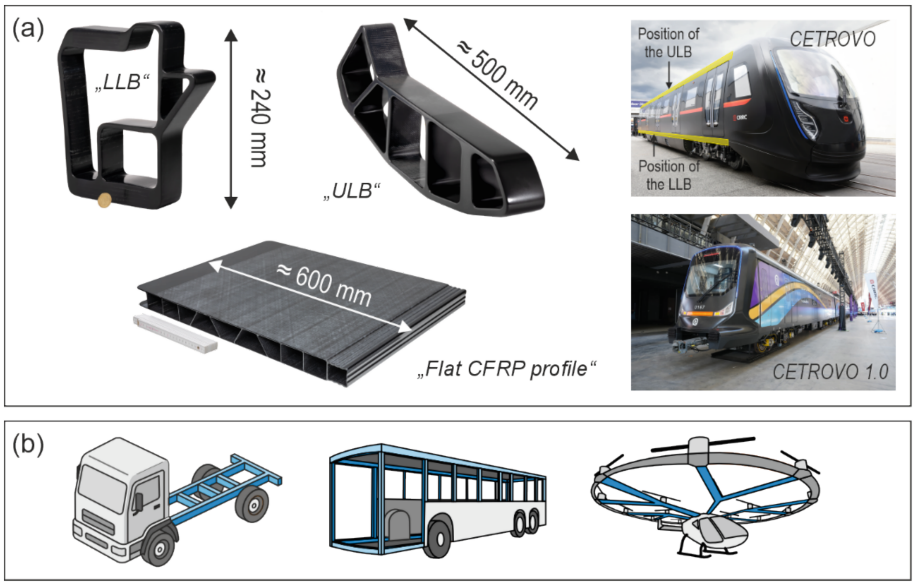


Fig. 3. (a) Exemplary CFRP pultrusion profiles with textile NCF reinforcement; (b) Potential future application fields.

The first two profiles shown are cross-sections of the lower (“LLB”) and the upper longitudinal beam (“ULB”), which are a main structural element of the car body of the world’s first metro in carbon-intensive lightweight design, named “CETROVO” [18]. The LLB is positioned in both lower longitudinal corners whereas the ULB is assembled in both upper longitudinal corners of the car body, where they ensure the transmission of the high longitudinal and bending loads during operation. The weight reduction for the LLB and ULB compared with aluminum reference beams was around 20%, with the

bending stiffness of the CFRP version of the LLB being around 30% higher and that of the ULB remaining at the same level. A further developed LLB and ULB is also used in the successor generation of the "CETROVO" train, the so-called "CETROVO 1.0" shown in Fig. 3 (a).

The third flat CFRP multi-chamber profile with a width of about 600 mm can be used for large floor, roof or sidewall sections in car bodies of rail vehicles. In this profile, quadraxial NCF is used to reinforce both the outer layers and the internal ribs. The chambers can also be foamed during the pultrusion process to improve thermal and acoustic insulation as part of functional integration. This can eliminate the need for additional thermal insulation, thereby achieving further secondary weight savings.

Such textile-reinforced pultrusion profiles can be used not only in rolling stock but also in commercial vehicle and aviation applications, like shown in Fig. 3 (b). So, in commercial vehicles, like trucks or buses, the chassis is mostly a welded steel frame. But the current trend to electric drives leads to increased masses due to heavy additional components like the batteries. Here the replacement of the steel frames by ultralight frame made of pultrusion profiles can help to break the weight spiral. An interesting field of application in aviation is drones, where lightweight frame structures are needed, for example, to mount the rotors or to realize the cabin structure.

References

1. Albers, A., Holoch, J., Revfi, S., Spadinger, M.: Lightweight design in product development: a conceptual framework for continuous support in the development process. Procedia CIRP. **100**, 494–499 (2021). https://doi.org/10.1016/j.procir.2021.05.109
2. Ulbricht, A., Zeidler, F., Bilkenroth, F., Soltysiak, S.: Structural lightweight components for energy-efficient rail vehicles using high performance composite materials. Transp. Res. Procedia. **72**, 1685–1692 (2023). https://doi.org/10.1016/j.trpro.2023.11.641
3. Tang, J., Zhou, Z., Tan, Y., Chen, H., Wang, S., Gutiérrez, A.: Research on NCF fabric CFRP pultrusion beam mechanical performance and laminate design for railway vehicle application. J. Compos. Mater. **56**(15), 2351–2365 (2022). https://doi.org/10.1177/00219983221094657
4. Hagnell, M.K.: Technical cost modelling and efficient design of lightweight composites in structural applications PhD thesis. KTH Royal Institute of Technology Stockholm, Sweden (2019)
5. Volk, M., Yuksel, O., Baran, I., Hattel, J.-H., Spangenberg, J., Sandberg, M.: Cost-efficient, automated, and sustainable composite profile manufacture: a review of the state of the art, innovations, and future of pultrusion technologies. Compos. Part B Eng. **246**, 110135 (2022). https://doi.org/10.1016/j.compositesb.2022.110135
6. Baran, I.: Pultrusion, 2nd edn. Elsevier, Amsterdam, Oxford, Cambridge (2023). https://doi.org/10.1016/C2020-0-03551-6
7. Seyfried, P., Taiss, E.-J.-M., Calijorne, A.-C., F.P, L., Song, Q.-F.: Light weighting opportunities and material choice for commercial vehicle frame structures from a design point of view. Adv. Manuf. **3**, 19–26 (2015). https://doi.org/10.1007/s40436-015-0103-8
8. Schnabel, A., Gries, T.: Production of non-crimp fabrics for composites. In: Lomov, S.V. (ed.) Non-crimp Fabric Composites – Manufacturing, Properties and Production, 1st edn. Woodhead Publishing Limited, Oxford, Cambridge, Philadelphia, New Dehli (2011)
9. Lebel, L.-L., Nakai, A.: Design and manufacturing of an L-shaped thermoplastic composite beam by braid-trusion. Compos. A: Appl. Sci. Manuf. **43**(10), 1717–1729 (2012). https://doi.org/10.1016/j.compositesa.2012.03.001

10. Boysen, S., Heimbucher, C., Schiebel, P., Marx, A.: Lokale Verstärkung von Pultrusionsprofilen durch lastgerechte Textilstrukturen zur Steigerung der Festigkeit in Fügebereichen. Forschungsbericht 71. Faserinstitut Bremen (2023)
11. Fauster, E., Schillfahrt, C., Hueber, C., Schledjewski, R.: Automated profile preforming for structural components. Sci. Eng. Compos. Mater. **24**(5), 631–650 (2017). https://doi.org/10.1515/secm-2015-0377
12. Döbrich, O., Gereke, T., Diestel, O., Krzywinski, S., Cherif, C.: Decoupling the bending behavior and the membrane properties of finite shell elements for a correct description of the mechanical behavior of textiles with a laminate formulation. J. Ind. Text. **44**(1), 70–84 (2013). https://doi.org/10.1177/1528083713477442
13. Altair Radioss Help: (2026). https://help.altair.com/hwsolvers/rad/topics/solvers/rad/mat_law58_fabr_a_starter_r.htm. Accessed 9 Feb 2026
14. DIN EN ISO 13934-1:2013-08: Textiles - Tensile properties of fabrics - Part 1: Determination of maximum force and elongation at maximum force using the strip method. Berlin (2013). https://doi.org/10.31030/2017288
15. DIN 53362:2024-11: Testing of plastic films and textile fabrics (excluding nonwovens), coated or not coated plastics - Determination of stiffness in bending - Method according to Cantilever. Berlin (2024). https://doi.org/10.31030/3575081
16. Rothe, S. et al.: Investigation of shear-induced deformation of reinforcing textiles by optical measurement devices. Materials. **12**(7), 1029 (2019). https://doi.org/10.3390/ma12071029
17. Prodromou, A., Chen, J.: On the relationship between shear angle and wrinkling of textile composite preforms. Compos. Part A Appl. Sci. Manuf. **28**(5), 491–503 (1997). https://doi.org/10.1016/S1359-835X(96)00150-9
18. Ulbricht, A.: Rail vehicle in CFRP-intensive design. In: Lightweight Design worldwide, vol. 12, pp. 34–39 (2019). https://doi.org/10.1007/s41777-019-0009-4

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The Use of Alternative Energy Sources or Railway Line Electrification from the Social Costs' Perspective

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Abstract. Currently, there is little research addressing the social costs of alternative energy sources in rail transport. The subject of most studies is the technological aspect of using alternative energy sources in rail transport conditions or their internal costs, often from a life cycle perspective. To better understand social costs, we need to look at the entire life cycle of trains and figure out the specific factors that affect the external costs of alternative energy rail vehicles. A more extensive and precise quantification of social costs, which would take into account the social costs of the entire life cycle of railway rolling stock and the social costs of alternative energy sources in rail transport, can contribute to a more effective achievement of the objective of reducing the external costs of transport in the European Union. The paper deals with the quantification of the social costs of railway rolling stock using alternative energy sources in rail passenger transport in comparison with the electrification of lines based on the LCA method. Our theoretical research will be applied in a case study on a selected non-electrified railway line in the Slovak Republic.

Keywords: Alternative energy sources · Electrification · LCA method · Railway rolling stock · Social costs

1 Introduction

One of the key components for achieving the goals of the European Green Deal is sustainable transport. The introduction of new technologies is a necessity in the transport sector. Currently, we can observe manufacturers' efforts to produce so-called clean vehicles with zero CO_{2eq} emissions. However, society must address other issues arising from this, such as hydrogen production, battery production and lifespan, etc. All these problems and their solutions create additional demands for financial resources in research and development and implementation of new technologies.

Rail transport is considered an environmentally friendly mode of transport. However, in the case of diesel traction, the environmental impact of rail transport may be worse than that of road transport, especially when older locomotives or diesel multiple units are

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used. It is therefore important that rail transport also contributes to achieving the EU's climate goals. There are two basic options on non-electrified railway line: the use of locomotives or multiple units with alternative energy sources (batteries, hydrogen) or the electrification of railway lines (if electricity production in the country is environmentally friendly). Slovak power plants, which produce more than 70% of electricity in Slovakia, will become producers of 100% electricity without direct CO_{2eq} emissions in 2024 [1]. Therefore, in a case study, we examined the overall costs of implementing passenger rail transport when electrifying the line and using electric multiple units (EMU) in comparison with using battery electric multiple unit (BEMU).

2 Literature Review

The Life Cycle Assessment (LCA) method is the most suitable approach for evaluating rail passenger transport with different energy sources in terms of social costs. It quantifies environmental impacts across the entire life cycle, from design and construction to operation, maintenance, and disposal [2]. LCA is governed by ISO 14040:2006 and ISO 14044:2006 standards, which define principles, phases, and methodological relationships. However, these standards do not provide detailed procedures for individual phases or analyses [3, 4]. Although widely applied, the full use of LCA is limited by the availability and quality of specific data. This constraint is particularly significant in railway infrastructure assessment [5]. Despite these limitations, LCA provides valuable insights into the sustainability of rail transport across its full life cycle [6]. Within LCA, both process-based and economic input-output approaches can be used [7]. The process approach enables detailed analysis but requires extensive data [8]. In contrast, the economic input-output approach is less detailed, simpler to apply, and less demanding in terms of data, but also less transparent [9].

The quantification of environmental burdens in rail transport differs between rolling stock and infrastructure. For infrastructure, LCA must include construction of the power supply system, electrification adjustments, and operation and maintenance phases. These phases are strongly dependent on train performance and traffic intensity. Accurate quantification therefore requires extensive detailed data, which may be impractical to obtain [10]. LCA is widely used to assess environmental impacts of transport projects due to its comprehensive nature. However, many studies remain partial, focusing mainly on subgrade and superstructure. They often neglect the construction and operation of electric traction equipment [11]. The external costs of electric traction are highly dependent on the energy mix. De Bortoli et al. developed an LCA model for high-speed rail infrastructure based on the Tours–Bordeaux line [12]. Their results indicate that traction power supply systems account for approximately two to 12 % share of individual environmental impacts.

The deployment of Battery Electric Multiple Units (BEMU) is suitable for non-electrified lines over distances of several tens of kilometers. Their main advantage lies in lower overall social costs compared to full line electrification. However, BEMU systems involve higher investment costs, including batteries and their replacement requirements [13]. Boev et al. [14] compared Diesel Multiple Units (DMU) and BEMU in terms of total costs and CO_{2eq} emissions. Their results indicate that BEMU fleets can be

up to 20% cheaper than diesel fleets. Additionally, greenhouse gas emissions may be reduced by as much as 98% [14]. The operation of BEMU depends on the availability of adequate charging infrastructure. Streuling et al. [15] analyzed the feasibility of charging BEMU using local renewable energy sources. They also examined the cost efficiency of charging infrastructure placement on a German non-electrified line [15]. The limitation of BEMU is their lower maximum speed compared to EMU. Battery-powered operation typically allows speeds up to 120 km/h. In contrast, EMU speeds are mainly constrained by infrastructure parameters. From an LCC perspective, the advantage of electrification over BEMU depends on rail line length and traffic capacity [13, 16].

Hydrogen Multiple Units (HMU) represent an alternative to full railway electrification. Their operation requires only appropriately located hydrogen refueling infrastructure. This may reduce internal costs compared to full line electrification [17]. Hydrogen conversion to electricity produces no direct emissions. However, overall environmental benefits depend on the hydrogen production method [18]. Most current HMUs rely on grey hydrogen derived from fossil fuels [19]. Kapetanovič et al. [20] found that hydrogen production using electricity (EU mix) may generate higher external costs than natural gas-based production. Marjani et al. [21] analyzed life cycle CO_{2eq} emissions for hydrogen and diesel trains in the UK. Their results indicate a 92.5% reduction in emissions when using green hydrogen. In contrast, grey hydrogen achieves a 27.7% reduction compared to diesel fuel.

The advantages of using alternative energy sources compared to electrification cannot be generalized. It is necessary to consider the different conditions of individual railway lines. For example, in the UK on the London St. Pancras – Leicester line, the average costs would be lowest for electrification at distances over 100 km and traffic density higher than 52 trips/day. In the case of traffic density lower than 45 trips/day, the average costs are lower for hydrogen fuel cell trains and BEMU has the lowest average costs at traffic density less than 52 trips/day and distances up to 100 km [22]. Similarly, Zhandg et al. [23] state that future carbon reduction LCA should consider technological innovations, mode optimization, and regional disparities.

3 Methodology

The social costs of railway rolling stock operation can be divided into infrastructure and vehicle subsystems across life cycle phases: production, operation, and disposal (Fig. 1).

For BEMU, the most significant impacts arise from electricity consumption and the production and disposal of traction lines, electrical equipment, and batteries. Electricity consumption can be quantified relatively accurately, though external costs are uncertain due to future energy mix variability. This uncertainty may lead to overestimation, given the transition from fossil fuels to renewable energy sources. Comprehensive assessment requires life cycle analysis of traction batteries and electrification, while improving battery efficiency complicates impact estimation but suggests negligible disposal costs.

The processes with the most significant impact on the external costs of operating hydrogen engine units include hydrogen consumption, installation or replacement of fuel cells and traction batteries, and processes associated with hydrogen production and filling. The processes associated with fuel cells cannot be precisely quantified due to

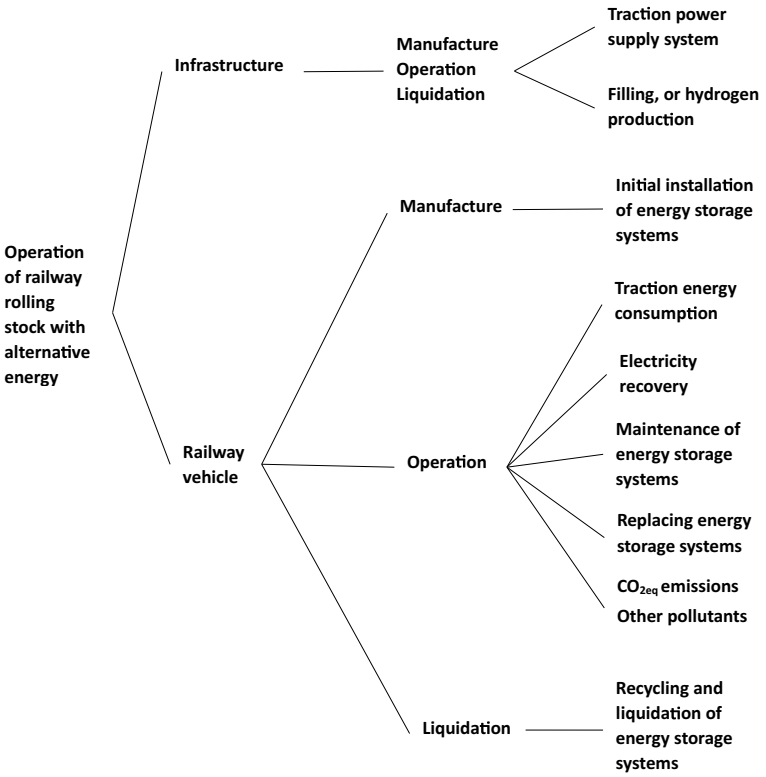


Fig. 1. Social costs of operating railway rolling stock with alternative energy sources.

their dynamic development and the youth of the technology, which is manifested by unexpected technical problems in operation.

4 Results and Discussion

Due to the lack of data on HMUs, our study compared the social costs of electrification of the line and the use of BEMUs on the Humenné – Medzilaborce railway line. When comparing costs, we did not consider those costs that are the same when using EMU and BEMU, e.g. costs for train drivers, train crews, LCA for railway line, indirect costs etc. In both cases (EMU and BEMU), we consider two units to maintain the current train set capacity, while the relative advantage of either alternative remains unchanged regardless of the number of EMU/BEMU units. The input data for EMU is given in Table 1.

Table 1. Input Data – EMU.

Item	Value	Unit
Investment costs for electrification	1.756	mil. €/km
Total length of electrification	51.864	km
Operating costs for an electrified line	1.6	€/thousand gross tone km
Electrification lifespan	40	years
Capital cost per EMU	4.72	mil. €
Number of EMU	2	pieces
EMU lifespan	30	years
Annual transport performance	346. 408	thousand train km
	38 312.67	thousand gross tone-km
Average traction energy consumption	4.72	kWh/train km
Infrastructure fees – U_3	1.048	€/thousand gross tone km
Infrastructure fees – U_4	0.228	€/thousand gross tone km
Average cost of traction energy	0.462	€/train km
Emission factor for electric traction	0.169	kg CO_{2eq}/kWh
Unit price of CO_{2eq}	0.2308	€/kg

Source: Authors by [16, 24, 28]

The input data in Table 1 were modeled based on the referenced sources. All cost items were recalculated to 2024 levels using HICP (Harmonised Indices of Con-sumer Price) data from the Statistical Office of the Slovak Republic. Investment costs were estimated using the EMU 15Ev Regiopanter (UIC series 650.2). Infrastructure charges included only U3 (operability of infrastructure) and U4 (use of electrical equipment). Other charges were excluded as they are identical for EMU and BEMU. Transport performance in train-km was derived from the current timetable assuming EMU operation. Gross tonne-km performance was calculated as the product of train-km and total EMU. Table 2 shows the social costs for line electrification and the use of EMUs. Given that the EMUs lifespan and electrical equipment lifespan are different, the costs were calculated on an annual basis. The social costs of electrification and the use of EMUs are high and at current performance represent €8.44/train km. However, it should be noted that the calculation does not include all costs, as stated in the introduction to this chapter.

For railway lines with lower traffic intensity, studies indicate higher efficiency of BEMU. Therefore, the social costs of BEMU operation were also evaluated. Unlike EMU, full electrification is not required, but partial (island) electrification is necessary for battery recharging. Input data for BEMU (Table 3) were converted to 2024 values analogously to the EMU case. Social costs include battery replacement, assumed every 8 years according to Klebsch et al. [16]. Infrastructure charges and CO_{2eq} external costs were calculated using the same inputs as for EMU.

Table 2. Social costs – EMU.

Cost item	Infrastructure		EMU				Total social costs
	Invest-ment	Opera-ting	Invest-ment	Traction energy	Infrastructure fees	CO_{2e}	
Thousand €	2 276.22	61.30	314.67	160.04	160.04	63.78	2 924.89

Source: Authors by [16, 24, 25, 26, 29]

Table 3. Input Data – BEMU.

Item	Value	Unit
Investment costs of island electrification	5	mil. €
Island electrification lifespan	40	years
Capital cost per BEMU	6.72	mil. €
Number of BEMU	2	
BEMU lifespan	30	years
Annual transport performance (ATP)	346. 408	thousand train km
	40 707.213	thousand gross tone-km
ATP - island electrification	1 354. 769	thousand gross tone-km
Average cost of traction energy	0.65	€/train km
Average traction energy consumption	5.74	kWh/train km
Annual incremental maintenance costs	34 640.75	€
Traction battery replacement costs	1 300	€/kWh

Source: Authors by [16, 24, 25, 26, 29]

The investment costs for electrification of the line are higher than the total social costs of using BEMU (Table 4). From the above, it can be concluded that on a given line with its current technical parameters and conditions, the use of BEMU is clearly a more efficient solution, even assuming that the line would be used more by passenger rail transport. Reaching the zero point (when the social costs of EMU would be equal to the social costs of BEMU) is technically impossible.

Table 4. Social costs – BEMU.

Cost item	Thousand €
Infrastructure	
Investment costs	125.00
Operating costs	2.17

(*continued*)

Table 4. (*continued*)

Cost item	Thousand €
BEMU	
Investment costs	447.69
Traction energy costs	225.16
Annual incremental maintenance costs	34,64075
Infrastructure fees	51.94
Traction battery replacement costs	331.50
External costs	
CO_{2eq} emissions	77.56
Total social costs	1 295.66

5 Conclusion

Decision-making processes in the field of decarbonization of transport are difficult and are often carried out on the basis of modeled data. Our research confirmed the findings of some other studies that for transport over shorter distances and at lower traffic intensity, the use of BEMU is more advantageous than electrification of the railway line. However, our study is limited by the fact that we did not take into account rail freight transport, given that the performance of rail freight transport on a given line is negligible. Similarly, research in the field of the use of alternative energy sources in rail transport is predominantly oriented towards rail passenger transport. In the future, we therefore want to focus our research on rail freight transport, not only from the perspective of quantifying social costs, but also from the perspective of rail freight carriers.

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References

1. SE EUCL: Homepage. https://www.seas.sk/en/press-releases/slovenske-elektrarne-is-the-europes-climate-leader-as-the-only-slovak-company/. Accessed 21 Sept 2025
2. da Fonseca-Soares, D.E., Sayonara, A., Galvincio, J.D., Ramos-Ridao, A.F.: Greenhouse gas emissions in railways: systematic review of research Progress. Buildings. **14**(2), 539 (2024). https://doi.org/10.3390/buildings14020539
3. ISO 14040:2006: Environmental Management - Life Cycle Assessment - Principles and Framework, 2nd edn. American National Standards Institute (2010)
4. ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines, 1st edn. American National Standards Institute (2006)

5. Olugbenga, O., Kalyviotis, N., Saxe, S.: Embodied emissions in rail infrastructure: a critical literature review. Environ. Res. Lett. **14**(21), 123002 (2019). https://doi.org/10.1088/1748-9326/ab442f
6. Merchan, A.L., Belboom, S., Léonard, A.: Life cycle assessment of rail freight transport in Belgium. Clean Techn. Environ. Policy. **22**, 1109–1131 (2020). https://doi.org/10.1007/s10098-020-01853-8
7. Jones, H., Moura, F., Domingos, T.: Life cycle assessment of high-speed rail: a case study in Portugal. Int. J. Life Cycle Assess. **22**(3), 410–422 (2016). https://doi.org/10.1007/s11367-016-1177-7
8. Noori, M., Kucukvar, M., Tatari, O.: Economic input-output based sustainability analysis of onshore and offshore wind energy systems. Green Energy. **12**, 939–948 (2015). https://doi.org/10.1080/15435075.2014.890103
9. Matthews, H.S., Hendrickson, C.T., Matthews, D.H.: Life cycle assessment: quantitative approaches for decisions that matter, Homepage. https://www.researchgate.net/publication/311192082_Life_Cycle_Assessment_Quantitative_Approaches_for_Decisions_that_Matter. Accessed 15 Jan 2026
10. Fridell, E., Bäckström, S., Stripple, H.: Considering infrastructure when calculating emissions for freight transportation. Transp. Res. Part D Transp. Environ. **69**, 346–363 (2019). https://doi.org/10.1016/j.trd.2019.02.013
11. Jiang, C., Yulai, W., Hangjun, Y., Zhang, A.: Impacts of high-speed rail projects on CO_2 emissions due to modal interactions: a review. Transp. Res. Part D Transp. Environ. **100**, 103081 (2021). https://doi.org/10.1016/j.trd.2021.103081
12. de Bortoli, A., Bouhaya, L., Féraille, A.: A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France. Int. J. Life Cycle Assess. **25**, 814–830 (2020). https://doi.org/10.1007/s11367-019-01727-2
13. Fedele, E., Iannuzzi, D., Del Pizzo, A.: Onboard energy storage in rail transport: review of real applications and techno-economic assessments. IET Electr. Syst. Transp. **11**(4), 279–309 (2021). https://doi.org/10.1049/els2.12026
14. Boev, P., Zimmermann, U., Ebrecht, B., von Mach, S.: First passenger operation of a state-of-the-art Battery-Electric Multiple Unit (BEMU) in Germany. Transp. Res. Procedia. **72**, 2510–2517 (2023). https://doi.org/10.1016/j.trpro.2023.11.757
15. Streuling, C., Pagenkopf, J., Schenker, M., Lakeit, K.: Techno-economic assessment of battery electric trains and recharging infrastructure alternatives integrating adjacent renewable energy sources. Sustainability. **13**(15), 8234 (2021). https://doi.org/10.3390/su13158234
16. Klebsch, W., Guckes, N., Heininger, P.: Bewertung klimaneutraler Alternativen zu Dieseltriebzügen: Wirtschaftlichkeitsbetrachtungen am Praxis-Beispiel Netz Düren. VDE Neue Technologien und Services, Frankfurt am Main (2020)
17. Ding, D., Wu, X.Y.: Hydrogen fuel cell electric trains: technologies, current status, and future. Technologies, current status, and future. Appl. Energ. Combust. Sci. **17**, 100255 (2024). https://doi.org/10.1016/j.jaecs.2024.100255
18. Sun, Y., Anwar, M., Hassan, N.M.S., Spiryagin, M., Cole, C.: A review of hydrogen technologies and engineering solutions for railway vehicle design and operations. Rail. Eng. Sci. **29**, 212–232 (2021). https://doi.org/10.1007/s40534-021-00257-8
19. Hermesmann, M., Müller, T.E.: Green, turquoise, blue, or Grey? Environmentally friendly hydrogen production in transforming energy systems. Prog. Energy Combust. Sci. **90**, 100996 (2022). https://doi.org/10.1016/j.pecs.2022.100996
20. Kapetanović, M., Núñez, A., van Oort, N.: Goverde RMP.: Analysis of hydrogen-powered propulsion system alternatives for diesel-electric regional trains. J. Rail Transp. Plan. Manag. **23**, 100338 (2022). https://doi.org/10.1016/j.jrtpm.2022.100338

21. Marjani, S.R., Motaman, S., Varasteh, H., Yang, Z., Clementson, J.: Assessing hydrogen as an alternative fuel for rail transport – a case study. Sci. Rep. **15**, 6449 (2025). https://doi.org/10.1038/s41598-025-90887-3
22. Jiang, K., Tian, Z., Wen, T., Hillmansen, S., Zhang, Y.: Cost modelling-based route applicability analysis of United Kingdom passenger railway decarbonization options. Int. J. Electr. Power Energy Syst. **160**, 110094 (2024). https://doi.org/10.1016/j.ijepes.2024.110094
23. Zhang, W., Li, Y., Li, H., Liu, S., Zhang, J., Kong, Y.: Systematic review of life cycle assessments on carbon emissions in the transportation system. Environ. Impact Assess. Rev. **109**, 107618 (2024). https://doi.org/10.1016/j.eiar.2024.107618
24. Methodology for the IEP personal carbon footprint calculator. Homepage. https://minzp.sk/files/iep/metodika_uhlikova_stopa.pdf. Accessed 16 Aug 2025
25. Methodological guide to creating cost-benefit analyses (CBA). Homepage. https://www.mindop.sk/transparentnost/rezortne-metodiky/metodika-pre-vypracovanie-cba. Accessed 18 Aug 2025
26. Internal material of Rail Infrastructure manager in the SR. Electrification costs (2025)
27. Modernization of lines. Feasibility studies. Homepage. https://www.zsr.sk/modernizacia-trati/studie-realizovatelnosti/. Accessed 7 Sept 2025
28. Measure No. 2/2018: Transport Authority of the SR. Homepage. https://nsat.sk/wp-content/uploads/2014/07/Opatrenie-2_2018.pdf. Accessed 19 May 2026
29. Framework agreement for the supply of BEMU140 vehicles. Homepage. https://tenderarena.cz/dodavatel/seznam-profilu-zadavatelu/detail/Z0003016/zakazka/ 576858. Accessed 23 June 2025

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Applying AI to Road Infrastructure Monitoring and Management: A Vision for Predictive Maintenance and Safety Management

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Abstract. This paper explores the integration of Artificial Intelligence (AI) across the road infrastructure lifecycle, highlighting state-of-the-art technologies and real-world applications. It examines the use of predictive modelling, digital twins, and knowledge graphs in planning; computer vision and deep learning for defect detection during construction; and edge computing, federated learning, and multi-agent reinforcement learning for adaptive traffic management. In maintenance, AI-driven inspections using drones, LiDAR, and vision transformers enable predictive upkeep. Novel approaches such as neuro-symbolic AI, explainable AI (e.g., SHAP, LIME), and two-stage knowledge frameworks enhance transparency and context-awareness. Considering regulatory frameworks (like GDPR, EU AI Act), organisational challenges, and best practices for implementation such as embedded influence into governance and infrastructure strategies can significantly improve resilience, safety, and efficiency in transport systems. The paper proposes such a complete AI system for European road networks (both primary and secondary roads) today, considering the real-world management of infrastructure in the EU today, identifying the gaps. The paper argues that overcoming these challenges requires a holistic framework that integrates technological innovation with robust regulatory compliance and societal engagement and concludes by proposing a strategic pathway for EU-wide adoption.

Keywords: Artificial Intelligence · Road Management · ITS Roads

1 Introduction

Road transport systems are undergoing a transition as they face increasing mobility demand alongside environmental and climate targets [1]. AI adoption is hindered by technical and non-technical barriers, including ethical constraints, sensitive data collection, and the need for privacy-by-design policies. This paper addresses the lack of a holistic EU-wide framework for embedding AI solutions across the entire transport infrastructure lifecycle from planning to renewal. The main objectives are:

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1. Analyse the AI applications and present emerging technologies across the lifecycle of road infrastructure;
2. Propose recommendations and a multidisciplinary approach successful AI adoption across the road network;
3. Present real cases from three European cities to showcase how the adoption of AI tools has enhanced the transport infrastructure sector as best practice examples.

Although a significant body of literature examines individual AI applications in transport, a critical gap remains: the absence of a holistic, lifecycle-spanning framework that integrates technological potential with regulatory compliance, ethical governance, and societal acceptance. This paper goes beyond a descriptive review of technologies. Its primary contribution is a synthesised vision and integrated recommendations that argue for a synergistic approach. It propose that successful embedding of AI in European road networks requires concurrent progress along four independent pillars: technology, regulation, organisational capacity, and social license. By examining the entire value chain - from planning to upgrades - through this multidisciplinary lens, the paper offers a strategic guide for policymakers, infrastructure managers, and technology providers, aiming to avoid siloed and hard-to-sustain AI deployments.

2 Methodology

The paper adopts a qualitative research design to ensure a provide an in-depth analysis of state-of-the-art AI developments across the transport infrastructure lifecycle: i) review and analysis of research publications, databases, reports, ii) three EU case studies and the full lifecycle (planning, construction, operations, maintenance, upgrades). The methodology is based on the following three components:

1. Lifecycle mapping: Presenting AI applications across the five phases of the road transport lifecycle;
2. Analysis of real-world pilots: Presenting the examples of Dortmund (Germany), Porto (Portugal), and Tallinn (Estonia), three cities that participate in the EU Mission for Climate-Neutral and Smart Cities that have implemented AI solutions;
3. Regulatory framing: Highlighting ethical constrains and analysing the GDPR and EU AI Act.

2.1 Regulatory Framing: GDPR and EU AI Act

Several studies examine how AI is regulated under the GDPR and the extent to which automated decisions are admissible, with emphasis on data protection by design and by default. The use of AI in transport infrastructure raises ethical questions because underlying algorithms rely heavily on data. Surveys indicate that Autonomous Vehicles (AVs) collect data from cameras, sensors, radar, Light Detection and Ranging (LiDAR), and Global Positioning System (GPS). GDPR applies to AI systems that capture and process personal data (e.g., license plates, GPS traces), requiring privacy-by-design, purpose limitation and minimisation data collection. In the road infrastructure sector, more advanced automation techniques for data collection are needed to improve data

quality, while anonymisation should be applied wherever possible to enhance transparency. In parallel, the AI Act (2024/1689) [2] establishes clear risk-based rules for AI applications, classifying transport infrastructure as a high-risk domain subject to strict obligations, including technical robustness, human oversight, and traceable documentation before market deployment [3]. This paper highlights three principles that support the deployment of AI technologies while respecting citizens' rights and resilience in Europe:

- **Interoperability:** Use of AI technologies such as Shapley Additive Explanations (SHAP) and Local Interpretable Model-agnostic Explanations (LIME) to make decision-making process understandable to engineers, policymakers, and the society;
- **Public trust and acceptance:** Fostering public acceptance through lawful and transparent systems;
- **Resilience:** Developing trust and adaptive transport systems able to withstand and recover from disruption.

3 Findings and Analysis

3.1 Planning and Design Phase

In the planning and design phase, the use of AI supports decision-making through predictive modelling and simulation. Geographic Information System (GIS) and data analysis can forecast demand, traffic growth, and congestion, informing lane capacity and junction design. Computer-based tools also support environmental modelling by simulating environmental impacts and assessing the sustainability of planned transport strategies. Digital twins further improve traffic flow by enabling "what if" scenarios that virtually replicate transport networks under conditions ranging from high-volume traffic to natural disasters [4]. Together, these tools lay the groundwork for a resilient and adaptable network, but they depend on harmonised data standards and sufficient technical capacity across administrations.

3.2 Construction Phase

Current AI developments are reshaping construction through automation, monitoring, and quality control. Deep learning and computer vision approaches enhance safety by detecting unsafe behaviour and non-compliance with standards and regulations. Unmanned Aerial Vehicles (UAVs), combined with image recognition, can accurately assess pavement conditions using indices such as the Pavement Condition Index .

3.3 Operation and Traffic Management Phase

In the operation and traffic management phase, AI plays a central role by using adaptive and decentralised management (Fig. 1) and (Table 1 and 2):

Table 1. Advantages of AI-activated technologies.

Technology	Advantage
Computer vision	Detect traffic conflicts, accidents & other incidents in real-time, faster emergency response.
Edge computing	Improved speed, accuracy & efficiency of fault detection, handling complex, multi-fault scenarios in critical areas [4]
Multi-agent solutions	Coordinate distributed AI-driven agents, improve speed & accuracy of fault detection in complex, multi-fault situations [5]
Reinforcement learning	Deep reinforcement learning using state and temporal abstraction to optimise signal timing and response strategies [6]
Federated learning	Enables multiple devices or entities to collaboratively train models while keeping data local, helping to protect sensitive data [7]

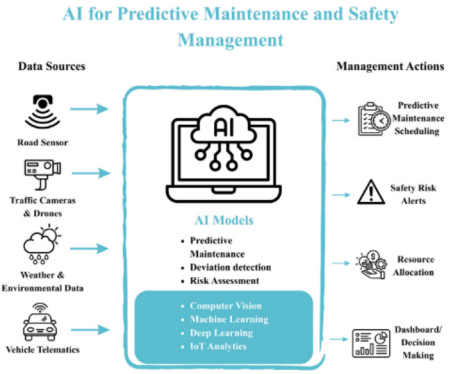


Fig. 1. AI for Predictive Road Maintenance and Safety Management.

3.4 Maintenance Phase

AI tools enhance predictive maintenance by forecasting infrastructure degradation using traffic, climate, and sensor data. Automated inspections using drones, LiDAR, and robotic inspections can detect defects and replace human inspections in hard-to-access areas. The use of 360° cameras allows full-direction image capture and richer quantitative data. The accuracy of human defect ratings in remote settings remain underexplored [8].

Table 2. Advantages of digital inspection vs. visual inspection of pavement conditions [9].

Aspect	Digital inspection	Visual inspection
Objectivity	Homogenised criteria, free from human bias	Subjective depends on human perception
Precision and detail	High resolution in defect identification, even micro-cracks	Limited capacity to detect small or early-stage defects
Speed and efficiency	Fast inspection, performed on the move at normal speed	Requires more time and slower movement
Linked information and tracking	Automatic recording of images, coordinates and data	Requires manual recording, increasing the likelihood of errors
Personal safety	Allows inspections without leaving the vehicle	Requires direct contact with motorised traffic, involving associated risks
Coverage and frequency	Enables frequent or even continuous monitoring	Isolated inspections, less frequent due to cost and logistics

3.5 Upgrading Phase

A critical gap persists in understanding how AI can enhance resilience and absorbing change and disturbance while preserving key interdependencies and state variables [10]. Road infrastructure networks require continuous improvement, typically involving large investments. AI can support lifecycle cost analysis and project the financial and operational impacts of different upgrade paths. Emerging approaches, such as neuro-symbolic AI that combines symbolic reasoning with deep learning, and explainable AI (XAI) that provides human-understandable explanations for model outputs, can clarify why certain signals or control strategies are adjusted, thereby increasing public trust. Simulation tools also help explore how infrastructure can be adapted to autonomous vehicles, improving long-term readiness.

4 Real-World Applications

Three European cities participating in the EU Mission for Climate-Neutral and Smart Cities were analysed. They differ in size and population, yet their AI deployments promote efficiency, sustainability, and climate-neutral measures.

Dortmund, Germany: This climate-neutral city has implemented numerous AI-powered projects, including digital twins and 3D mapping across 15,000 km in the Ruhr area. These initiatives have improved traffic flow, reduced congestion, and supported more effective planning.

Porto, Portugal: Portugal's second largest city has integrated AI for traffic prediction and environmental monitoring, resulting in improved mobility management, better-informed policy decisions, and rapid actions towards carbon neutrality.
Tallinn, Estonia: The Estonian capital is piloting AI-powered camera systems mounted behind the windshields of two transit buses to detect parking violations in bus lanes and at bus stops. The measure has led to better compliance and increased reliability of public transport services [11].

5 Current Challenges and Best Practices

The barriers of integrating AI technologies into the road infrastructure lifecycle are not only technical but also organisational, financial, and societal. Recognising these challenges is crucial for developing effective strategies to embed AI in transport and road infrastructure.

5.1 Technical Challenges

AI systems depend on an ecosystem of sensors, inductive loops, LiDAR, cameras, and related devices that require regular calibration and frequent maintenance. AI models are also vulnerable to data drift, where changes in traffic flow or road surfaces degrade performance. This underlines that AI systems are not 'set-and-forget' solutions but require continuous data governance and monitoring, linking technical reliability to long-term organisational strategy.

5.2 Organisational Challenges

The rapid pace of technological change and the push for a human-centric approach to AI make AI literacy increasingly important. The 2024 Digital Economy and Social Index (DESI) shows that 45% of EU citizens aged 16–74 lack basic digital skills, let alone AI-related competences This skill gap constraints the capacity of organisations to deploy, manage and oversee AI systems effectively [12].

5.3 Financial Challenges

Deploying AI solutions in the transport sector involves significant capital expenditure on software, hardware, and training. These costs can be substantial for organisations, while the Return On Investment (ROI) often materialises only in the long term. Large cities and municipalities are more able to absorb such costs, whereas smaller cities may struggle to finance deployment and maintenance [3].

5.4 Societal Challenges

Proactive communication and meaningful citizen participation are essential. Citizens can identify everyday priorities that technically sound solutions may overlook. Without transparency and engagement, technical solutions may lack legitimacy and therefore face resistance from the public [13].

6 Best Practices

AI clearly plays a growing role in transport infrastructure and in transport systems more broadly. Combined with other emerging technologies, AI solutions can unlock more efficient, smart, and advanced transport infrastructures. In response to the challenges outlined above, several best practices emerge for responsible AI adoption: i) phased rollouts (reduces risk, allows the workforce to adapt, supports practical testing and facilitating iterative adjustments [14]), ii) transparent procurement (prioritises interoperability, fosters innovation, reduces or eliminates risks [15]), iii) integration into governance strategies (not as add-ons**,** alignment with key EU objectives such as the Green Deal, Vision Zero, and the EU Digital Strategy), iv) citizen participation (builds trust, inclusivity and societal acceptance through participatory tools [13]).

7 Discussion

AI in road infrastructure contributes to three systemic functions: prediction (anticipating demand and degradation), adaptation (adjusting operations), and explanation (transparent decisions). These benefits depend on overcoming fragmentation not only in technology but also in governance and skills. AI offers substantial advantages for road transport infrastructure; however, adoption remains uneven, as urban centres and metropolitan areas can support advanced pilots, while secondary and rural roads often lag in digitalisation and investment [3]. EU-level strategies that promote harmonised standards, shared platforms, and continuous upskilling and therefore increasingly important. Moreover, all AI-related developments should align with EU priorities for a greener, more sustainable, and more competitive transport sector built on trust, interoperability, and robustness.

8 Conclusion

AI is reshaping European road infrastructure across its entire lifecycle, from predictive planning to adaptive traffic management and lifecycle renewal. It acts as a transversal enabler of resilience, safety, and efficiency across the transport system and should be treated as an integrated component of the sector rather than a temporary add-on. The primary contribution of this paper has been to move beyond isolated technological reviews and to present a synthesised, holistic vision for AI adoption. This vision frames AI as an integrated governance enabler whose success depends on the simultaneous advancement of four pillars: 1) Technology, 2) Regulatory Compliance, 3) Workforce Upskilling, and 4) Societal Engagement. Aligning these pillars allows the EU to develop road networks that are predictive, secure, transparent, and inclusive. The results show that this integrated approach is essential for building transport infrastructure systems that are more predictive, secure, and adaptable for all citizens. Future Research, development, and innovation policies should therefore elevate AI from a sub-topic of digitalisation to a strategic pillar that jointly addresses decarbonisation goals, physical infrastructure, governance, and participation [13].

References

1. European Environment Agency Homepage: https://www.eea.europa.eu/en/europe-environment-2025/thematic-briefings/climate-change/trends-in-the-mobility-system. Accessed 5 Nov 2025
2. Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Artificial Intelligence Act) (Text with EEA relevance) (PE/24/2024/REV/1). In: Official Journal of the European Union (L 2024/1689) (2024).
3. European Commission Homepage: https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai. Accessed 5 Nov 2025
4. Batty, M.: Digital twins. Environ. Plan. B Urban Anal. City Sci. **45**(5), 817–820 (2018)
5. Feng, J., Yu, T., Kuozhen, Z., Lefeng, C.: Integration of multi-agent systems and artificial intelligence in self-healing Subway power supply systems: advancements in fault diagnosis, isolation, and recovery. Processes. **13**(4), 1144 (2025)
6. Hamida, Z., James, G.A.: Hierarchical reinforcement learning for transportation infrastructure maintenance planning. Reliab. Eng. Syst. Saf. **235** (2023)
7. Siniosoglou, I. et al.: Shaping the Future of IoT with Edge Intelligence: How Edge Computing Enables the Next Generation of IoT Applications, 1st edn. River Publishers, New York (2024)
8. Nepomuceno, D., Vardanega, P., Tryfonas, T., Pregnolato, M., Bennetts, J., Webb, G.: Bridge safety, maintenance, management, life-cycle. In: Resilience and Sustainability, 1st edn, pp. 846–854. CRC Press, Boca Raton (2022)
9. De la Peña, E.: AI-powered road maintenance inspections. Safer & Greener Transport Infrastructures in the context of AI & big Data developments. In: Smart Transportation Alliance Conference & Innovation Awards 2025 Proceedings (2025)
10. Vega, G., Hadjidemetriou, G.M.: On artificial intelligence applications for resilient transport infrastructure. In: 2025 European Conference on Computing in Construction Proceedings (2025)
11. Tallinn City Homepage: https://www.tallinn.ee/en/business/news/tallinn-pilots-ai-increase-road-safety-and-efficiency. Accessed 5 Nov 2025
12. Eurostat Homepage: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Skills_for_the_digital_age. Accessed 5 Nov 2025
13. Bartolomé, C., De la Peña, E., Alfonso Kurano, J., Papí Ferrando, J.F., Kühl, F.L., Koliou, E.: Priorities and Recommendations for Research, Development and Innovation in European Transport Infrastructures (2025)
14. Safapour, E., Kermanshachi, S., Jafari, A.: Investigating implementation level of phase-based strategies in transportation infra-structure projects. Can. J. Civ. Eng. **49**(5) (2021)
15. International Transport Forum: AI for Transport Authorities: Principles and Practical Guidance. OECD Publishing, Paris (2025)

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Regional Rail Rolling Stock for the FutuRe

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Abstract. Regional railway lines with lower usage need to be renewed to make them economically and environmentally sustainable, and this is the aim of FutuRe – a project supported by the Europe's Rail Joint Undertaking. Research is being conducted in several areas, such as traffic management, train positioning, automatic train control, wayside assets, multimodal travel and the vehicle itself, with the propulsion system and running gear being key research areas.

FutuRe proposes that this regional train should have a lightweight body, possibly with sections made of composite, and two single-axle running gears with active wheelset steering for improved curving performance. It is further proposed that train should be battery-powered and that the braking energy should be fully recovered into the battery. A control command and signalling concept dedicated to regional lines without the need to be interoperable with mainlines is being developed, enabling full automation (GoA4 –driverless, no train crew onboard). The concept matches the European initiatives in satellite communications and federated data spaces.

FutuRe's Key Performance Indicators show that the proposed vehicle will have lower energy consumption, generate less noise, require less maintenance and reduce the need for operational personnel compared to the regional trains that the market offers today.

Keywords: Regional railway · Rolling stock · Lightweight design · Battery powered · Automatic train operation

1 Introduction

Regional railway lines are vital for connecting rural areas and supporting the main rail network. However, many have been abandoned in recent decades due to high operational and maintenance costs. With changing mobility needs, several countries, particularly Germany and France, are now reconsidering the revitalization of these routes [1].

Given the typically low passenger volumes on rural lines, financial pressures are considerable. Avoiding costly infrastructure upgrades, such as overhead electrification, is therefore essential. A sustainable, cost-effective strategy for both rolling stock and infrastructure is required. Addressing these challenges is the focus of FutuRe, Flagship Project 6 (FP6) of Europe's Rail Joint Undertaking.

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FutuRe has produced a state-of-the-art report on small regional trains [2]. Current vehicles are mostly based on modular multiple-unit families. The smallest sustainable options for non-electrified branch lines are often two-car units, approximately 42–45 m long, with Jacobs bogies and around 120 seats for example, Siemens' Mireo Plus B and the Stadler Flirt Akku. From 2024, Stadler is also offering a single-car, two-bogie version powered by battery or hydrogen [3].

Innovative initiatives have developed even smaller zero-emission vehicles, such as TELLi in France and the Aachen Rail Shuttle in Germany [2, 4].

To keep regional railways economically viable, socially beneficial, and environmentally sustainable while meeting modern mobility demands, it is crucial to identify suitable vehicle concepts, propulsion technologies, and signalling systems. This paper presents the status of FutuRe developments and evaluates them against key performance indicators: energy consumption, exterior noise, and maintenance and personnel costs compared with existing regional trains.

2 Lightweight Body

Building a vehicle with low energy consumption, low acquisition and maintenance costs, and high sustainability requires trade-offs, especially for structural components like the car body and running gear frames. Materials must offer high mass-specific strength for lightweight construction, be easy to source and process, affordable, sustainable, and simple to dispose of. Manufacturing methods must be fast, scalable, low in energy use and CO_2 emissions, reliable, and produce minimal waste. Components must be easy to manufacture, assemble, maintain, and repair, while remaining durable and lightweight. Many of these requirements conflict, some materials enable lighter designs but are more expensive or require complex production, and developing durable lightweight components increases development time and cost.

To balance these factors, the FutuRe vehicle's car body development considers two construction methods to better address this complex challenge.

The first approach aims to minimize manufacturing and end-of-life cost and environmental impact. It uses welded steel frame structures for the load-carrying elements. With topology optimization guiding material distribution, this method still offers strong lightweight potential while relying on common, inexpensive manufacturing processes and an easily sourced, sustainable material [5].

The second focuses on maximizing weight reduction through a composite sandwich structure for the vehicle body. This design promises greater mass savings but requires more expensive materials, more complex production, and more challenging disposal. It also enables functional integration, such as noise and thermal insulation, which can further reduce weight. Lower mass reduces operational energy consumption and CO_2 emissions, potentially offsetting the higher manufacturing impact, since most of a train's environmental footprint occurs during its operational life [6].

To decide on the best solution, two car body structures using the two construction methods are developed in parallel. The complete designs are then analysed with respect to their overall cost and environmental impact over their whole product life.

In addition to those construction methods, a combination of both is also considered. The steel design is well suited for highly, localized load introduction, as occurs in the

running gear interfaces and at the vehicle front during crash. Sandwich structures excel at providing high stiffness on bigger surfaces while having low mass. A hybrid structure could potentially combine both construction methods in a multi material design approach where each material is used in the area where it can best utilize its advantages. Highly loaded areas like the running gear and crash absorber interfaces can be realized with a strong steel frame while the more uniform and lightly loaded middle sections can be realized with the lighter composite structures. For this, a reliable and easy to realize connection method has to be found to keep costs low. Also, this combination of materials requires a more complex manufacturing process and disposal tends to be more difficult. Further analysis is necessary to examine, whether the increased effort is offset by lower weight. A possible design for such a hybrid structure is shown in Fig. 1. It has topology optimized welded steel frames at the car ends and a sandwich structure in the middle.

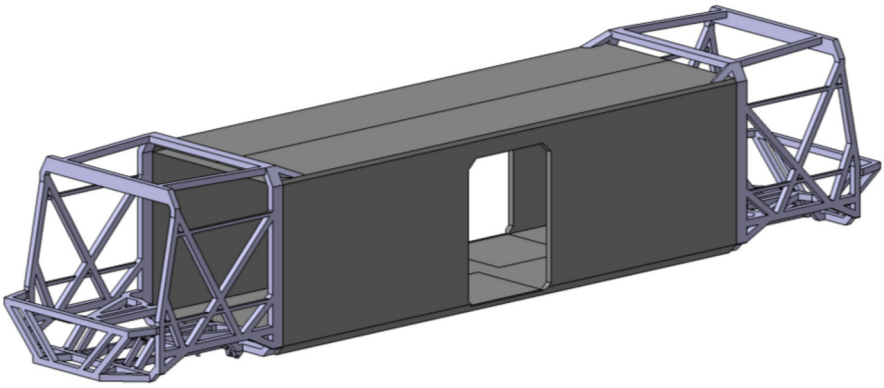


Fig. 1. Hybrid carbody structure, centre part in composite and ends in topology optimized steel.

3 Single-Axle Running Gear

Single-axle running gears have been used in rail vehicles since the first days of railway operation. They have primarily been applied in freight transport, where acquisition cost has typically outweighed performance requirements. These running gears are simple, lightweight, compact, and cost-effective compared to conventional bogies. For small regional vehicles, single-axle running gears enable the incorporation of a large low-floor area, making level boarding possible. Two different running gear concepts are developed and investigated, one with independently rotating wheels enabling the low floor section to extend throughout the entire vehicle, and one conventional wheelset design with an axle between the wheels. Single-axle running gear typically suffers from poor ride comfort and curving performance. In the concept with independently rotating wheels Fig. 2, a two-stage suspension improves the ride comfort, while curving is enhanced by individually controlling the traction motors to steer the wheels within the track channel. In the axle-based concept, both deficiencies are addressed via electrodynamic active control, as also proposed in Shift2Rail's Run2Rail project [7, 8]. It also enables a vehicle design without compressed air, using a simple coil spring for passive suspension.

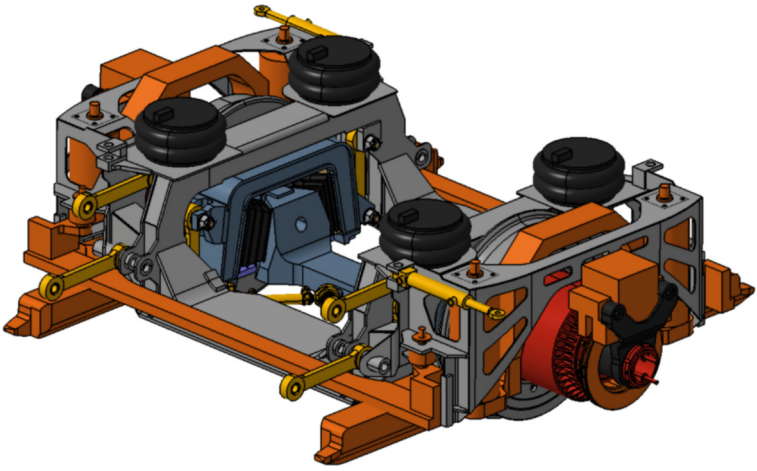


Fig. 2. Running gear with independently driven rotating wheels.

4 Battery Propulsion

Most low-density rail lines are not electrified, and since zero emissions at the vehicle level is a prerequisite, batteries have become the preferred energy storage solution. However, depending on the intended service, the distance between available charging opportunities can pose a challenge. Today's battery-powered trains typically have a shorter range between charges compared to battery-electric road buses. This is partly due to the higher operating speeds of rail vehicles, which lead to greater running resistance, and partly due to their significantly higher weight. Advancements in battery technology are essential for enhancing the performance, range, and sustainability of electric rail vehicles, developments that are largely being driven by the rapid progress in the electric road vehicle sector, [2, 9].

Adopting solutions from road vehicles has the potential to significantly reduce the weight and cost of the propulsion system. The planned propulsion power of 2 x 195 kW in the developed vehicle with conventional running gears is comparable to that of electric road buses, making the rail vehicle market attractive to suppliers from the road transport sector. In addition to the battery, the main components of the propulsion system are the inverters and traction motors, which could also be sourced from road vehicle suppliers. One key requirement is that all kinetic energy must be fully recovered to the battery during braking (emergency braking excluded). While this reduces the energy consumption and maintenance costs, but it results in high charging power levels, which can potentially reduce the battery's lifespan.

The maximum allowed axle load and available space for equipment limits the size of the battery package and thereby the possible distance between charging stations. Range extension can be achieved using hydrogen, which provides a lighter form of storage for large amounts of energy. The stored hydrogen must be converted into electrical energy, either via fuel cells or through hydrogen combustion. As total weight and space are limited, the hydrogen tanks and associated conversion systems would replace part of

the battery system. However, producing hydrogen and converting it to electrical energy is less efficient than using electrical power directly. Therefore, this solution should be evaluated in relation to the alternative of installing additional charging stations.

5 Signalling Concept

The used and adapted Control-Command and Signalling (CCS) low density lines architecture in FutuRe is based on four main inter-related building blocks which can be decomposed from an Operational, Functional and System point of view as seen in Fig. 3 [10].

The building blocks are	
Traffic Management and Control Centre	Communication data network
On-board equipment	Wayside equipment

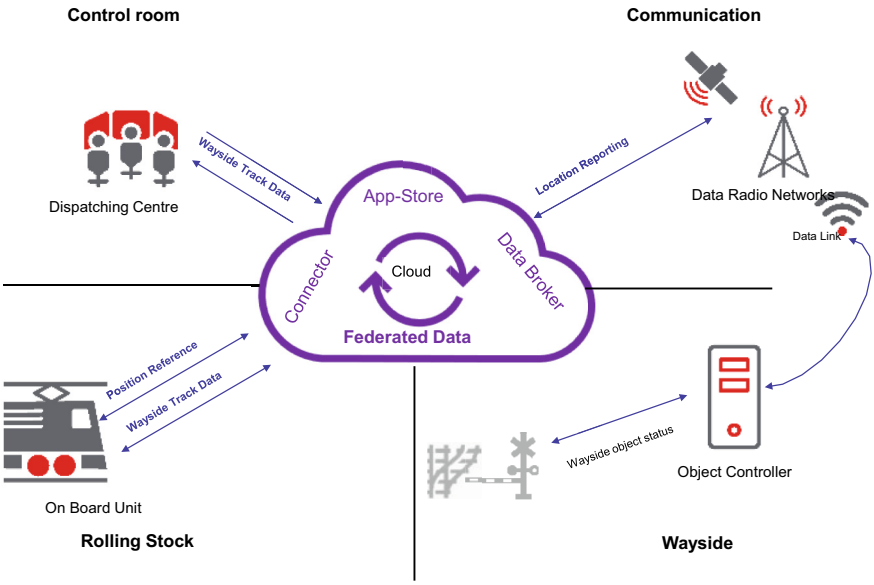


Fig. 3. Low density lines high level CCS architecture

On-board assembly of the CCS low density lines architecture uses the well-known concept of Communication Based Train Control (CBTC), with which positioning based on radio communication technologies can now be integrated. Modern train control solutions are generally radio based (such as various CBTC systems for automatic metros, railways using ERTMS Level 2 and Positive Train Control). Information among traffic control rooms, trains and wayside elements is exchanged wirelessly, using various

available communication means: public or private mobile networks and satellite communications. This approach allows optimisation of the data connectivity and utilisation of the EU based Federated Data Space while benefiting from the most performant and cost-efficient means.

In the proposed concept, radio and satellites provide train positioning data to the on-board unit (augmented for high precision, where required), which can use this to index an onboard digital track map (resulting from a standardized validation process), thus removing the need for wayside balises/transponders along the track. For safety reasons, to eliminate the need for high-cost track circuits and axle counters, the system requires the on-board unit to determine train length and train integrity.

Positioning technology performance is mature, currently to a precision of a few centimetres using satellites in conjunction with publicly available correction services. Soon, 6G & 7G will make localization cheaper and easier to implement (integrating cellular with satellite technology).

Such technologies will evolve more quickly than railway technology, and the CCS architecture must allow for this evolution, separately from the railway applications.

The CCS low density lines approach will enable the implementation of cost-effective, interoperable, fail-safe, highly accurate train positioning (including dead reckoning where required) based on data fusion of information from hybrid, multi sensor technologies, digital maps, onboard database.

This will not only increase operational efficiency and decrease Total Cost of Ownership in the context of regional lines, in addition, it will allow smooth adoption of higher grades of Automatic Train Operation (up to GoA 4), enabling driverless services on rural lines – a much-needed innovation that strengthens the competitiveness of regional rail.

6 Key Performance Indicators

The analysis compares four FutuRe-defined KPIs for resource efficiency between the proposed small regional vehicle and current market alternatives. The service plan assumes 16 daily trips in each direction, hourly from 6:00 to 21:00, with the smaller vehicle operating in multiple-unit formation for two morning and two afternoon peak services. The Swedish Gårdsjö–Håkantorp line (121 km, non-electrified) is used as an example. Its intermediate stops, gradients, and speed limits yield a simulated journey time of about 1 h 55 min including dwell times. The simulation accounts for system efficiency as a function of speed and power, as well as average auxiliary loads.

The energy consumption is simulated for peak and off-peak services as detailed in Table 1. The advantage of using smaller vehicles in off-peak are clear. The low weight and pure dynamic braking optimize the energy feedback to the battery. Furthermore, the FutuRe vehicle is designed for remote (automatic) driving, which optimizes the driving compared to what a driver can do, but this difference is not accounted for in the simulations. The average energy consumption reduction becomes 48%.

The remaining three KPIs focus on external noise emissions, maintenance costs, and personnel requirements. For a moving regional train, the primary source of external noise is the wheel-rail contact. Since the FutuRe vehicle has only two wheelsets compared to

Table 1. Simulated energy consumption

	Today's		FutuRe	
Service	Off-peak	Peak	Off-peak	Peak
Passengers per trip	20	60	20	2 x 30
Number of trips a day	28	4	28	4
Energy consumption per trip (kWh/km)	2.59	2.68	1.21	2.26

four on current vehicles, the sound energy is expected to be halved. This corresponds to a noise reduction of approximately 3 dB.

Put simply, maintenance costs for rail vehicles (and the infrastructure) are determined by the number of wheelsets multiplied by the kilometres travelled, assuming the axle load is about the same. Today's vehicles produce 32 trips * 121 km * 4 wheelsets = 15488 wheelset km a day, while the FutuRe vehicle produces 36 * 121 * 2 = 8712 wheelset km, corresponding to a reduction of 44%.

The smaller vehicle is assumed to be operated fully automatic (GoA4) with a remote train control as a backup option. This reduces the personnel demand significantly, as today a train driver in each vehicle is needed (Table 2).

Table 2. KPI summary

Property	Influence
Energy consumption	−48%
External noise emission	-3 dB
Maintenance	−44%
Personnel	−80%

7 Conclusion

The development of the regional vehicle introduces a new system design for low-density lines, combining modern approaches that improve competitiveness in rural areas by reducing vehicle CAPEX and OPEX, control-command equipment needs, and overall system maintenance. The vehicle targets non-electrified lines, using a lightweight car body and innovative running-gear concepts to enable a flat low-floor interior, ensuring seamless boarding and independent PRM access.

A battery-based power pack is central to the design, balancing capacity with required range. Energy management optimises overall consumption, including HVAC, and recovers braking energy. The vehicles will operate within a highly automated traffic management and train control framework, requiring minimal trackside infrastructure while meeting performance targets.

Despite progress, further development is needed within upcoming Europe's Rail Joint Undertaking projects. Physical demonstrators of key subsystems are planned for 2028, followed by full vehicle testing under future EU flagship initiatives.

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References

1. EU-Rail: FP6 FutuRe homepage. https://rail-research.europa.eu/rail-projects/fp6-future/. Accessed 5 Feb 2026
2. EU-Rail: FP6 FutuRe WP5, Deliverable D5.1: State-of-the-Art Report for Regional Lines Rolling Stock. https://rail-research.europa.eu/rail-projects/outputs/d5-1-state-of-the-art-report-for-regional-lines-rolling-stock/. Accessed 5 Feb 2026
3. Stadler: RS Zero: https://www.stadlerrail.com/en/solutions/rolling-stock/mainline-rs-zero. Accessed 30 Mar 2026
4. Schindler, C.: The Aachen rail shuttle ARS-autonomous and energy self-sufficient feeder transport. J. Rail Transp. Plan. Manag. **21**. https://doi.org/10.1016/j.jrtpm.2022.100299
5. König, J. Müller, T. Persson, R. Lochmann, L., Guicheney, P.: Small, Lightweight, Driverless Rail Vehicle for Rural Areas in Europe. IRSA 2025 Stuttgart Germany. https://publications.rwth-aachen.de/record/1024828. https://doi.org/10.18154/RWTH-2026-00357
6. Özdemir, A., Önder, A.: An environmental life cycle comparison of various sandwich composite panels for railway passenger vehicle applications. Environ. Sci. Pollut. Res. **27**, 45076–45094 (2020)
7. RUN2Rail: Innovative Running gear solutions for new dependable, sustainable, intelligent and comfortable rail vehicles. https://projects.shift2rail.org/s2r_ip1_n.aspx?p=s2r_RUN2RAIL. Accessed 5 Feb 2026
8. Persson, R., Wikaranadhi, P. & Stichel, S.: Resource efficient regional train facilitated by single-axle running gears. https://www.rev2025.org/?page_id=3549. Accessed 30 Mar 2026
9. Torkiharchegani, A., Alaküla, M.: Enhancing regional rail efficiency and reducing emissions with dual electric traction machine drivetrain. IEEE J. Magaz. IEEE Xplor. (2025). https://doi.org/10.1109/TVT.2025.3637539
10. Lochmann, L., Mascis, A., Burro, F.: CCS for low density lines. ASPECT. (2025) https://irse.org.au/event/aspect-2025-yokohama/

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A Harmonised Transport-Specific LCA Approach - Final Results of the CSA TranSensus LCA

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Abstract. Our road transport system is rapidly transforming in response to climate change and resulting demand for high sustainability over the full value chain and the full life cycle. New propulsion systems are achieving steadily increasing market shares, and new infrastructures and mobility concepts will be needed for connected and auto-mated vehicles, as well as to achieve the vision of smart and climate-neutral cities. To define realistic sustainability goals – for all stakeholders in the mobility sector – and to select the most sustainable solutions, the environmental, economic and social impact of technologies and mobility concepts must be assessed and continuously monitored in a holistic way.

Within this context, the CSA TranSensus LCA developed a baseline for a European-wide harmonised, commonly accepted and applied single cycle assessment (LCA) approach for a zero-emission road transport system. TranSensus LCA brought together relevant stakeholders from industry and research elaborating an evidence- and real-life data-based LCA approach embracing environmental and social aspects by consensus.

Keywords: Environmental & social LCA · environmental impact · road transport

1 Introduction

For the transformation of our transport system towards climate-neutrality, a reliable and comparable assessment of the environmental footprint of different solutions and technologies becomes essential. Although all stakeholders already recognise the importance

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of life cycle assessment, the transport sector is still struggling to adopt LCA approaches. As outlined in the 2Zero SRIA [1], standardised and comparable results are still lacking due to limitations in accessing and managing real-life data or applying non-harmonised, non-coherent methods, tools and system boundaries, to name some. Within this context, considering upcoming technologies leveraging emission reduction strategies, circular economy targets as well as social aspects poses significant challenges in making the best choice in terms of sustainability as an integral part of product development and mobility solutions.

As such, the CSA TranSensus LCA [2] aimed to develop a baseline for a European-wide harmonised, commonly accepted and applied single life cycle assessment (LCA) approach for a zero-emission road transport system. A European single LCA approach is seen as a key element in achieving the Green Deal targets, making Europe the first digitally enabled circular, climate-neutral and sustainable economy. Bringing together relevant stakeholders, an evidence- and real-life data-based LCA approach has been conceptualised and harmonised embracing environmental and social aspects.

TranSensus LCA moderated the consensus-building process for a European-wide single LCA approach with all relevant stakeholders. This was done through a consensus building approach, which engaged the consortium, associated partners, defined scientific and industry advisory boards as well as the wider stakeholder community including the European Commission and member states. The conceptual framework for such a transport-specific LCA was developed by uptaking and refining the known SotA based on a Needs & Gaps analysis, by building on relevant past and ongoing activities. These insights were merged into one consistent approach considering environmental and social aspects. Where open gaps were identified, recommendations and processes have been derived to remove them. Furthermore, key elements for implementing a single LCA approach and framework at the European level have been described and tested. As such, TranSensus LCA was not researching new methodologies or tools, nor developing new datasets, but provided the needed framework to implement and conduct a consistent and comparable assessment of the environmental footprint over the lifetime.

2 Analysis of the SotA, Needs and Gaps

2.1 State of the Art

Life Cycle Assessment (LCA) is a key method for evaluating environmental impacts of products and services and is essential for advancing fossil-free transport in Europe. However, inconsistent methodological choices across studies—such as system boundaries, modelling approaches, or functional units—often lead to non-comparable results, limiting LCA's usefulness. To strengthen LCA's role, harmonization is needed across all phases, including clear reporting, uncertainty analysis, independent verification, and systematic scenario modelling.

A review of academic, industrial, and policy sources highlighted the following [3]:

- Transparency is often lacking mixing principles or omitting the modelling approach.
- The choice of functional unit (FU) is a major challenge. For batteries, lifetime energy delivered (kWh) is most meaningful, while mass-based units are inadequate. For vehicles, distance-based FUs (e.g., passenger*km) dominate.

- Data availability is another bottleneck, particularly for raw materials and end-of-life stages.
- Secondary data remain essential but vary in quality and assumptions, influencing results.
- Multifunctionality in recycling, co-production, and battery second life also lacks consistent treatment.
- Electricity modelling is highly variable, with most studies relying on static mixes and ignoring projected changes in energy systems.
- Climate change is often the sole impact category assessed, raising the risk of burden shifting.

2.2 Needs and Gaps

The study [4] identified the key needs, gaps, and prescriptions for the development of the TranSensus LCA method to ensure consistency, credibility, and usefulness. The method must be understandable, standardized, accurate, auditable, widely accepted, and trustworthy. Lower priority but still important requirements include alignment with EU legislation and international standards, simplicity without loss of rigor, and transparency while balancing confidentiality.

Environmental LCA Gaps
Significant gaps were found across all LCA phases. In goal and scope definition, there is no harmonized approach for functional units, lifetime activity, or system boundary rules. In life cycle inventory, challenges include resolving multifunctionality (e.g., co-products, recycling, second-life batteries), lack of rules for mandatory use of primary data, inconsistent integration of secondary data, and weak guidance on proxies. Electricity and hydrogen modelling remain unharmonized, as does end-of-life treatment, with debate over the EU's Circular Footprint Formula. In im-pact assessment, there is no standardized set of categories or methods, particularly for mineral resource indicators; broader indicators such as cumulative energy demand and circularity should be considered. Finally, in interpretation, gaps exist in uncertainty/sensitivity analysis, scenario use, and credible verification processes.

Social LCA Gaps
For S-LCA, issues arise in goal and scope definition (e.g., weak adherence to UNEP-SETAC guidelines, unclear functional units, inconsistent activity variables). Data collection lacks standardized tools and granularity, while multifunctionality and outdated databases limit robustness. In impact assessment, the reference scale dominates due to the underdevelopment of impact pathways, reducing comparability and quantification. Interpretation is hindered by non-standardized methods and insufficient stakeholder and cultural integration.

3 The TranSensus LCA Approach

3.1 Ontology and Data Management

Ontologies provide a formal framework for organizing, defining, and linking data by representing concepts and their relationships. They support interoperability, data integration, and knowledge reuse. Building on existing ontologies reduces effort while ensuring connectivity and consistency. In the ORIENTING project [5], which integrates environmental, social, and economic dimensions into Life Cycle Sustainability Assessment (LCSA), the ORIONT ontology was developed as a baseline structure and adapted for the TLCAO (TranSensus Life Cycle Assessment Ontology).

A key element in understanding product composition is the use of hierarchical structures or taxonomies. Standardized nomenclature ensures clear identification of components. A decomposition tree was created as an informational basis to support collaboration across tasks, with applications in visualization, boundary setting, inventory data collection, and impact assessment. For vehicles, the GREET model (US Department of Energy) [6] was adapted, while for batteries, the JRC's Carbon Footprint of Electric Vehicle Batteries (CFB-EV) was used. OEM feedback through surveys and meetings refined the tree, improving clarity, detail, and adaptation to zero-emission vehicles. Modifications included splitting categories, adding process details, and detailing battery subcomponents. Nevertheless, limitations remain: multiple subdivision options create inconsistencies, the GREET-based vehicle structure is not fully suited to Zero Emission Vehicles, and inconsistencies exist between GREET vehicle decomposition and JRC battery decomposition, particularly in fluid and component classifications.

For Social Life Cycle Assessment (S-LCA), the ontology integrates UNEP guidelines [7] with ILCD [8], BONSAI [9], and ORIONT elements. Its key feature is adopting the Reference Scale approach for evaluating and comparing social impacts. While developed for S-LCA guidelines, its definitions can also apply to other phases such as Goal and Scope and Social Life Cycle Impact Assessment (S-LCIA).

Finally, data maintenance emerged as a critical issue. Responsibilities depend on the managing organization, available technical expertise, scope, and software capabilities for updating back-ground data. The choice of database governance structure—whether centralized, shared, or independent—has distinct benefits and drawbacks, highlighting the importance of clear decisions regarding ownership and management of ontology data systems.

3.2 TranSensus E-LCA and S-LCA Methodology

The TranSensus LCA methodology was developed iteratively based on a series of proposed methodological recommendations together with a broad group of stakeholders (beneficiaries, associated partners, Advisory Boards). The TranSensus LCA approach focuses on environmental (E-) and social (S-) LCA of existing product, prospective, and fleet LCA including all life cycle stages and circularity aspects, focusing not only on GWP but also on other pertinent impacts for a wide range of zero emission vehicles technologies. In TranSensus LCA, zero-emission vehicles (ZEV) are defined as vehicles without any significant tailpipe emissions including battery electric vehicles and fuel

cell electric vehicles. The TranSensus LCA methodology covers four types of LCA: product LCA, prospective vehicle LCA, OEM fleet LCA and macro fleet LCA.

It is important to note the differences in maturity of environmental life cycle assessment (E-LCA) and social life cycle assessment (S-LCA). This is reflected in the level of guidance provided for the two methodologies. Thus, in the case of S-LCA, the guidance is provided only as a recommendation; in order to be compliant with TranSensus LCA methodology, it is not mandatory to conduct a S-LCA yet, knowing the gap in systems in place to collect primary data for social assessment.

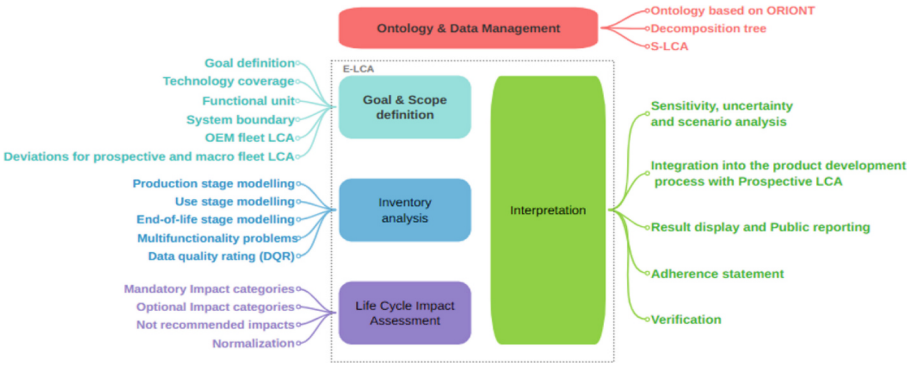


Fig. 1. Requirements of TranSensus-LCA methodology (summary, only E-LCA)

The derived and harmonised guideline for an automotive LCA presents requirements for all life cycle stages providing information on how to apply the TranSensus LCA methodology for ZEV. This TranSensus LCA guideline [10] outlines the methodological requirements for the four LCA steps of environmental and social LCA:

- Goal & scope including definition, technology coverage, functional unit, system boundary for all types of LCA.
- Life Cycle Inventory with details for data collection, electricity modelling and multifunctionality.
- Life Cycle Impact Assessment giving rules and requirements on mandatory and optional impact categories as well as normalisation.
- Interpretation & Reporting of level of exigence (mandatory, recommended, optional) and level of adherence to the TranSensus-LCA methodology.
- Social LCA (S-LCA) providing specific considerations structured around the four phases, similarly to environmental LCA.

In addition, complementary information is provided, for example on the way the outlined recommendations were built, on the selection of options, and on the inclusion or exclusion of certain items.

An overview of the methodology structure and main requirements is summarised in a mindmap format shown in Fig. 1. The final harmonised and agreed upon TranSensus-LCA methodology includes 144 methodological specific requirements (59 of which being mandatories) for E-LCA and 50 requirements for S-LCA (15 of which being

mandatories). For details on the proposed approach, it is referred to the final guideline, which can be downloaded from the project's homepage (www.lca4transport.eu).

3.3 Road Testing

To ensure broad applicability, the TSLCA methodology was tested with diverse stakeholders. Feedback loops were established to refine the methodology, and structured decision-making mechanisms were implemented to resolve disagreements. The findings emphasize the need for clarity and consistency, particularly in definitions and hierarchical transitions (e.g., electricity modelling). Harmonized secondary datasets remain essential for comparability of vehicle LCA studies, also for UNECE Levels 3 and 4. Current documentation requirements for energy certificate safeguards are burdensome; referencing these in supplier contracts is proposed as a practical alternative. The UNECE Level 3 requirement for tier-1-specific data is currently unfeasible, and the methodology should treat it as a benchmark rather than a mandate. Networks like Catena-X are critical for enabling efficient data exchange. Solutions to all editorial and methodological remarks are presented in the report D 3.3 [11].

LDV BEV Modelling
A full-vehicle LCA was conducted for a lower-medium-segment passenger car using Sphera LCA software. The production phase emerged as the most impactful in most categories, with traction battery cells and aluminium being major contributors. The use phase dominated cumulative energy demand. Sensitivity analyses showed that vehicle lifetime and electricity mix significantly influence results. The guideline proved practical and timesaving for LCA practitioners.

HDV BEV Modelling
Testing for heavy-duty vehicles (HDVs) revealed gaps specific to this segment, such as payload estimation and charging losses. A cradle-to-grave LCA of a 40-ton BEV truck showed the use phase as the most impactful, except in resource use and eutrophication. Improvements in grid mix and payload efficiency are key to reducing impacts. Scenario analyses highlighted the significant influence of grid mix assumptions.

FCEV Modelling
Here, only hydrogen production was modelled. The methodology was found to be understandable and feasible, aided by default data. Four hydrogen production pathways were tested, with electrolysis using renewable electricity showing the lowest impacts. Steam reforming had slightly higher impacts than electrolysis with a dynamic grid mix.

Database Comparison
A simplified test compared the Sphera and ecoinvent databases for truck material production. While climate change impacts were similar, other categories showed significant variation. Eutrophication and resource use impacts were notably higher with ecoinvent. These findings under-score the importance of database choice and the need for further comprehensive assessments. The chosen LCA method and secondary databanks must be aligned in order to produce consistent results.

LDV S-LCA Modelling
Social LCA (S-LCA) was conducted for an LDV BEV using OpenLCA and the PSILCA database. Key risks identified include fair salary, corruption, forced labour, and hazardous conditions, particularly in raw material sourcing countries like the DRC, Russia, and Chile. The use phase also revealed governance-related risks in European countries (Fig. 2). These findings highlight the need for stronger global governance and supply chain transparency.

Additional Scenarios The TSLCA methodology is adaptable to emerging sustainability topics. It supports circular economy applications, future battery chemistries, and vehicle-to-grid (V2G) technologies, though refinements are needed for specific use cases. For mobility services, adjustments are also required to account for service-specific factors like occupancy and vehicle lifetime.

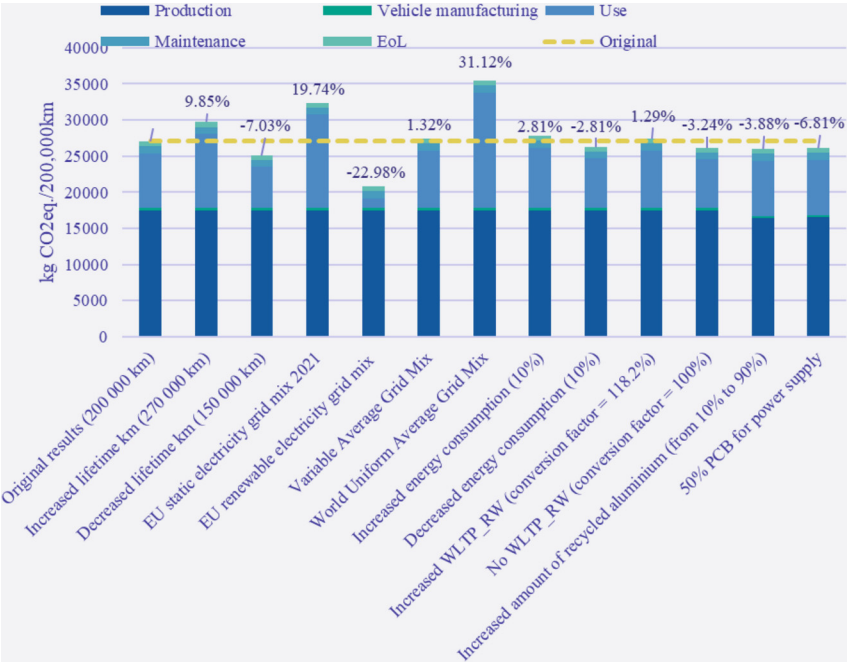


Fig. 2. Sensitivity/scenario analyses results for Climate Change per full vehicle lifetime

4 Conclusion and Outlook

TranSensus Life Cycle Assessment (LCA) was a coordination and support action project funded by the European Union. The project aimed to establish a commonly accepted and applied single LCA approach for LCA of so called "zero-emission" road transport systems in Europe. This was done through a consensus building approach, which

engaged the consortium, associated partners, defined scientific and industry advisory boards as well as the wider stakeholder community including the European Commission, standardisation bodies and member states.

The result of TranSensus LCA's efforts to develop a harmonised methodology are published as a guideline comprising 194 methodological requirements, of which 94 are mandatory, covering environmental and social LCAs for products, prospective scenarios, and fleet analyses. The guidelines are structured according to the different steps in conducting an LCA specifically, i) goal and scope definition, ii) life cycle inventory, iii) life cycle impact assessment and iv) interpretation. The document also provides guidance on reporting to ensure adherence to the TranSensus methodology. The guidelines conclude with a section on future perspectives, highlighting areas for future research that may be applied to future iterations of the methodology. It is important to emphasize that these guidelines are a "living" document and will be updated regularly.

All results of the project can be downloaded from the project's homepage.

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References

1. 2ZERO Partnership, Strategic Research and Innovation Agenda 2021–2027. https://www.2zeroemission.eu/what-we-do. Accessed 12 Aug 2025
2. TranSensus LCA: Homepage, Towards a European-wide harmonised transport-specific LCA Approach. www.lca4transport.eu. Accessed 6 Feb 2026
3. TranSensus LCA: D 1.1 - Review of current practices on life cycle approaches along the electromobility value chain. Deliverable. www.lca4transport.eu. Accessed 6 Feb 2026
4. TranSensus LCA: D 1.2 - Analysis of needs and gaps for the development of a harmonised LCA/S-LCA approach. Deliverable. www.lca4transport.eu. Accessed 6 Feb 2026
5. ORIENTING: Homepage, Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy. https://orienting.eu/. Accessed 12 Aug 2025
6. Argonne National Laboratory: R&D GREET® Model. https://greet.anl.gov/. Accessed 28 Apr 2026
7. UN Environment Programme: The Life Cycle Initiative. https://www.unep.org/topics/finance-and-economic-transformations/driving-transformation-science-and-knowledge/life-cycle. Accessed 12 Aug 2025
8. Joint Research Centre: International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment – Detailed Guidance. Publications Office of the European Union (2010) https://data.europa.eu/doi/10.2788/38479
9. BONSAI: Big Open Network for Sustainability Assessment Information. https://bonsai.uno/. Accessed 12 Aug 2025

10. TranSensus LCA: Consolidated Guidelines for a transport-specific Life Cycle Assessment (LCA), Deliverable. www.lca4transport.eu. Accessed 6 Feb 2026
11. TranSensus LCA: D 3.3 - Road testing with Advisory Boards. Deliverable. www.lca4transport.eu. Accessed 6 Feb 2026

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Astéria: A MBSE Framework for Railway Systems Design and Digital Continuity

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Abstract. The railway systems design involves stakeholders that share multidisciplinary knowledge in order to deliver compliant and resilient systems. The rising complexity of these systems limits the interdisciplinary collaboration throughout the system's lifecyle and generates intricate interfaces. Currently, system engineering activities are based on traditional document-centric approaches that fall short in managing both technical and organizational challenges. Besides, deployment projects require high adaptability of heterogeneous teams and fragmented toolchains in order to successfully implement concurrent engineering practices. In this work, the complementarity between Building Information Modeling (BIM) and Model-Based Systems Engineering (MBSE) is explored by emphasizing their shared goals of digital continuity, semantic coherence, and cross-disciplinary collaboration. The adoption of ontologies and semantic interoperability is central to our approach since they enable shared conceptual models, enhance traceability and decision-making within a multi-enterprise context. Astéria Framework is introduced as a solution bridging system of systems theoretical advances and industrial needs. It features a collaborative modeling framework throughout system life-cycle and aligns with standards such as ISO 15288. Preliminary case studies demonstrate its efficiency as a pivotal step towards scalable and concurrent MBSE in complex systems development. Furthermore, Astéria improves digital continuity and establishes the interface with BIM and Digital Twin tools.

Keywords: MBSE · BIM · Digital Continuity · Ontologies · Astéria Framework

1 Introduction

Future railway systems integrate new technologies that improve overall performance and then generate several interfaces between subsystems. With the raising complexity of railway systems, the need for efficient design methods, processes and tools arises in order to face technical challenges [1]. Furthermore, designing modern railway systems requires the integration of expertise from various domains: systems engineering, infrastructure design, safety, etc. Each stakeholder uses its own tools, languages, and methodologies—yet all contribute to a single,

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increasingly complex system. Therefore, this ambiguous interpretation causes inconsistency between teams and increases the risk of late-stage design conflicts and the need of practices homogeneity becomes crucial. Moreover, interface management becomes a critical pain point with technical and organizational complexity.

In this context, achieving digital continuity, the seamless and traceable flow of information across design phases, is no longer optional. It is essential for resilience, compliance, and efficiency in asset management and large-scale railway projects. The identified challenge is to bridge the gap between systems design and asset management in order to enhance quality and collaboration. Model-based approaches are widely used and known to address this challenge by providing suitable methods, tools and modeling languages. In this work, we propose a structured framework connecting Model-Based Systems Engineering (MBSE) with Building Information Modeling (BIM) and fostering interdisciplinary collaboration. The proposed framework called Astéria, is based on a novel tool-based approach that supports semantic interoperability and collaborative systems design.

The remainder of this paper is organized as follows. Section 2 provides technical background related to the complexity of railway systems. Section 3 presents the complementarity between the MBSE and BIM approaches, regarding our issues. Section 4 describes the benefits of ontologies in the context of railway multi-disciplinary projects. Section 5 presents Astéria Framework, while Sect. 6 concludes the paper and outlines directions for future work.

2 Railway Systems Complexity

The complexity of the French rail network modernization projects arises at different levels since the challenges to be met are both technical, human, organizational, economic and geopolitical. The technical complexity arises from the dynamics of the digitalization of companies and the aim to create digital twins: the factory 5.0. Intelligent algorithms are also beginning to be integrated into railway IT subsystems, raising the question of controlling the system's safe behavior in degraded situations or those not foreseen during design studies.

This is where the challenges of appropriating new knowledge and sharing information between different teams are concerned and the organization of the company needs to evolve. Systems engineering and particularly MBSE seems to be the discipline most suited to working towards the success of these complexities. Beyond this, there are also the challenges of establishing an interoperable and safe European railway system: European Rail Traffic Management System (ERTMS). This involves compliance with European Union Agency for Railway (ERA) requirements that must be taken into account.

In complex projects, the system under study is a system of systems. Therefore, to be efficient, the system engineering with a MBSE approach must begin at the same time with all the engineering specialties involved in the project [2]. The first step is to successfully move from document-based systems engineering

to model-based systems engineering. Then, ontology takes its rightful place in studies to define common vocabulary from the very beginning of projects.

SNCF Réseau works with several external companies, and alignment with MBSE best practices is a key to success. The level of MBSE knowledge must be homogeneous among all stakeholders involved, the MBSE tools must be shared and solid systems engineering governance is necessary at the organizational level.

To achieve these goals, we have opted for the implementation of open-source software although their deployment requires paid customization. This gave birth to the Astéria MBSE Framework project. The heart of the problem then lies in the digital continuity of two digital engineering universes: BIM and MBSE.

3 The Synergy Between Model-Based Systems Engineering (MBSE) and Building Information Modeling (BIM)

MBSE activities are beginning to be widely deployed in railway projects since they improve quality and facilitate collaboration using common models. MBSE handles system complexity by providing structured methods, processes and powerful tools that offer a consistent and traceable system architecture [3]. In our context, National Company of the French Railways (SNCF) set up the digital transition as a key factor of projects success. In order to have a systemic approach of digital continuity throughout the overall life-cycle, the need to make a bridge with other tools, used in complex projects, arises [5]. Building Information Modeling (BIM) is adopted by SNCF as it provides several benefits, namely a well-defined project organization, a key framework of geometrical and physical modeling of infrastructure assets (tracks, energy, signaling, Telecommunications) and a set of documents used for cross-disciplinary traceability [4].

The synergy between both approaches is explored in [6] that demonstrate the valuable feedback of BIM and MBSE combination. It enables early verification and validation of design choices, improves data consistency and continuity and facilitates the development of Digital Twins (DT). Figure 1 shows the top-down approach used from the first design stages by combining MBSE models and BIM models. Internet of Things (IoT) is then integrated to gather real-time data which are analyzed using Artificial Intelligence (AI) and Machine Learning (ML). This data-driven approach allows the development of DT for performance monitoring, predictive maintenance and efficiency optimization [7].

The complementarity between BIM and MBSE is obvious, especially by aligning the requirements, process, and functions from MBSE with three-dimensional modeling and parametric design of physical objects from BIM. In order to achieve this integration, several challenges have to be addressed:

– Different modeling levels: MBSE models describe system architecture and behavioral diagrams, whereas BIM models describe spatial constraints and provide geometrical representation and 3D location.

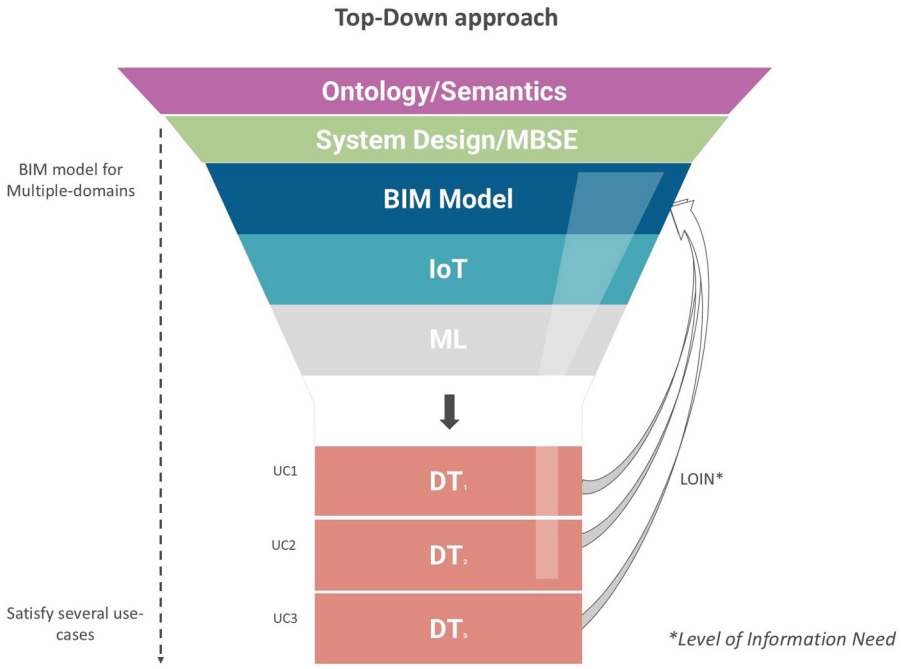


Fig. 1. The Synergy between MBSE and BIM for Digital Twin Development

- Heterogeneous data exchange formats and standards: BIM relies on the open standard IFC (Industry Foundation Classes), while MBSE often uses XML/XMI (Extensible Markup Language/Metadata Interchange) based model formats.
- Lack of common and shared semantics: MBSE and BIM models are realized independently by different teams using heterogeneous terminologies.
- Fragmented tool ecosystems: BIM tools (e.g., Civil 3D) are not natively interoperable with MBSE tools, such as Capella [8] and this generates gaps in verification and traceability.

In this work, these challenges are tackled with a focus on system lifecycle management and the use of ontologies for semantic bridging between BIM and MBSE models.

4 The Adoption of Ontologies and Semantic Interoperability

Ontologies are defined as a shared and explicit formalization of a conceptualization [9]. They provide a machine-readable representation of a domain knowledge which is also interpreted unambiguously by humans. In our industrial context,

ontologies enable semantic interoperability between heterogeneous tools by acting as a common vocabulary. Furthermore, they help to clarify ambiguous terminology across disciplines and teams. For example, the concept of a "track circuit" can be precisely defined in terms of its function (detecting train presence), physical location (installed along a segment of track), and logical role (contributing to the train control system). This clarity enables linking BIM elements (geometry, cable routing) with MBSE elements (signal processing logic, system components). In previous works, the coupling between ontologies and MBSE activities is well-argued with the aim to enhance the railway digital continuity [10]. As shown in Fig. 1, ontologies have to be used at an early stage in order to guide modeling activities and establish a common base of terminology. Indeed, the development of digital twins requires reliable, up-to-date and semantically consistent information across lifecycle phases.

The integration of BIM and MBSE demands a semantic bridge, capable of translating between engineering views. A preliminary phase is to define core concepts shared by both activities, such as interface, function, physical object, etc. In order to reach the interoperability between BIM and MBSE models, there is a need to align BIM and MBSE models, using a semantic mapping. The ontology representation helps to check the consistency between them. Therefore, this semantic foundation is a prerequisite for scalable digital continuity and the future deployment of DT in railway systems.

5 Astéria MBSE Framework

Astéria MBSE Framework was designed to meet the challenges of complexity, interoperability, and lifecycle integration in railway systems design. This framework provides a collaborative and model-based environment that bridges engineering domains and promotes digital continuity from early requirements to operational validation. Astéria is grounded in industry-proven tools and open standards, with a focus on scalability, traceability, and cross-discipline collaboration.

As represented in Fig. 2, the Astéria Framework is a toolchain composed of different integrated components. Polarion Application Lifecycle Management (ALM) is a web-based application lifecycle management tool that manages requirements, test cases, validation steps, and change tracking. It ensures traceability across lifecycle stages and aligns with ISO 15288 processes. Team for Capella is a collaborative modeling platform supporting the Arcadia methodology. It allows the definition of system architectures, functional chains, scenarios, and interfaces, all structured across logical and physical levels. Publication for Capella is a documentation generator that automates the production of system engineering deliverables (e.g., specification reports, interface control documents) from Capella models, improving consistency and reducing manual effort. Python for Capella is a scripting interface that allows custom queries, batch model transformations, and semantic rule checking, enabling advanced automation and integration capabilities.

All of these applications run on a secure virtual server, allowing safe collaborative remote use. This toolchain forms a closed-loop system engineering environment, where models are not isolated artifacts but living representations of the system, constantly updated and reused throughout the project lifecycle.

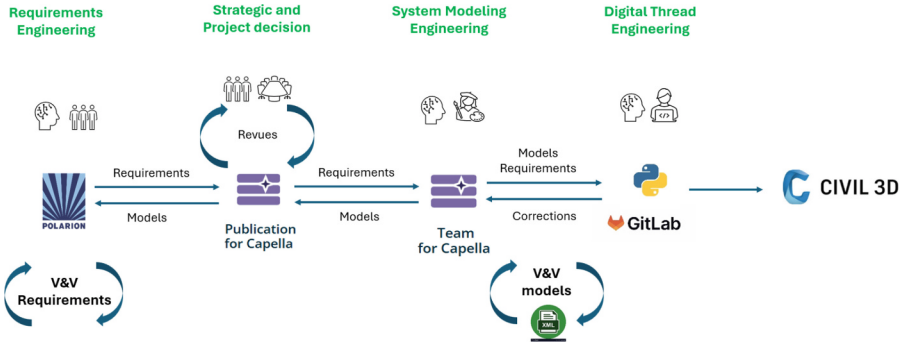


Fig. 2. Astéria MBSE Framework

Astéria supports different key capabilities such as collaborative modeling across disciplines, with access control, change tracking, real-time sharing and lifecycle traceability, from stakeholder needs to system requirements and architecture. Astéria enables integration with external tools, including the ability to interface with BIM platforms such as Civil 3D, enabling links between physical infrastructure and system functions.

The ongoing development aims to strengthen the interface with BIM tools. This includes extracting and synchronizing geometry or layout constraints from Capella logical views into Civil 3D, linking system elements with BIM objects via semantic mappings and enabling spatial validation of systems based on BIM models.

While the interface between MBSE and BIM is a cornerstone of Astéria, true interoperability requires more than simple data exchange. Geometric and topological validation is still largely performed manually. Temporal alignment between system scenarios and construction phases is limited. Then, cross-domain simulation remains fragmented.

A tighter coupling of MBSE models with BIM platforms and scheduling tools is needed to support construction-aware system design and enable 4D/5D DT. This integration lays the foundation for a DT strategy, where both static infrastructure and dynamic system behavior are modeled, monitored, and co-simulated throughout the asset lifecycle.

Small-scale experimentation with the Astéria MBSE framework has shown clear benefits in improving collaboration, traceability, and model consistency within complex railway development projects. However, its deployment also sheds light on a number of organizational, technical, and cultural challenges

that must be addressed to fully unlock the potential of digital continuity. Despite the richness of the toolchain, adoption between departments is not automatic. In large railway companies, engineering activities are often fragmented between silos, each with its own legacy tools, processes, and data formats. Aligning these practices requires strong governance and sponsorship to promote the MBSE-BIM strategy throughout the organization.

Without these elements, there is a risk that digital models become isolated or misused, defeating the purpose of continuity. Although ontologies are the key to semantic interoperability, their adoption is still in its infancy within the organization. As a result, mappings between domains are still mostly manual. Therefore, an incremental ontology strategy is recommended, starting with controlled vocabularies and gradually evolving toward formalized ontologies tied to standard frameworks.

Overcoming these barriers is essential for industrial deployment at the program level and across multi-enterprise ecosystems. To be efficient, the Astéria MBSE Framework can and must be thinking as a system to be integrated into a human system. For now the Astéria MBSE Framework is not accessible to everyone. How Astéria MBSE Framework can be integrated in a complex human organization? How can it be upgraded?

6 Conclusion and Perspectives

New automation systems, like ERTMS, increase the complexity of railway systems and need a radical shift in engineering practices. In order to efficiently manage interactions and risks, model-based frameworks are crucial in such collaborative context.

The Astéria MBSE Framework provides a pragmatic response to these challenges by integrating leading tools such as Team for Capella, Polarion, and Civil 3D, and fostering collaborative, model-based systems engineering. By promoting digital continuity, enhancing traceability, and preparing for semantic interoperability, Astéria serves as a foundation for concurrent engineering and lifecycle integration across domains. This work highlights several key outcomes. MBSE and BIM are complementary rather than competing paradigms, and their integration is necessary to support holistic system design. Furthermore, a shared semantic layer based on ontologies is central to achieve meaningful interoperability between tools and teams. Organizational change and engineering culture evolution are critical and suitable tools ensure successful deployment.

As perspectives, different strategic directions are specified. We intend to progressively adopt ontologies, starting with lightweight taxonomies and evolving toward formalized semantic models aligned with international standards. Then, the synchronization BIM–MBSE has to be enhanced, namely data exchanges for operations and maintenance. Models developed with Astéria will be used for DT implementation as the backbone for monitoring, simulation, and predictive analytics throughout the asset lifecycle. With the aim to enhance the scalability of the framework, we plan the development of reusable model libraries for multi-partner collabration.

In conclusion, the Astéria Framework represents a key enabler for the future of railway systems engineering. It enhances collaboration, consistency, and continuity in order to promote innovation and resilience in increasingly complex environments.

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References

1. Pyrgidis, C.N.: Railway Transportation Systems: Design, Construction and Operation. CRC Press (2021)
2. Chen, J.: A systematic review of MBSE-based safety analysis techniques in railway systems. Railw. Sci. **5**(2), 1–12 (2026)
3. Henderson, K., Salado, A.: Value and benefits of model-based systems engineering (MBSE): evidence from the literature. Syst. Eng. **24**(1), 51–66 (2021)
4. Biancardo, S., Intignano, M., Viscione, N., Guerra De Oliveira, S., Tibaut, A.: Procedural modeling-based BIM approach for railway design. J. Adv. Transp. **2021**(1) (2021)
5. Chapelin, J., Steck, L., Voisin, A., Iung, B., Ros, B.: Digital continuity to improve the performance of the Industry 4.0. IFAC-PapersOnLine **55**(10), 761–766 (2022)
6. Bolshakov, N., Rakova, X., Celani, A., Badenko, V.: Operation principles of the industrial facility infrastructures using building information modeling (BIM) technology in conjunction with model-based system engineering (MBSE). Appl. Sci. **13**(21) (2023)
7. Nguyen, T.D., Adhikari, S.: The role of BIM in integrating digital twin in building construction: a literature review. Sustainability **15**(13) (2023)
8. Baron, C., Grenier, L., Ostapenko, V., Xue, R.: Using the arcadia/capella systems engineering method and tool to design manufacturing systems-case study and industrial feedback. Systems **11**(8), 429 (2023)
9. Gruber, T.: Ontology: Encyclopedia of Database Systems, pp. 1963–1965. Springer, Boston (2009)
10. Debbech, S., Collart-Dutilleul, S., Bon, P.: MBSE approach for railway digital continuity. In: 10th Transport Research Arena (TRA) Conference, Dublin, pp. 189–192 (2024)

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Bridging Policy and Practice: Enabling Robust GHG Emission Accounting Across Transport Services

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Abstract. Reliable and harmonised GHG emission factors are essential for enabling fair and transparent climate impact comparisons across transport services. However, current methodologies are fragmented, with limited treatment of emerging fuels, inconsistent data handling, and poor integration of upstream energy carrier pathways. This paper presents the scientific and methodological basis of the CLEVER framework, a new EU supported standard to calculate lifecycle based GHG emission factors for transport fuels and energy carriers. Designed in alignment with ISO 14083 and as a core component of the upcoming CountEmissionsEU regulation, CLEVER introduces a modular, attributional LCA based approach that integrates upstream well to tank and operational tank to wheel emissions. The framework improves on existing approaches by clarifying system boundaries, harmonising modelling rules, and incorporating additional climate relevant sources such as indirect land use change, methane slip, black carbon, and hydrogen leakage. It supports both default factors and operator specific data, enabling comparability while also rewarding more accurate, fuel pathway specific assessments. CLEVER advances best practice in data quality scoring, certification linkage, and reporting granularity, creating a credible foundation for industry wide decarbonisation tracking and digital emissions integration in transport.

Keywords: GHG emission accounting · Emission factors · Well-to-wheel emission modelling · Fuel pathway differentiation · Non-CO_2 climate forcers

1 Introduction

The decarbonisation of transport requires not only technological transformation but also robust accounting systems capable of tracking progress. Greenhouse gas (GHG) emission factors are central to such systems, converting fuel and energy use into lifecycle emissions comparable across operators, modes, and countries. Policymakers rely on them to enforce regulations, allocate incentives, and monitor progress towards climate neutrality. Industry depends on them for corporate disclosure, lifecycle assessments, and investment decisions. Despite this role, methodologies remain fragmented. Life

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Cycle Assessment (LCA) is well established but allows flexibility in key choices such as allocation, treatment of upstream processes, and inclusion of indirect effects [1]. As a result, different databases can generate divergent emission factors for the same fuel pathway, undermining both climate policy and corporate accountability. The need for harmonisation has increased with the emergence of zero-emission fuels. Pathways such as hydrogen, e-fuels, and advanced biofuels expose weaknesses in current accounting, as upstream emissions and fugitive factors are often omitted. For example, hydrogen leakage and methane slip can offset expected benefits if not consistently included. Without harmonised and comprehensive factors, decarbonisation claims risk losing credibility. To address this, the European Commission proposed the CountEmissionsEU regulation, mandating harmonised GHG reporting across all modes. In parallel, ISO 14083 provides a global reference for transport chain emissions reporting. The CLEVER framework, developed under Horizon Europe, provides the methodological backbone for CountEmissionsEU while aligning with ISO 14083. Its ambition is to bridge scientific rigour and regulatory applicability by delivering emission factors that are transparent, modular, and adaptable to both default and operator-specific data.

2 Policy Context

Transport contributes roughly one quarter of EU GHG emissions, making it a central pillar of the European Green Deal, which commits to a 90% reduction in transport related impacts by 2050. Achieving this target requires not only deployment of zero-emission fuels and vehicles but also a harmonised methodology for emissions accounting. Without a credible basis for comparing fuels and services, the transition risks being undermined by inconsistent reporting and a lack of trust from regulators, industry, and the public. The proposed CountEmissionsEU regulation responds directly to this challenge [2]. It establishes a mandatory framework for reporting across all modes, covering passenger and freight, logistics services, and multimodal chains. Importantly, it requires both direct and indirect emissions to be included and results to be comparable across Member States. Operators must report emissions using harmonised GHG emission factors, which must be comprehensive, transparent, and suitable for both large operators, and small and medium-sized enterprises (SMEs). CountEmissionsEU is only as strong as the methodological backbone it rests upon. The CLEVER framework has been designed to provide this backbone, ensuring scientific robustness and practical usability.

Several EU measures create strong synergies. The Renewable Energy Directive (RED III) defines and accounts for renewable fuels, including advanced biofuels, renewable fuels of non-biological origin (RFNBOs), and recycled carbon fuels [3], requiring pathway-specific lifecycle emissions factors. FuelEU Maritime sets intensity targets for shipping fuels based on well-to-wake performance, while ReFuelEU Aviation mandates increasing shares of sustainable aviation fuels, also measured on a lifecycle basis. The Corporate Sustainability Reporting Directive (CSRD) expands disclosure requirements, requiring emissions data that is auditable and comparable [2]. Together, these initiatives create demand for a harmonised framework serving both regulatory and voluntary disclosure.

At the global level, ISO 14083 provides a standard for quantifying and reporting emissions from transport chain operations [4], establishing rules for system boundaries,

activity data, allocation, and reporting formats. However, it allows flexibility in areas such as upstream energy carriers and additional climate forcers. CLEVER builds on ISO 14083 by specifying how well-to-tank and tank-to-wheel emissions are combined, and by integrating additional sources such as indirect land use change, methane slip, black carbon, and hydrogen leakage. In doing so, it strengthens ISO 14083 with the granularity needed for regulatory enforcement. International aviation and maritime add further complexity. ICAO's CORSIA requires lifecycle reporting for sustainable aviation fuels but applies narrower boundaries than those proposed in Europe. The IMO is developing lifecycle guidelines for maritime fuels, but these are not yet harmonised. CLEVER ensures consistency with these developments while addressing gaps that could lead to underestimation or double counting.

CLEVER addresses two key gaps. First, it provides the methodological detail needed to operationalise CountEmissionsEU. Second, it ensures international alignment while remaining scientifically robust, enabling fair comparisons across fuels, modes, and regions. In this way, CLEVER supports both the integrity of European climate policy and the credibility of voluntary reporting systems used by industry.

3 Methodology

The CLEVER methodology applies an attributional LCA approach as the foundation for emission factor development. This approach reflects average conditions in existing energy systems and avoids the uncertainties of consequential modelling. While consequential LCA can provide insights into system wide impacts of marginal changes, its assumptions on market dynamics and substitution effects are too variable for regulatory use. In contrast, attributional LCA provides stable average values usable as common denominators across actors and is widely recognised as the most suitable basis for generating consistent GHG emission factors for both regulatory frameworks and voluntary disclosure schemes.

The architecture of CLEVER is modular, separating upstream well-to-tank emissions from operational tank-to-wheel emissions. This reflects both scientific and policy logic. Upstream processes such as extraction, refining, transport, and distribution are distinct from operational energy use in vehicles, while upstream pathways evolve rapidly as the energy system decarbonises, whereas operational performance is more closely tied to vehicle technologies. This separation allows each stage to be updated transparently as new data becomes available and aggregated into complete well-to-wheel factors, preserving flexibility and ensuring methodological transparency. It also enables regulators, operators, and researchers to clearly identify emission sources and assess the impact of improvements across the value chain.

A major innovation of CLEVER is its explicit clarification of system boundaries (Fig. 1 and 2). Previous frameworks have often differed in the inclusion of certain processes and indirect effects, leading to incomparable results. CLEVER systematically integrates climate impact sources often treated inconsistently or omitted. For biofuels, it incorporates indirect land use change where feedstocks are at high risk of displacement, reflecting IPCC guidance and RED III criteria [3, 5]. For combustion-based fuels, it accounts for short lived climate forcers such as black carbon, which can represent a

significant share of climate impact in shipping and heavy-duty transport. For gaseous fuels, methane slip is included as a standard component, acknowledging its high global warming potential. For hydrogen, the framework recognises leakage during production, storage, and distribution as a relevant but emerging climate forcer [9, 10]. Although consensus on characterisation factors is still developing, CLEVER ensures such leakage is treated transparently and consistently. By addressing these elements systematically, CLEVER ensures lifecycle emissions are comprehensive and credible across all energy carriers.

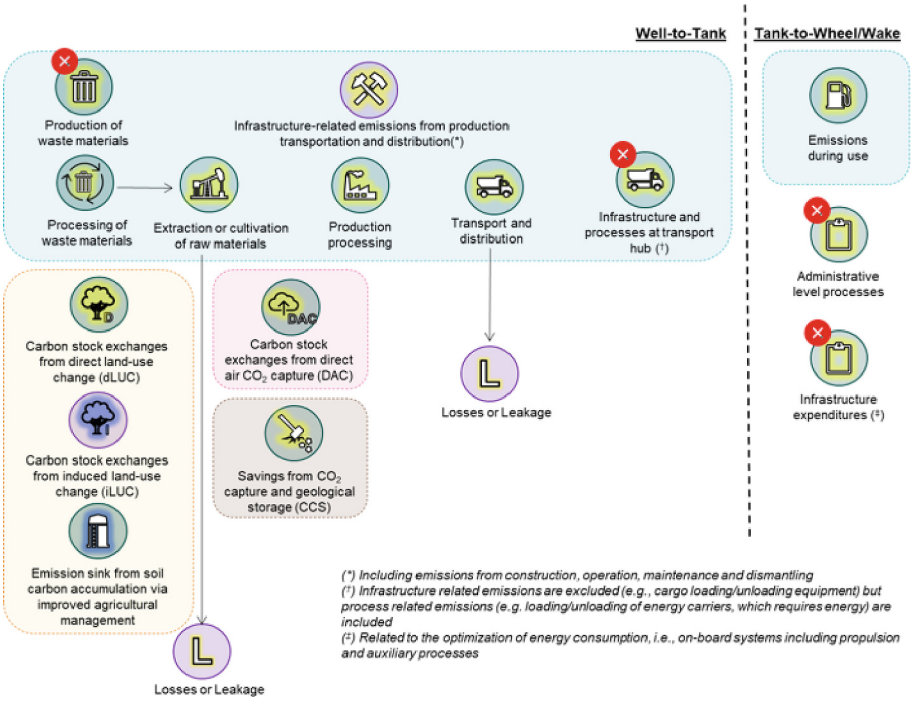


Fig. 1. Simplified depiction of the CLEVER system boundary.

The development of default emission factors builds on established scientific and policy baselines. The JEC Well to Tank reports produced by the Joint Research Centre provide harmonised European data for a wide range of fuels [6]. Complementing this, the GLEC Framework offers a globally recognised methodology for logistics emissions accounting [7] and is referenced in ISO 14083. By combining JEC and GLEC, CLEVER ensures that default values are scientifically robust, aligned with EU regulation, and relevant to industry practice. It also integrates recognised data sources such as the EMEP/EEA air pollutant guidebook [8] and national inventories, ensuring consistency with European and global reporting systems. Alongside default values, CLEVER enables operators to report actual data where reliable evidence is available. This dual system provides both comparability and flexibility. For example, operators sourcing renewable electricity or certified RFNBOs can report lower lifecycle emissions than

default values. This creates incentives for investment in cleaner supply chains while ensuring all operators can report on a common basis where specific data is unavailable.

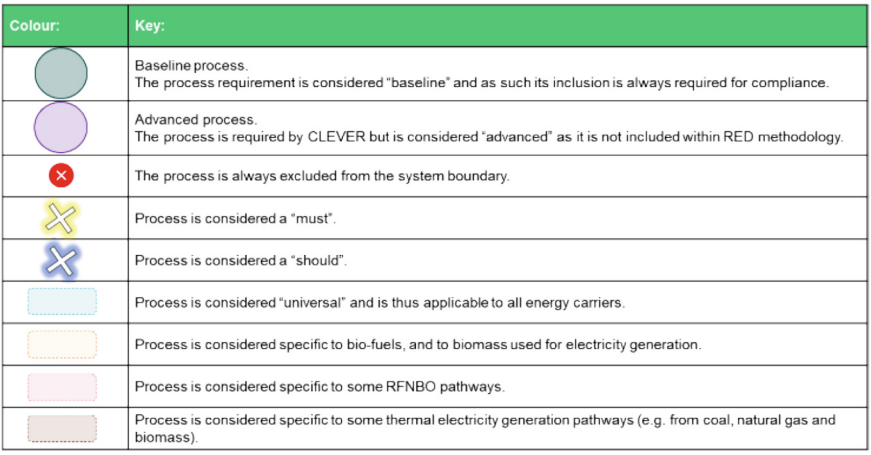


Fig. 2. CLEVER system boundary explanation.

To safeguard credibility, CLEVER introduces a structured data quality scoring system assessing representativeness across geography, technology, and time, transparency of methodological choices, and verification through certification or third party auditing. Scores determine whether actual data can replace defaults, with linkage to recognised certification schemes ensuring that claimed reductions are trustworthy and auditable. Reporting flexibility is further supported through multiple levels of granularity. Operators can apply fuel pathway specific factors, such as distinguishing between grey, blue, and green hydrogen, or use generic carrier averages such as the EU electricity mix. Simplified mode level factors are also available for smaller operators. This tiered system ensures broad applicability across actors, from multinational companies with advanced carbon management systems to small operators.

4 Implementation and Practical Use

The CLEVER framework is designed to be cross-modal, enabling consistent comparison of emissions across fuels, energy carriers, and transport modes. Harmonised boundary definitions and modelling rules allow alignment between pathways that would otherwise be difficult to compare. Under CLEVER, an electric truck powered by renewable electricity can be assessed on the same basis as a hydrogen bus using certified green hydrogen or a bio-LNG vessel using advanced biofuels. The same structure applies across road, maritime, aviation, and multimodal chains, supporting fair comparison and informed decision making in policy and industry. The need for harmonisation is illustrated by current variability across emission factor sources. For example, comparisons of well-to-tank emission factors for fossil diesel across widely used databases show significant differences, despite covering similar process stages (Fig. 3). Default values ensure

accessibility. Smaller operators can use harmonised default factors to meet reporting obligations, creating a level playing field for participation in CountEmissionsEU and voluntary disclosure. Regulators can use these as benchmarks, while operators with advanced data can report actual values to reflect improved performance. For instance, renewable electricity sourcing or certified RFNBO use can lead to lower reported emissions than default values. This combination ensures comparability while incentivising cleaner supply chains. The implementation logic extends beyond compliance. Emission factors are machine-readable and designed for integration into calculators, logistics optimisation platforms, and carbon management systems. This supports reporting under the Corporate Sustainability Reporting Directive and frameworks such as the GHG Protocol [11] or Science Based Targets initiative. Integration into digital infrastructures, including urban digital twins, enables real-time emissions calculation, shifting accounting from a retrospective exercise to a planning and optimisation tool.

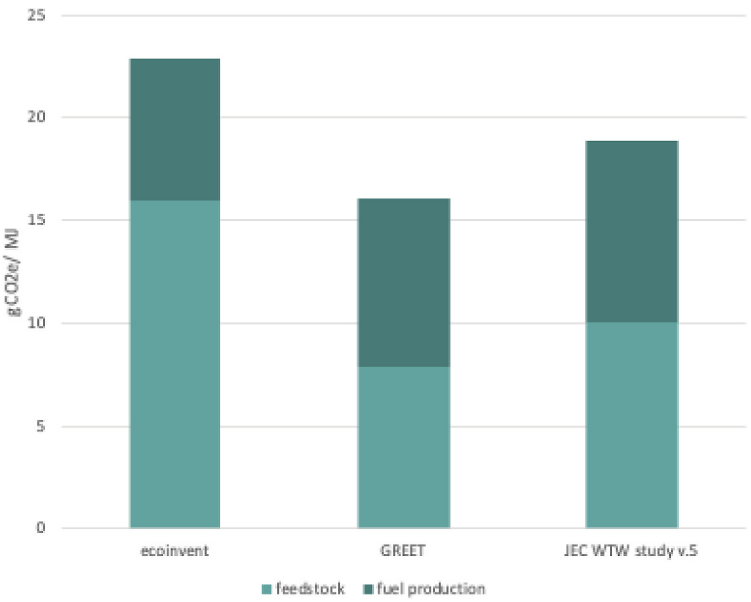


Fig. 3. Comparison of WTT Diesel Emission Factors from three Major Refinery Models.

Use cases illustrate this applicability. Authorities can compare lifecycle emissions across transport options, freight operators can assess alternative vehicle and fuel choices, and airlines can ensure consistency between EU and international reporting frameworks. In all cases, CLEVER provides a harmonised basis for decision making, reducing uncertainty and increasing trust. Integration also improves efficiency and reduces costs. Standardised emission factors reduce reliance on multiple conflicting databases [12] or proprietary tools, lower compliance burdens, and enhance credibility through comparable and auditable results. At the same time, embedding emissions accounting into digital systems strengthens its role in operational and strategic decision making. The practical value of CLEVER lies in its ability to bridge regulatory requirements, industry practice,

and digital innovation. It functions as a regulatory instrument, ensuring comparability and enforcement under CountEmissionsEU. It supports industry in meeting both compliance and voluntary disclosure needs. And it enables integration into digital systems that make emissions accounting part of daily decision making. In doing so, CLEVER turns fragmented and retrospective reporting into a harmonised and forward-looking tool for managing the transition to zero-emission fuels and climate neutral transport.

5 Discussion

The CLEVER framework delivers advances across scientific, policy, and practical dimensions. Scientifically, it strengthens rigour by resolving inconsistencies in boundary setting and systematically incorporating additional emission sources previously neglected. By adopting attributional LCA as default and modularising results, CLEVER reduces variability and improves comparability across fuels and modes, directly addressing gaps identified earlier.

From a policy perspective, CLEVER operationalises CountEmissionsEU by providing emission factors applicable across all Member States. Its alignment with ISO 14083 ensures global compatibility, while inclusion of previously neglected emissions improves completeness. CLEVER also supports implementation of related EU legislation, including RED III, FuelEU Maritime, ReFuelEU Aviation, and the CSRD. In practical terms, CLEVER balances usability and accuracy. Default factors ensure accessibility and comparability, while reporting of actual data incentivises frontrunners to improve supply chains. Data quality scoring and certification linkage further strengthen credibility. For operators, this reduces compliance costs through a clear and consistent methodology. For investors and customers, it increases trust in reported emissions.

Challenges remain. Data for emerging fuels such as RFNBOs and ammonia is still limited, and consensus on the global warming potential of hydrogen leakage is not yet established. This uncertainty is managed through a modular and transparent approach. Hydrogen-related impacts are reported separately using best-available scientific values, ensuring assumptions remain visible and updatable as knowledge evolves. Alignment with international organisations such as ICAO and IMO may prove complex if methodologies diverge globally [13]. Maintaining credibility will require periodic updates reflecting technological advances and evolving fuel pathways. Nevertheless, CLEVER represents the most comprehensive attempt to date to bridge the gap between science and policy in transport emissions accounting.

6 Conclusion

This paper has presented the CLEVER framework, developed under Horizon Europe to harmonise GHG emission factors across transport services. By clarifying lifecycle boundaries, modularising upstream and operational stages, and including additional emission sources such as indirect land use change, methane slip, black carbon, and hydrogen leakage, CLEVER provides a robust methodological basis bridging scientific knowledge and policy application. The framework underpins the forthcoming CountEmissionsEU regulation and aligns with ISO 14083, ensuring both European regulatory

compliance and international compatibility. Its modular design and reporting flexibility make it suitable for regulators and operators, while its dual system of default and actual values balances comparability with incentives for innovation. CLEVER enables fair comparison across energy carriers, incentivises investment in cleaner fuels, and supports digital integration of carbon accounting by providing a credible basis for emission factors. In doing so, it strengthens regulatory and voluntary disclosure schemes and contributes to EU climate neutrality goals. The framework also offers a blueprint for harmonised emission accounting globally, linking scientific rigour with practical implementation in the transport sector.

References

1. Acciaro, M., Van de Voorde, E.: Strategies for decarbonising shipping: a critical review. Maritime Econ. Logist. **22**(3), 335–351 (2020)
2. European Commission: Directive (EU) 2022/2464 amending regulation (EU) no 537/2014 and related directives as regards corporate sustainability reporting. Off. J. Eur. Union. **L322**, 15–64 (2022)
3. European Commission: Directive (EU) 2023/2413 amending directive (EU) 2018/2001 and related acts as regards the promotion of energy from renewable sources. Off. J. Eur. Union. (2023)
4. International Organization for Standardization: ISO 14083: Quantification and Reporting of Greenhouse Gas Emissions from Transport Chain Operations. ISO, Geneva (2023)
5. Intergovernmental Panel on Climate Change: Climate Change 2023: Synthesis Report. IPCC, Geneva (2023)
6. Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R.: JEC Well-to-Tank Report v5. JRC, Ispra (2020)
7. Smart Freight Centre: GLEC Framework for Logistics Emissions Accounting and Reporting, Version 2.0, Smart Freight Centre, Amsterdam (2019)
8. European Environment Agency: EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023. European Environment Agency, Copenhagen (2023)
9. Ocko, I.B., Hamburg, S.P.: Climate consequences of hydrogen emissions. Atmos. Chem. Phys. **22**(14), 9349–9368 (2022)
10. Sand, M., Stohl, A., Berntsen, T.K., et al.: A multi-model assessment of the global warming potential of hydrogen. Commun. Earth Environ. **4**, 146 (2023)
11. Greenhouse Gas Protocol: Land Sector and Removals Guidance. WRI, Washington, DC (2022)
12. emissionfactors.eu: Emission Factors for Transport and Energy Carriers, https://emissionfactors.eu/, Accessed 25 Mar 2026
13. Warwick, N., Pringle, K., Archibald, A., Shine, K.: Atmospheric Implications of Increased Hydrogen Use. UK Government (2022)

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Standardizing GHG Emission Factors: A Critical Review and Gap Analysis

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Abstract. Emission factors (EFs) are crucial in greenhouse gas (GHG) emission calculations, ensuring consistency in converting fuel and energy use into accurate emission accounting. However, inconsistencies and lack of transparency among sources were observed. Variations in how EFs are defined and calculated can distort the environmental impact assessment of energy carriers. The CLEVER project, which supports the CountEmissionsEU initiative, aims at developing a harmonized methodology to assess climate impacts of energy carriers used in transport. In addition, a selection of EFs applying the harmonized methodology is generated to support calculation, reporting, and decision making. Systematic identification of technical gaps and methodological inconsistencies in existing frameworks were an essential initial task. Main findings were inconsistencies in the choice of modelling approach, handling of multifunctionality, design of the system boundary and applied underlying data and a lack of transparency of the implemented approaches. While LCA as a method to assess environmental impacts offers valuable flexibility, this same flexibility can hinder comparability of results, assuming methodical choices or applied data differ. Therefore, developing a consistent, transparent, and comprehensive methodological framework is essential to harmonize EFs use in GHG accounting, support policy development and improve the accuracy of environmental impact assessments.

Keywords: Sustainable transportation · Greenhouse gas (GHG) emission accounting and reporting · Life Cycle Assessment (LCA) · Fuel emission factor standardization

1 Introduction

Emission factors (EFs) are critical parameters for accurately quantifying greenhouse gas (GHG) emissions in the transport sector. They are primarily derived from Life Cycle Assessment (LCA) tools and databases, alongside frameworks, standards, regulations

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and methodological guidelines. These sources show significant interdependencies, and emission factors developed for operational use in the transport sector, as opposed to those tailored for LCA specialists, often integrate data from multiple detailed sources to enhance accessibility for end users. However, this practice can lead to inconsistencies in the resulting EFs.

Previous studies have highlighted the need to harmonize GHG EFs across sectors and geographies, recognizing that such harmonization is essential for ensuring consistency and reliability in emission assessments [1]. A survey within stakeholders provided additional insights into the current state of EF development, highlighting existing gaps and clarifying user requirements.

The objective of this study, conducted as part of the CLEVER project [2], is to investigate the technical gaps and inconsistencies in the current landscape of EF definition, scope, methodology, and calculation. In particular, the study examines how EFs are presented for practical use and how they align with regulatory requirements applicable to companies.

The findings aim to inform the development of a systematic framework for harmonizing the construction of GHG EFs across different energy carriers, addressing technical, regulatory and stakeholder-specific needs. This approach supports European Union initiatives, including the European Green Deal, the Renewable Energy Directive III (RED III) and the CountEmissionsEU regulation, by enabling evidence-based integration of renewable energy into transport systems.

2 Methodology

To perform the gap analysis, a systematic scientific investigation was conducted to investigate the fundamental issues related to the production and presentation of EFs, addressing the root causes of the discrepancies observed. To understand how EFs are structured and compiled, this gap analysis begins with a high-level examination of their structural and methodological foundations, including the rules used to construct life-cycle analyses that influence the subsequent application of EFs.

A cross-comparative analysis of more than 20 fuel types was conducted, demonstrating significant variability driven by allocation assumptions, electricity mix and system boundaries. To support the gap analysis, 52 semi-structured, in-depth interviews were conducted with key stakeholders from the transport sector to identify priority areas of concern.

The gap analysis assessed the relationship between structural components and the energy carriers used in the transport sector to support the fair and comparable development of EFs. Energy carriers were classified according to the Renewable Energy Directive, though alternative classifications and inconsistencies were noted.

3 Results

3.1 Methodological Considerations

EFs are derived from LCAs conducted for specific energy carriers, encompassing the entire chain from raw material extraction to end use. The goal and scope of each LCA determine the methodological choices applied. During this methodological assessment,

potential gaps were identified, particularly where relevant aspects were entirely omitted, such as the exclusion of specific emission types or life-cycle processes. This highlights the importance of establishing robust, consensus-driven conventions for methodological choices across different energy carrier categories, ensuring they accurately reflect the full life-cycle of the product.

Two principal approaches for the system modelling and assessment of transport sector energy-related EFs were identified, attributional which refers to an actual existing average product system and its value chain in a static environment approximating a real-life situation, and consequential that focuses on the impacts of a product system as a consequence of a change, where the environment of the product system is assumed to be dynamic [3]. Although most of the evaluated sources use the attributional approach, which appears more suitable for the generation of EFs, certain situations require the use of the consequential approach such as when considering elements like indirect land-use change (iLUC) [4, 5].

Since a process can result in multiple products, and in many cases cannot be further subdivided, a key methodological consideration is how to address multifunctionality. The chosen approach depends on the modelling framework and may involve system expansion, substitution (commonly used in consequential modelling), or allocation (typically applied in attributional modelling). The methodological choice can lead to significant differences in the resulting GHG EFs. The choice of method for addressing multifunctionality directly influences, and is influenced by, the definition of system boundaries.

System boundaries define the elements included in LCA modelling and represent a critical step in the methodological framework. In the transport sector, system boundaries are typically segmented into different stages: 'Well-to-Tank' (WtT), 'Tank-to-Wheel/Wake' (TtW), and the integrated 'Well-to-Wheel/Wake' (WtW) approach, which is the most relevant. A major methodological gap lies in the inconsistency of system boundary definitions across sources, which has a substantial impact on results, their interpretation, applicability, and comparability. Addressing these inconsistencies is essential. Establishing a sector-wide, standardized methodological framework would help bridge this gap and enhance the transparency, robustness, and comparability of EFs assessments.

Life Cycle Impact Assessment (LCIA) is a core component of LCA. In the CLEVER project, the scope of the LCIA is limited to the impact category of 'Climate Change,' assessed using the most commonly applied metric, Global Warming Potential over a 100-year time horizon (GWP100). However, even when this standardized metric is used, notable differences and inconsistencies can still be observed across sources and studies. These arise from factors such as the use of different or outdated characterization factors - the latest source should be the IPCC 6th Assessment Report [6] - inconsistent treatment of short-lived climate forcers (e.g., black carbon) and varying approaches to the inclusion or exclusion of non-fossil (biogenic) CO_2 emissions [7].

One of the greatest challenges to achieving a harmonized and consistent approach to the generation of EFs lies in the varying goals and intended applications considered during LCA development. The inherent flexibility of LCA allows for multiple methodological choices, including different definitions of system boundaries. This flexibility, while valuable, leads to substantial variation in how EFs are calculated and presented

across different sources. The absence of a standardized framework for system modelling and boundary setting reinforces these inconsistencies. This issue was further substantiated through stakeholder interviews, where a lack of methodological transparency and a strong demand for harmonization emerged as frequent concerns.

3.2 Energy Carrier Categories and Fuel Types

The transition to a more sustainable transport sector is linked to the use of energy sources with low life cycle GHG EFs. Therefore, it is essential to understand the EFs associated with the different types of energy carriers used in the transport and logistics sectors. The European Green Deal establishes a binding target for the EU to source at least 42.5% of its overall gross energy consumption from renewable sources by 2030. Although the Directive focuses on promoting renewable energy use, rather than imposing strict source categorizations, it offers terminology that helps define fuel categories, despite the lack of global alignment. According to the RED, energy sources are categorized as either renewable or non-renewable. Renewable sources are defined as non-fossil and naturally replenishing, including wind, solar, and biomass. Notably, the RED does not classify nuclear energy as a renewable source [8].

3.3 Electricity and Biofuels

Electricity classification depends on its generation pathway, as both emission type and intensity are determined by the production method. Distribution-related factors, such as transmission losses and grid infrastructure, also influence its environmental impact. The CLEVER project highlighted the need for consistent methodologies in reporting electricity generation and emissions, starting with clearly defined system boundaries. Variations in boundary definitions and allocation methods can hinder direct comparisons across different models. However, it noticed these discrepancies arise from methodological choices aligned with the specific goals and scope of each study, rather than from technical limitations.

Biofuels are considered a renewable energy source and can be produced through various pathways using different feedstocks and conversion technologies. While they hold substantial potential to support the achievement of the 2030 renewable energy targets in the transport sector, concerns regarding their sustainability remain. Specifically, biofuels produced from food and feed crops, or from feedstocks associated with a high risk of iLUC, are subject to regulatory constraints. Under current legislation, such high-iLUC-risk biofuels are excluded from counting toward the renewable energy targets for transport [8, 9]. A key challenge in evaluating the environmental impact of biofuels is the limited comparability and great variability of results, highly influenced by methodological assumptions. These include differences in pathway coverage, classification, assessment criteria, mandates and the treatment of biogenic carbon and CO_2. As with other fuel pathways, biofuel value chains are complex and the flexibility inherent in LCA often leads to divergent system boundaries.

3.4 RFNBOs, Hydrogen and RCFs

Renewable fuels of non-biological origin (RFNBOs) include fuels such as renewable hydrogen, which also serves as a feedstock for other RFNBOs like e-kerosene and e-gasoline. In contrast, fuels made using carbon monoxide from industrial off-gases (e.g., steel production) are classified as recycled carbon fuels (RCFs). RCFs can also include syngas from waste, provided the carbon source is non-biological; in the case of municipal solid waste gasification, the syngas is classified partly as a biofuel (proportional to its biogenic content) and partly as an RCF. RFNBOs covers a wide variety of fuels and offer alternatives to fossil fuels, but classification depends entirely on production pathways, only fuels produced from non-biological renewable sources qualify. A key challenge in assessing RFNBO EFs is their limited representation in life cycle data sources: while some references in the CLEVER state-of-the-art review reported WTT emissions for e-fuels in general, only a limited number addressed RFNBOs specifically.

Hydrogen serves as a precursor for the synthesis of other RFNBOs, depending on the selected conversion pathway and associated process conditions. Hydrogen is considered a cleaner alternative to conventional energy carriers and can be produced via multiple pathways, each with varying environmental impacts. EFs associated with hydrogen production differ across sources. The GREET model [10] offers the most comprehensive coverage of production pathways, followed by the International Maritime Organization (IMO) [9]. However, the latter presents challenges in data traceability, limiting its applicability in certain calculations. It is important to note that no single database fully captures the complete range of possible hydrogen production routes.

Differences in the EFs can be due to many reasons. Our work was able to summarize gaps and difference in the hydrogen production (WTT phase). Hydrogen production's environmental impact is highly dependent on system boundaries, which present high variation across data sources. Some databases include distribution and storage impacts beyond the production facility ("gate"), while others stop at the hydrogen production point, causing inconsistencies in GHG EFs. Additionally, differences in characterisation methods, such as how emissions like CO_2, CH_4, and especially H_2, are accounted for, create further divergence. Hydrogen is not currently classified as a GHG by the IPCC, but recent studies propose assigning it a global warming potential of around 11 due to its indirect climate effects [11–14]. This represents a major modelling gap, especially given the wide variance in hydrogen leakage estimates during transport and distribution, which could dramatically affect GHG outcomes.

Several technological and methodological factors contribute to emission variability. The production process, whether hydrogen is obtained via methane reforming, electrolysis, or other chemical routes, has significant implications for GHG emissions. Electrolysis, particularly green and pink hydrogen pathways, remains underrepresented in current databases, with most data still based on outdated chlor-alkali systems. Technology efficiency and electricity sourcing further affect modelling outcomes, as renewable electricity inputs and electrolysis performance can substantially affect EFs result. Infrastructure emissions are often omitted, especially those from electricity generation and hydrogen transport, represent another important source of variation. In addition, allocation methods for dividing emissions between co-products (mass-, energy-, or economic-based) can lead to considerable divergence in life cycle results.

Transport and distribution practices are also a major source of inconsistency. While GREET includes detailed modelling of road and pipeline transport, most other sources omit logistics entirely or treat hydrogen as generic freight, ignoring unique requirements such as pressurization and losses. Liquid and gaseous hydrogen differ greatly in distribution energy demand and loss rates. Existing LCA databases contain only a limited number of transparent or suitable methodologies for alternative transport modes, such as pipelines or maritime shipping. Accurate modelling requires that future databases incorporate realistic logistics pathways, include storage and refuelling station energy use and apply hydrogen-specific emission intensities to reflect real-world infrastructure and transport conditions.

RCFs are an emerging class of fuels derived from waste materials of non-renewable origin, such as plastic and industrial off-gases, which are no longer suitable for conventional recycling pathways. As a relatively novel fuel category, both the production technologies and methodologies for EF quantification are still under development. Harmonized estimation of EFs for RCFs is influenced by multiple factors, including feedstock heterogeneity, production process variability, regional and technological differences, data availability and quality, and the specific scope and boundaries of the LCA, resulting in a critical need to establish dedicated and robust EFs specifically tailored to the RCF category.

3.5 Operational Emissions Not Directly Linked to the Energy Carrier

Traditional emission factor methodologies often oversimplify real-world impacts by only considering the carbon content of the fuel and assuming complete combustion to CO_2. This omits other significant operational emissions such as unburned hydrocarbons (e.g., methane and N_2O), combustion of non-fuel substances like lubricants or urea and other pollutants. These underestimated emissions vary greatly depending on vehicle type, engine technology, and aftertreatment systems. To ensure comprehensive and accurate emission accounting, especially in the context of modern fuels and technologies, it is critical to consider these additional operational phase impacts in methodologies [15].

Methane emissions, particularly methane slip from engines using natural gas or biomethane, are an example of underreported operational emissions. Despite its lower CO_2 output upon combustion, the high global warming potential (GWP100 = 29.8) [6] of the methane makes even minor leakages highly significant. While many emission factor databases acknowledge methane slip and sometimes vary estimates by engine type, the transparency and granularity of such data differ significantly between sources. Where engine-specific data is lacking, standards like the GHG Protocol recommend using the highest plausible slip values to avoid underestimation. However, implementation of this precautionary principle is inconsistent across datasets, highlighting the need for harmonized, transparent approaches in operational emission modelling.

Selective Catalytic Reduction (SCR) systems, widely used to reduce NOx emissions in vehicles and industry, introduce challenges in accurately calculating EFs due to byproducts formed during the process. While SCR effectively converts NOx to nitrogen and water, the decomposition of urea used as a reductant releases CO_2, and side reactions can generate nitrous oxide (N_2O), a potent GHG. Current EF models, such as COPERT and HBEFA, generally do not differentiate N_2O emissions from SCR systems separately

from those produced by fuel combustion, resulting in gaps and uncertainties in quantifying their true climate impact. Although CO_2 emissions from urea consumption can be estimated using standardized methods based on urea usage, the contribution of N_2O remains underrepresented, especially as its formation depends on factors like catalyst condition, dosing strategies, and operational variables.

Similarly, high-altitude emissions from aviation introduce significant uncertainties in EF calculations due to complex non-CO_2 climate impacts, including ozone formation, contrails and water vapor effects, which are sensitive to altitude, latitude, and atmospheric conditions. Most EF databases omit or inadequately represent these effects, leading to underestimation of aviation's true climate impact. Some advanced models, such as NEATS and TREMOD [16], are developing more accurate approaches by incorporating flight-specific data, but many current methodologies rely on simplified emission weighting factors that cannot fully capture the variability and complexity involved. Together, these gaps highlight the need for improved, transparent and harmonized EF methodologies to better quantify indirect and secondary emissions from SCR catalysts.

4 Discussion and Conclusions

This study assessed the consistency and transparency of the EF methodologies across energy carriers and identified key methodological gaps impacting GHG emission accounting. Emerging fuels showed greater variability due to differences in production pathways and feedstock sources. For most energy carriers evaluated, data fragmentation was observed, alongside inconsistencies in land-use considerations and sector-specific issues. Harmonizing EF methodologies emerged as a key priority to support the sustainability of the transport sector and to reduce the fragmentation caused by independent development of EFs by multiple institutions. The current lack of alignment across regions, sectors and regulatory bodies leads to discrepancies in methodologies, hindering meaningful cross-comparisons.

To address these challenges, adoption of a harmonized and transparent approach to EF calculation is recommended, based on consistent assumptions and clear documentation. The next steps of the CLEVER project focus on developing a unified methodology for calculating fuel EFs across energy pathways. This methodology is intended for integration into the CountEmissionsEU initiative as a default EF database, supporting consistent GHG reporting and alignment with CSRD requirements.

This implementation is expected to strengthen comparability, enhance transparency and improve the application of EFs in both policy and operational contexts.

References

1. Roux, M., Ekvall, T., Schmidt, J., Vega, G.: Which rules to follow? How differences in renewable fuel standards obscure the potential climate impact of transportation fuels. Front. Energy Res. **12** (2024). https://doi.org/10.3389/fenrg.2024.1490137
2. CLEVER Emission Factors Website. https://emissionfactors.eu. Accessed 23 Mar 2026
3. Prussi, M., Yugo, M., De Padra, L., Padella, M., Edwards, R., Lonza, L.: JEC well-to-tank report V5. Publications Office of the European Union. (2020). https://doi.org/10.2760/959137

4. International Civil Aviation Organization: CORSIA Methodology for Calculating Actual Life Cycle Emissions Values (2025)
5. JRC-IES: International Reference Life Cycle Data System (ILCD) Handbook - General Guide for Life Cycle Assessment - Detailed Guidance. Publications Office of the European Union, Luxembourg (2010)
6. IPCC: Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change. In: Intergovernmental Panel on Climate Change, vol. 184, (2023). https://doi.org/10.59327/IPCC/AR6-9789291691647
7. Greenhouse Gas Protocol: Land Sector and Removals Guidance, Draft for Pilot Testing and Review (2022)
8. European Commission: DIRECTIVE (EU) 2023/2413 of the European Parliament the Council amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council Directive (EU) 2015/652 (2023)
9. International Maritime Organization: MEPC81/WP.4 REDUCTION OF GHG EMISSIONS FROM SHIPS (2024)
10. Argonne National Laboratory: Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (2023)
11. European Commission: Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (2022)
12. Ocko, I.B., Hamburg, S.P.: Climate consequences of hydrogen emissions. ACP. **22** (2022). https://doi.org/10.5194/acp-22-9349-2022
13. Sand, M.: A multi-model assessment of the global warming potential of hydrogen. Commun. Earth Environ. **4** (2023). https://doi.org/10.1038/s43247-023-00857-8
14. Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., Shine, K.: Atmospheric implications of increased hydrogen use (2022)
15. European Environment Agency: EMEP/EEA air pollutant emission inventory guidebook 2023 - technical guidance to prepare national emission inventories. In: Publications Office of the European Union (2023). https://doi.org/10.2800/795737
16. Allekotte, M., Kräck, J., Knörr, W.: Weiterentwicklung TREMOD – Clustermodell Flugverkehr Integration von Nicht-CO2-Effekten in TREMOD-AV. IFEU. (2024)

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Introducing Circularity in Public Transport for Greater Sustainability: From Strategy to Action

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Abstract. Public transport (PT) systems are vital to society, providing access to goods, services, and opportunities. However, the construction, maintenance, and decommissioning of PT assets contribute to carbon emissions, resource depletion, and ecological disruption. The CE4CE (Circular Economy for Central Europe) project addresses this by promoting a shift from a linear to a circular model using the "Avoid-Extend-Transform-Enable" life-cycle framework. This framework has been applied to develop three strategies focused on rolling stock, infrastructure, and energy, based on consultations with public transport operators (PTOs) from Central Europe and beyond. These three strategies serve as the foundation for localized, stakeholder-aligned action plans in Leipzig, Bergamo, Gdynia, and Maribor.

This paper provides a concise overview of these strategies, covering: 1) the application of the life-cycle thinking framework to each pillar; 2) a status quo analysis of circularity integration in PT systems; 3) a catalogue of practical cases for implementing circularity; and 4) a set of tailored indicators for monitoring and measuring impact. The paper also discusses how these strategies have been adapted into action plans, supporting the transition from isolated initiatives to more strategic, life-cycle-oriented approach in PT, with a greater focus on resource efficiency and a significant reduction in ecological impacts.

Keywords: Circular Economy · Public Transport Systems · Life-Cycle Framework

1 Introduction

Public transport assets are fundamental to the functioning of mobility systems. They provide the physical foundation for the movement of people and goods, enable equitable access to opportunities, and lower the ecological footprint of transport compared

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to private modes. Yet their production, construction, operation, and eventual decommissioning generate ecological pressures that are still only partially addressed. Linear models of extraction and disposal (i.e. a make-use-throw approach), have fuelled high resource demand and systemic inefficiencies, resulting in waste generation and subsequent embodied emissions that extend well beyond operational activities.

The CE4CE project (Circular Economy for Central Europe) responds to these challenges by advancing a circular paradigm for public transport through its Circularity Compass framework. This is built on the Avoid–Extend–Transform–Enable (AETE) approach: *Avoid* reduces impacts through resource-efficient design and procurement; *Extend* prolongs service life via maintenance, refurbishment, and retrofitting; *Transform* ensures that end of life materials is reused, repurposed, or recycled; and *Enable* provides the governance, policy, and organisational conditions for implementation. Using this framework, CE4CE has developed strategies for three key asset groups—rolling stock, infrastructure, and energy—that assess both direct and embodied emissions and provide sector-specific recommendations. These strategies form the basis for four local action plans, translating circularity into concrete measures with commitments from public and private stakeholders to accelerate the transition toward net zero public transport (Fig. 1).



Fig. 1. Circularity in Public Transport (Source: [1])

This paper synthesizes the three strategies, drawing on their conceptual basis, methodological approach, and results. It highlights the potential of circularity to reduce environmental impacts across PT systems, elaborates the role of stakeholders in co-creating action plans, and discusses how these strategies can be scaled across Central Europe and beyond.

The paper contributes to the growing field of circular public transport by operationalising the Avoid–Extend–Transform–Enable (AETE) framework across three key asset domains—rolling stock, infrastructure, and energy. It translates a life-cycle perspective into actionable strategies and locally validated action plans, bridging the gap between high-level circular economy principles and implementation in real-world public transport systems. The added value lies in integrating stakeholder-driven insights with practical tools (e.g. procurement criteria, second-life applications, and digital solutions), offering a replicable model for advancing circularity and reducing both operational and embodied emissions in European public transport.

2 Literature Review

Circularity in public transport, understood as a holistic life cycle vision that addresses the full ecological impacts of assets from manufacturing to decommissioning, remains a relatively new field of research and practice. To date, practices to improve environmental performance have been dominated by electrification in the case of rolling stock and by energy efficiency measures in the case of built infrastructure such as rail systems, both aimed primarily at reducing emissions and energy demand from operational activities (Scope 1). While this focus has been undeniably important, it has tended to overlook the equally significant impacts arising from non- operational activities, namely the production, maintenance, and end of life management of vehicles, batteries, and infrastructure, which together account for substantial embodied emissions. The CE4CE strategies do not primarily generate new empirical evidence but rather review and compile existing sources, foregrounding a life cycle perspective that brings these overlooked dimensions into view and situates them alongside operational concerns.

The literature underpinning the rolling stock strategy seeks to move beyond the well-established focus on fleet electrification by examining impacts across the entire life cycle, both upstream and downstream. At the avoid stage, studies show that vehicle production embeds large volumes of carbon intensive materials such as steel and aluminium, making procurement choices decisive for lifetime emissions [2]. At the extend stage, the literature highlights how predictive maintenance and refurbishment can prolong vehicle use, while modular components and interoperable spare parts reduce the need for premature replacement [3]. At the recover stage, however, most rolling stock is still dismantled without high value recovery, and secondary markets remain limited [4]. In conclusion, the strategy argues that a more comprehensive life cycle approach should prioritise remanufacturing and established, reliable and harmonized second-hand platforms as key pathways to improve circularity, supported by governance measures such as public procurement requiring design for disassembly to create the enabling conditions for systemic change [5].

The literature reviewed for the infrastructure strategy shows that the heaviest ecological burdens are often concentrated at the *Upstream and operational* stage. The construction of rail and public transport facilities depends on carbon intensive materials such as steel, cement, and aggregates. This locking in resource flows prevail for decades during the operational stage since many assets exceed fifty years of service life [6, 7]. At the end-of-life, and despite steady improvements in recycling rates for construction and demolition waste in the European Union, a large share of recovered material continues to be downcycled into low grade applications such as road sub bases, which does little to displace the demand for virgin resources [3]. The strategy also highlights that reliable life cycle data remains scarce and fragmented across stakeholders, limiting informed decision making and obscuring the scale of embodied emissions in public transport infrastructure [8].

The literature reviewed for the energy strategy shows that electrification, while central to decarbonising public transport, is shaped by upstream energy sources and downstream recovery practices. At the avoid stage, the European Green Deal and the REPowerEU Plan emphasise that climate benefits depend on renewable electricity, since fossil-based generation can negate well-to-wheel reductions [9]. During operation, the *Global EV Outlook 2023* reports that battery efficiency and longevity are strongly influenced by charging patterns and grid integration, with unmanaged charging accelerating degradation and increasing energy demand [10]. At the recover stage, end-of-life batteries remain a critical challenge: although recycling technologies can technically recover most key materials, real-world recovery rates remain far lower [11]. Recent assessments underline that without stronger investment and regulation, Europe risks missing the opportunity to build a closed-loop battery value chain [12].

3 Methodology

Since the strategies aim to provide strategic guidance for advancing circularity, it was first necessary to assess the current status of circular practices in public transport systems in Central Europe and to translate these findings into practical recommendations. Achieving this objective required collecting first-hand insights from key stakeholders, in particular public transport operators (PTOs) and public transport authorities (PTAs).

Primary data collection differed across the three strategies. For infrastructure, surveys based on the Circularity Compass self-assessment tool were distributed to public transport operators and complemented by follow-up interviews to deepen the analysis. For rolling stock and energy, information was gathered mainly through targeted consultations, workshops, and exchanges with operators, authorities, and industry partners, which served to validate the literature review and highlight barriers and opportunities specific to Central European contexts. In the case of the energy strategy, this process was reinforced by desk research on EU policy frameworks, industry roadmaps, and case studies of charging and storage solutions. These findings were further enriched through discussions with project partners and operators, offering insights into practical challenges such as interoperability of charging infrastructure, grid integration, and battery end-of-life management.

4 Key Results and Takeaways

When it comes to rolling stock, the procurement process is central to defining circularity strategies, covering both upstream aspects (design, materials, components) and downstream phases (maintenance, refurbishment, end-of-life, and second-life applications).

To pursue circularity objectives, several recommendations emerge. Fleet renewal plans within decarbonisation strategies should include long-term approaches and indicators to forecast impacts. Procurement value should be assessed using tools such as cost-benefit analysis (CBA) and life cycle assessment (LCA). Circular requirements – such as the use of secondary materials, modularity, repairability, and recoverability – should be integrated into tender documents, with higher scores awarded to innovative solutions like closed-loop models and material passports.

Tendering procedures should encourage joint procurement, shared frameworks, and knowledge exchange among stakeholders to pool demand, reduce costs, and accelerate innovation. Early supplier engagement is essential to support collaboration. Procurement approaches may also integrate rolling stock, infrastructure, and energy, alongside different acquisition models such as purchase, leasing, or service-based solutions.

A key element of circular value chains is the battery of e-buses. Procurement requirements, including battery characteristics, battery management systems, and compliance with EU regulation, should enable circular practices and recovery potential. Repurposing second-life batteries allows their reuse for energy storage, supporting renewable energy integration, grid stability, and EV charging. This can also take place at depots. Cross-sector applications require collaboration, standards, and value-sharing mechanisms.

In Public Transport Infrastructure (PTI), circularity remains limited by data gaps and coordination challenges. In the 'Avoid' phase, operators often lack ownership of assets, constraining action. Energy reduction is a key priority, while insufficient material data remains a barrier.

In the 'Extend' phase, reuse practices are common but often financially driven rather than strategic. Constraints include spare parts availability and limited supplier warranties. In the 'Transform' phase, fragmentation, lack of know-how, and insufficient recycling systems persist, although metals such as steel and copper show high recycling rates. Construction waste remains a major challenge.

In the 'Enable' phase, policies have increased awareness, but funding gaps and permitting barriers remain. Digital tools, such as Building Information Modelling (BIM) and digital twins, are key enablers.

Energy acts as the linking element between vehicles and infrastructure, requiring an integrated lifecycle approach. Procurement choices are critical to enabling circular and energy-efficient systems. Green procurement should prioritise durability, repairability, recyclability, and LCA criteria.

Infrastructure investments must align with fleet and grid requirements, integrating charging, storage, and renewable energy. Mobility hubs can function as energy nodes, improving efficiency and system resilience.

Digital tools support optimisation through predictive maintenance, eco-driving, and smart energy management. At end-of-life, components—especially batteries—should

prioritise reuse and second-life applications before recycling. EU policies, including the Battery Regulation and Digital Product Passports, support material tracking and recovery.

Overall, this transition shifts public transport energy use from a linear to a circular system, integrating procurement, operation, infrastructure, and end-of-life management into a coherent framework.

5 Discussion and Conclusions

Circular mobility solutions can generate environmental, economic, and operational benefits. Environmentally, they reduce lifecycle emissions (kg CO_2e per vehicle/km/asset) and increase material recovery (% recycled or reused materials). Economically, they lower total cost of ownership (€/km over lifecycle) and retain value through reuse (% residual component value). Operationally, they extend asset lifetime (average service life in years) and improve efficiency and reliability (energy consumption per km; asset downtime %).

The CE4CE strategies examine the public transport ecosystem through the lens of the AETE circularity framework, offering a life cycle approach that can drive transformative change in energy generation and integration, infrastructure planning, fleet renewal and management. It promotes a more holistic way of planning, using, maintaining, and decommissioning assets to reduce resource use, boost resilience, and respond to environmental, social, and economic challenges.

The following actionable lessons emerge from the results. First, embed circularity in procurement, since procurement is the main leverage point for influencing life-cycle impacts. Secondly, prioritise life-cycle extension strategies, especially maintenance, refurbishment, retrofitting, and battery second life. Third, strengthen collaboration across the value chain, as circularity depends on coordination among operators, authorities, suppliers, and recyclers. Invest in data and digitalisation, including LCA, BIM, digital twins, and material information systems, to support decisions and monitoring. Last but not least, integrate fleet, infrastructure, and energy planning so that improvements in one domain reinforce rather than undermine the others.

The proposed strategies are closely aligned with key EU policy frameworks, reinforcing their relevance for European stakeholders. They directly support the objectives of the European Green Deal and Fit for 55 package by addressing both operational and embodied emissions. The focus on circular procurement and resource efficiency contributes to the Circular Economy Action Plan, while battery reuse and recycling pathways are consistent with the EU Battery Regulation (EU 2023/1542). Furthermore, the emphasis on renewable energy integration and system efficiency aligns with the REPowerEU Plan, and the use of digital tools such as BIM and digital product passports reflects the EU's digitalisation agenda. This alignment ensures that the proposed strategies not only respond to local needs but also contribute to achieving EU-wide climate neutrality and resource efficiency targets.

The strategies serve as a flexible foundation for developing Action Plans with the CE4CE project scope and beyond, aiming to support wider adoption of circularity principles among European public transport organizations.

So far, the strategies have been translated into four action plans in Leipzig (focusing on circular management of tram infrastructure and its predictive maintenance), Gdynia (aiming at increasing resource-efficiency, resilience and sustainability), Bergamo (where the main findings align with the ambition of the PTO to become circular, from procurement to infrastructure and fleet management), and Maribor (focused on the reuse of batteries for renewable energy storage). Beyond these results, the comprehensiveness and complementarity among the three strategies will allow for their replication in different contexts, integrating circularity principles to accompany the decarbonisation process of public transport, supporting its effectiveness and long-term sustainability.

The main limitation of the proposed approach relies in the fact that, although the circularity measures identified and proposed across the three strategies show a range of proven positive impacts at environmental, economic and social level, a systematic impact assessment has not yet been developed, to quantify the potential contribution of circularity paradigms across the public transport ecosystem.

References

1. López, L.: The circularity compass: advancing circular economy innovation in public transport systems. Rupprecht Consult and trolley:motion. (2025) https://circularity4publictransport.eu/circularity-compass/
2. González-González, E., Nogués, S., Stead, D.: Circular economy in urban transport: refurbishment, remanufacturing, and lifetime extension of rolling stock. J. Clean. Prod. **352**, 131528 (2022). https://doi.org/10.1016/j.jclepro.2022.131528
3. UITP: Towards Circularity in Public Transport: Asset Management and Lifetime Extension. International Association of Public Transport, Brussels (2022)
4. European Environment Agency: Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy. EEA, Copenhagen (2020)
5. ICLEI: Local Governments for Sustainability: Circular Procurement in Transport Systems: a Practical Guide for Public Authorities. ICLEI, Freiburg (2021)
6. Liljenström, C., Malmqvist, T., Erlandsson, M., Fredén, J.: LCA and LCC of railway infrastructure: environmental and economic impact of maintenance strategies. Eur. J. Transp. Infrastruct. Res. **19**(2), 97–113 (2019). https://doi.org/10.18757/ejtir.2019.19.2.4378
7. DecarboN8: Embodied emissions in rail infrastructure. DecarboN8 Research Network, York (2021). https://decarbon8.org.uk/EmbodiedEmissions-rail/
8. BSI: BS EN 15978: Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method. British Standards Institution, London (2011). https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/
9. European Commission: REPowerEU Plan (COM/2022/230 Final). European Commission, Brussels (2022) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0230
10. International Energy Agency: Global EV Outlook 2023: Catching up with Climate Ambitions. IEA, Paris (2023) https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf
11. Harper, G. et al.: Recycling lithium-ion batteries from electric vehicles. Nature. **575**(7781), 75–86 (2019). https://doi.org/10.1038/s41586-019-1682-5
12. Transport & Environment: From Waste to Value: the Potential for Battery Recycling in Europe. Transport & Environment, Brussels (2024) https://www.transportenvironment.org/articles/from-waste-to-value-the-potential-for-battery-recycling-in-europe

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Assessing Waste Management and Sustainability at Riga Airport Through a Life Cycle Assessment Lens

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Abstract. This study presents an environmental analysis of Riga Airport (RIX) with a specific focus on waste management systems and the application of Life Cycle Assessment (LCA) as a methodological framework. Research aims to assess current airport waste handling capabilities, sustainability objectives, infrastructure deployment, and alignment with regional and national environmental policies. Despite growing ambition, several performance gaps remain, including limited real-time waste tracking, incomplete recycling coverage, and a lack of integrated LCA modelling in operations. The analysis draws from primary survey data, expert interviews, airport sustainability reports, and national policy frameworks. RIX has the structural potential to leapfrog its peers through coordinated LCA adoption, investment in smart segregation infrastructure, and alignment with circular economy strategies. This research contributes to the evolving discourse on sustainable aviation management in Eastern Europe. It offers actionable recommendations for airport operators, urban planners, and policymakers, supporting the development of a data-driven, regionally harmonized sustainability roadmap anchored in LCA and circular economy principles.

Keywords: Sustainable Aviation Infrastructure · Life Cycle Assessment · Environmental Analysis · Waste Tracking

1 Introduction

Riga Airport (RIX) stands as the largest air transport hub in the Baltic region, encompassing Latvia, Estonia, and Lithuania. From a geographical and infrastructural perspective, RIX operates as a critical gateway layer, shaping the aviation framework of Northern Europe by integrating transport flows and providing essential services ranging from passenger processing to logistics and air freight. The airport's infrastructure, including terminal facilities, ground transportation connections, and cargo handling capacities, reflects broader regional development plans aimed at fostering sustainable mobility.

The environmental footprint of the aviation sector, including waste generation from airport operations, is significant due to increasing passenger and cargo traffic and addressing this impact is crucial for sustainability [1]. There is a distinct lack of site-specific Life Cycle Assessment (LCA) research on airport waste management (WM) in the Baltics.

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RIX's scale and regional importance necessitate a targeted LCA study on its WM to fill a critical research gap and drive effective, sustainable operational improvements. At RIX, a lack of site-specific LCA data and limited integration of LCA outputs into decision-making hinders the effectiveness of current WM.

The primary aim of this research is to assess the current WM capabilities at Riga Airport through the lens of LCA. Two main research questions formulated are: (1) Which gaps exist in RIX's WM infrastructure, and how can LCA integration address these gaps? (2) How we can specify a LCA framework by targeted stakeholder input, provide the necessary data-driven recommendations for systemic improvement? By answering in these questions, the study seeks to identify areas of improvement and provide actionable recommendations that support RIX's transition towards a more sustainable and environmentally responsible operation.

2 Literature Review

The LCA represents a rigorous analytical framework designed to evaluate the environmental burdens of activities throughout their entire lifecycle from cradle to grave [2]. It systematically quantifies inputs, outputs, and impact categories such as emissions intensity, resource depletion, and toxicity [3]. In airport WM, LCA is particularly relevant due to the complexity of waste streams generated by passenger services, catering, retail, and maintenance operations [4]. It is well suited to assessing heterogeneous materials plastics, organics, metals, and hazardous waste where optimized treatment and disposal are essential [5]. Applications of LCA in airport waste systems have proven effective in identifying inefficiencies and recommending material or process improvements to reduce environmental footprints [6].

For RIX, LCA enables alignment with evolving regulations and sustainability objectives, while supporting circular economy principles and operational efficiency critical for addressing non-CO_2 emissions, waste generation, and resource conservation in the Baltic aviation sector [7]. Research indicates that single-use plastics remain dominant and segregation inefficiencies persist, with trade-offs between conventional and biodegradable materials highlighted in LCA studies [8]. Most aviation LCAs still prioritize flight emissions, often overlooking full waste lifecycle impacts [9]. This underscores the need for locally tailored, transparent, and data-driven LCA models to strengthen circular WM transitions, policy alignment, and comprehensive sustainability assessment. Transitioning from linear to circular WM models, evaluated through LCA and supported by renewable energy adoption, enhances both environmental and operational performance [10]. However, consistent, transparent methodologies remain under development, and assumptions must be well documented to ensure reproducibility. There is a clear need for locally tailored, data-driven LCA models to support continuous improvement, policy alignment, and multi-criteria sustainability assessment.

3 Research Methodology

Life Cycle Assessment (LCA) for waste management (WM) evaluates environmental impacts across the entire lifecycle of a product or service, moving beyond disposal to assess full system alternatives (e.g., recycling vs. incineration). It follows four phases:

(1) Goal and Scope Definition, establishing boundaries, functional unit, and included processes; (2) Life Cycle Inventory (LCI), collecting data on inputs (energy, materials) and outputs (emissions, waste); (3) Life Cycle Impact Assessment (LCIA), translating inventory data into environmental impact categories using scientific models; and (4) Interpretation, identifying hotspots, conducting sensitivity analysis, and informing policy decisions. Stakeholder surveys are particularly relevant in 1st and 2nd phases. In the 1st phase, they help define functional units, system boundaries, and priority impact categories. In the impact assessment phase, surveys support weighting of impact categories, incorporating social values and stakeholder preferences into decision-making.

This study establishes an empirical foundation for LCA at RIX through a structured survey conducted online and face-to-face stakeholder interview, designed to capture insights into RIX WM practices, system effectiveness, and barriers to circularity. The survey applied a purposive sampling approach targeting major operational categories within the RIX ecosystem. Invitations for survey participation were extended to airport operators, ground handling companies, environmental managers, airline and catering staff, and regulatory officials.

The questionnaire included 24 questions and was divided into 7 sections. The first section consisted of general information about role of respondents. The second section dedicated to current state of sustainability at RIX and included 3 questions. Section 3 included 3 questions about goal definition, Sect. 4 - questions about scope; Sect. 5 - questions about inventory analysis; 6 - questions about impact assessment and interpretation, last section - questions about final considerations. Respondents were asked to rate each indicator in a Likert scale or chose the three most important aspects.

The survey was conducted in August to September 2025, and responses were received from 32 participants, and included airline operators, ground handlers, airport operators, environmental managers, air traffic controllers, and security staff. Insights from these primary sources were supported by interviews with RIX airport officials and operational and policy document analysis providing a comprehensive understanding of system strengths and ongoing challenges.

4 Survey Results: Current WM Practices at RIX

The results are based on a targeted RIX airport stakeholder survey responses and with in-depth interviews to examine RIX's WM system and to triangulate operational, technical, and organizational perspectives. The stakeholder survey and interviews at RIX revealed persistent inefficiencies in WM across all principal streams, terminal (passenger), cabin (catering), operational (maintenance), and hazardous waste, with terminal waste being the most voluminous and prone to inconsistent segregation and recycling outcomes. Although infrastructure such as compactors, ballers, and transfer stations is in place, the application of renewable or biodegradable materials is still confined to pilot initiatives within in-flight catering, signalling slow and fragmented system-wide adoption.

Table 1 is created as summary of the survey responses; the stakeholder analysis underscores three overarching insights regarding sustainability management at RIX. First, data and measurement emerge as systemic weaknesses, with airport operators, ground handlers, and airlines consistently citing manual measurement, data gaps, and poor integration as barriers. This suggests that despite the presence of ISO certifications, the lack

of standardized and digitalized tools significantly constrains the comprehensiveness of sustainability assessments.

Table 1. Stakeholder Response & Perception Analysis

Stakeholder Role	Certification	Effectiveness Score	Top Challenge	Circular Economy Awareness
Airport Operator	ISO 14001	Moderately to Very effective	Manual measurement	Moderate
Ground Handler	ISO 14001, ISO 9001	Slightly to Moderately eff.	Budget, data integration	Limited
Environmental Manager	ISO 14001	Very effective	Staff training	High
Security & ATC	ISO 14001	Slightly effective	Data/system fragmentation	Low to Moderate
Airline Operator	ISO 9001	Moderately effective	Data gaps, engagement	Low to Moderate

Second, circular economy awareness is unevenly distributed across stakeholder groups. While environmental managers demonstrate high levels of understanding, other actors such as ground handlers, airlines, and security services report only limited to moderate awareness, reflecting a fragmented knowledge base and underscoring the need for cross-departmental training and cultural alignment. Third, perceptions of effectiveness vary by role and proximity to sustainability functions. Environmental managers perceive the framework as very effective, while peripheral stakeholders including ATC, security, and airline operators express only slight or moderate confidence, indicating that sustainability practices are concentrated within specialist units rather than embedded across the wider airport ecosystem.

A key weakness identified by respondents is the absence of an integrated, airport-wide data management system. Waste data collection relies largely on manual weighing and ad hoc reporting, resulting in errors, incomplete records, and limited visibility of contamination rates and recycling performance. Although ISO 14001-certified divisions rated their waste management (WM) systems as moderately effective, ground handlers and support staff highlighted weak feedback loops, limited cross-departmental communication, and poor information sharing. These issues are compounded by irregular staff training and the lack of standardized circular economy (CE) guidelines.

Most staff reported only basic to moderate familiarity with CE principles, with few confident in applying them operationally. WM decisions at RIX remain primarily compliance driven. While CE benefits are recognized, implementation is constrained by weak incentives, inconsistent training, and uneven leadership support. Monitoring and reporting are largely event-driven linked to audits or major changes rather than based on systematic, real-time data, hindering continuous improvement. Training gaps are widespread, particularly in onboarding, advanced waste segregation, circular practices,

and technology use. Despite alignment with national and EU targets in selected initiatives, deficiencies in compliance monitoring and misalignment between procurement and sustainability remain. All interviewed stakeholders emphasized that integrating Life Cycle Assessment (LCA) is critical to overcoming these structural limitations.

Key quantitative findings are followings:

- Terminal waste identified as the largest stream, with segregation rates estimated by staff to range from 50–75% in priority zones, but only ~30% in non-priority or public-facing areas.
- Cabin waste recycling opportunities are primarily realized in flights serving EU destinations, correlating with regulatory requirements; other routes lag in compliance and circular practices.
- Hazardous and operational waste such as de-icing liquid consistently reported as under-measured due to safety protocols and lack of full digital integration.
- Staff training frequency for 30% of respondents stated they receive training less than once per year, others reported ad hoc based on regulatory changes.
- Frequency of data review as most departments indicated they update waste data only after major operational changes, audit events, or the introduction of new legislative requirements.

Moreover, the survey data makes clear that all respondent groups recognize LCA as an essential tool for advancing RIX's WM objectives. They expect it to improve compliance, enable cost and resource efficiencies, and accelerate sustainable innovation, provided that supportive infrastructure and training are instituted as part of the LCA implementation process. Fig. 1 shows that the most stakeholders (13) favoured reviewing the LCA every 2–3 years, reflecting a preference for structured periodic updates. Annual reviews (11) were also supported, while fewer respondents (8) preferred revisions only after major changes, indicating less support for reactive approaches.

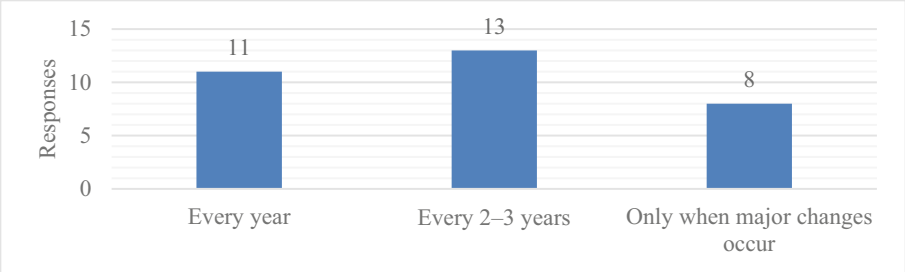


Fig. 1. Expected intervals for reviewing and updating the LCA

The Fig. 2 shows that stakeholders most frequently identified driving innovation in recycling and energy recovery (14) as the key contribution of LCA. Economic and regulatory aspects, such as cost savings in waste handling (7) and compliance with EU directives (6), were also valued, with reputational benefits (5) seen as less critical

In Fig. 3, the dominant response (18) was somewhat confident, suggesting cautious optimism about LCA's influence on decision-making. Smaller groups expressed either

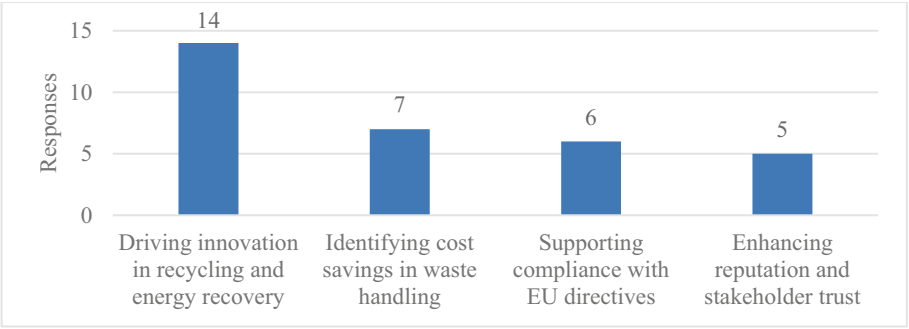


Fig. 2. LCA integration as a driver of long-term sustainability at RIX

limited trust (slightly confident, 8) or more extreme views, with 3 each reporting very confident and not confident.

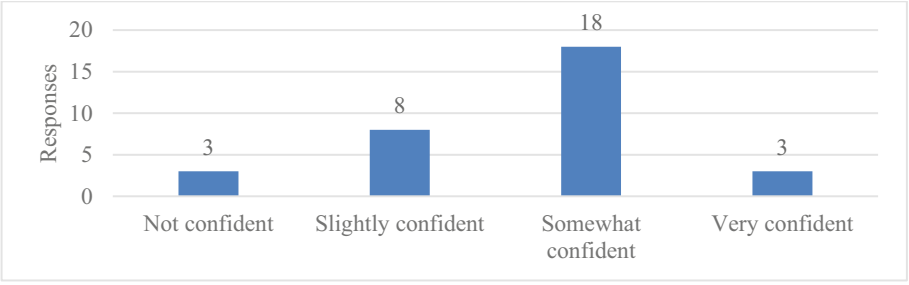


Fig. 3. Stakeholder confidence in LCA impact at RIX

LCA was recognized as uniquely capable of supporting consistent benchmarking, revealing inefficiencies, and guiding cost-saving and resource-efficient interventions. Staff emphasized that integrating LCA with digital data infrastructure and ongoing training would allow targeted, transparent, and measurable improvements. Embedding LCA-informed processes was universally viewed as key to achieving genuine circular economy transformation and continuous operational improvement at RIX. Collectively, these findings highlight the necessity of strengthening data integration, expanding awareness initiatives, and embedding sustainability practices across all operational roles to support RIX's transition towards a circular economy.

5 Recommendations for LCA Integration in RIX WM

Current WM at Riga Airport is hampered by fragmented data, manual processes, and short-term decision-making, resulting in difficult-to-locate environmental "hotspots" and missed recycling opportunities. Stakeholders agree that integrating LCA is the necessary step toward systematic, evidence-based WM improvement and alignment with circular economy goals. Critical opportunities for improvement are followings:

- Identify Environmental Hotspots & System Gaps: LCA moves beyond basic disposal metrics to quantify impacts from contamination, poor segregation, and inefficient logistics. With terminal recycling rates varying by up to 40% seasonally, LCA enables targeted, data-driven interventions while addressing current barriers such as fragmented data systems, infrequent metric updates, and inconsistent training.
- Support Integrated, Evidence-Based Decision-Making: LCA allows managers to objectively balance environmental, financial, and social impacts, strengthening alignment between operational performance, long-term sustainability goals, and national/EU regulatory compliance.

Stakeholders strongly advocated integrating LCA into both planning and operational oversight, focusing on the following strategic areas:

1. Centralized Data Platform (Priority 1): Implement a centralized LCA data platform to replace fragmented, real-time tracking. This is a critical barrier to continuous improvement and is necessary for scenario modelling and performance benchmarking.
2. Mandatory Training (Priority 2): Bridge existing knowledge and training gaps among all staff (especially ground handling and cleaning) by providing regular, role-specific training on both LCA fundamentals and practical waste handling.
3. Targeted Technical Interventions: Leverage LCA outputs to identify high-impact fractions (e.g., mixed plastics or organics) for targeted solutions, such as implementing automated sorting systems and restructuring collection processes.

RIX can align its WM system with both circular economy goals and measurable sustainability outcomes embedding these recommendations.

6 Conclusions

The integration of LCA into WM operations at Riga Airport is essential for driving substantial gains in environmental sustainability, operational efficiency, and progress toward circular economy objectives.

The implementation of the survey and interview at RIX provided the essential empirical foundation for the LCA of its WM system. The results of survey were useful to the LCA methodology in two phases. By surveying key operational stakeholders, the study ensured the LCA's relevance and define the most appropriate functional unit, system boundaries, and selecting the environmental impact categories that matter most to RIX. The stakeholder input is crucial for justifying the weighting assigned to different impact categories (e.g., prioritizing climate change over acidification), ensuring the final LCA recommendations accurately reflect the values intended to inform RIX's future decision-making. Recommendations include implementing LCA-derived performance standards, mandating robust source separation, and establishing continuous improvement feedback loops. A face-to-face interview with members of RIX Board on the same questions provided a deeper understanding of the context of the conclusions, revealing nuances regarding operational obstacles and highlighting unresolved issues in the areas of technology or training. Future research will be needed to track the systemic impacts of persistent LCA adoption, develop airport-specific life cycle sustainability assessment frameworks, and

evaluate new materials, technologies, and collaborative models for WM in the aviation context.

References

1. Rupcic, I., Pierrat, L., Saavedra-Rubio, K., Thonemann, N., Ogugua, C.J., Laurent, A.: Environmental impacts in the civil aviation sector: current state and guidance. Transp. Res. Part D: Transp. Environ. **119**, 103717 (2023). https://doi.org/10.1016/j.trd.2023.103717
2. Zemite, L., Backurs, A., Vonda, K., Batjuskovs, S., Cnubbern, P., Jansons, L.: Comparative study of waste management and sampling practices in Latvia and Estonia. Latv. J. Phys. Tech. Sci. **61**, 36–57 (2024). https://doi.org/10.2478/lpts-2024-0035
3. Farr, J.A., Llantoy, N., Chfer, M., Gmez, G., Cabeza, L.: Life cycle assessment (LCA) of two pneumatic urban waste collection systems compared to traditional truck collection in an airport. Sustainability. **14**(3), 1109 (2022). https://doi.org/10.3390/su14031109
4. Alcubilla, G.: B.: life cycle assessment of the cabin waste management in the aviation sector. Tesi Ddoctoral, UPC. **111** (2021). https://doi.org/10.5821/dissertation-2117-359686
5. Almadhi, A., Abdelhadi, A., Alyamani, R.: Moving from linear to circular economy in Saudi Arabia: life-cycle assessment on plastic waste management. Sustainability. **15**(13), 10450 (2023). https://doi.org/10.3390/su151310450
6. Berticelli, R., Pandolfo, A., Reichert, G.A., Salazar, R.F.D.S., Kalil, R.M.L.: Support system for decision-making processes related to municipal solid waste management by taking into consideration a sustainable life cycle assessment: review on environmental, economic and social aspects. Int. J. Environ. Waste Manag. **26**(2), 147–167 (2020). https://doi.org/10.1504/ijewm.2020.10028691
7. Nurzhan, A., Ruan, X., Chen, D.: A review of life cycle assessment application in municipal waste management: recent advances, limitations, and solutions. Sustainability. **17**(1), 30 (2025). https://doi.org/10.3390/su17010302
8. Nubi, O., Murphy, R.J., Morse, S.: Life cycle sustainability assessment of waste to energy Systems in the Developing World: a review. Environments. **11**(6), 123 (2024). https://doi.org/10.3390/environments11060123
9. Budihardjo, M.A., Huboyo, S., Kurniatama, D.V.P.: Comparative study of the life cycle assessment model for agricultural solid waste management: case studies in east Ungaran and west Ungaran districts, in proceeding. IOP Conf. Ser.: Earth Environ. Sci. **1248**(1), 012013 (2023). https://doi.org/10.1088/1755-1315/1248/1/012013
10. Tjahjono, M., Ünal, E., Tran, T.H.: The circular economy transformation of airports: an alternative model for retail waste management. Sustainability. **15**(4), 3860 (2023). https://doi.org/10.3390/su15043860

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Tracking the Unreported Used Vehicle Trade in Europe

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Abstract. Each year, vehicles leaving national fleets are either scrapped or exported as used vehicles. However, the used vehicle trade is significantly underreported, leaving millions of vehicles unaccounted for. This lack of transparency complicates regulating the sector, particularly in preventing the illegal export of hazardous or highly polluting vehicles. Understanding used vehicle exports is also essential in assessing the pace of electrification and the potential for CO2 emission reductions in the transport sector. This study provides the first quantitative assessment of unreported used-passenger car exports in Europe and offers new estimates of the true scale of the European used passenger car market. Using a comprehensive database of passenger car registrations and imports, we find that a quarter of cars deregistered in Europe (2.8 million vehicles per year on average) are of unknown whereabouts; these cars are either being scrapped without being catalogued as end-of-life vehicles or are unreported used exports. Germany alone accounts for 61% of unreported deregistrations (1.7 million vehicles per year on average from 2008–2022), with volumes of such cars far greater than other Member States. We also show that official statistics underestimate intra-EU used-car exports by at least 50% and extra-EU exports by a factor of four.

Keywords: Used vehicles · second-hand · end-of-life · fleet · scrappage

1 Introduction

This paper examines the fate of end-of-life passenger cars in the European Union (EU). As vehicles age, they typically pass through multiple owners before being deregistered and leaving the national fleet. Once deregistered, they usually follow one of two pathways: scrappage (dismantling) or export for a second life abroad.

EU Member States differ in how they acquire vehicles. In North-West Europe and Scandinavia, the majority of newly registered cars are brand new. Conversely, in Eastern and parts of Southern Europe a significant share of vehicles entering the vehicle fleet each year are used imports from other European countries.

While used vehicles are important from the perspective of making private mobility more affordable, a reliance on used imports results in older fleets with worse safety

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and fuel-efficiency performance. The EU has sought to regulate these flows through the End-of-Life Vehicle (ELV) Directive, introduced in 2000 [1]. The Directive introduced the Extended Producer Responsibility (EPR) principle, based on which producers of products need to take back, collect, or finance collection/treatment of their products once they become waste. Member States must also report periodically to the Commission on how the Directive is being implemented. A decision adopted in 2005 [2] laid out specific rules on the monitoring of the reuse/recovery and reuse/recycling targets that underpin the Eurostat end-of-life vehicle (ELV) statistics.

A major obstacle is the persistent under-reporting of used-vehicle exports. While governments have reliable data on annual sales of new cars and on total new registrations (the sum of both new cars and used imports), official export statistics (typically collected by customs agencies) do not capture the full extent of cross-border flows. Reported used exports to a country are often lower than the used imports reported by that country [3]. This discrepancy is likely mainly due to vehicles being driven across borders and re-registered without being formally deregistered in the country of origin. Such gaps complicate efforts to track and regulate the trade, and estimating exports beyond Europe is even more challenging.

Improving the transparency in the trade in used vehicles is important to avoid the trade in stolen, illegal or dangerous vehicles. Many emerging economies also seek to avoid the dumping of illegal vehicle waste in their countries and to rejuvenate their vehicle fleets with high quality vehicles. In this context, strengthening monitoring and reporting systems is central to the effectiveness of the EU's End-of-Life Vehicle Directive and its potential revisions.

Previous studies have examined the trade in used vehicles within Europe, but typically only for a subset of countries, and none have assessed the scale of under-reported deregistrations across the EU as a whole. A recent European Commission study [4] examined the trade of used vehicles from the four largest EU Member States (Germany, France, Italy and Spain) and highlighted that trade data on used exports is likely under-reported but did not estimate the magnitude of the gap. Earlier work by the authors [3] revealed significant discrepancies between reported exports and declared imports of used vehicles, but again without estimating their overall scale.

This paper addresses that gap. For the first time, we quantify the share of deregistered passenger cars across EEA Member States that remain unaccounted for - neither reported as scrapped nor as exported. By comparing national car deregistration and export data with reported imports, we provide a systematic estimate of the extent of under-reported exports and, in turn, a more accurate picture of the true scale of Europe's used car market.

2 Methods

This section explains the development of the underlying historical database of car registrations and the methods used to estimate unreported deregistrations from the stock.

2.1 Database

Data was collected for countries in the European Economic Area for three primary indicators for passenger cars (M1 vehicles): total new registrations, new sales and used

imports. However, data is often not available for all three of these in all years and countries and must therefore be estimated. When total new registrations and new sales are available but used imports are not, then the latter are estimated by taking the difference between new registrations and new sales. The same applies when two other indicators are known but a third is missing (e.g. in cases where total new registrations are missing but new sales and used imports are known).

Numerous data inputs are compared to cross-validate and ensure internal consistency; these include statistics collected by international organisations, national sources, and private sector sources. The sources of data used in this report are available publicly and some have been uploaded to the Transport Data Commons [5].

Data on used exports from EU Member States are sourced from EUROSTAT [6]. These are complemented with used export data from other non-EU countries published publicly in previous work [3]. These data come primarily from customs agencies in each Member State. However, particularly for exports, these are likely to significantly underestimate the true scale of the trade in used vehicles.

Data on end-of-life (EoL) vehicles in EEA countries are collected from EUROSTAT [7]. As discussed earlier, these data are collected by the European Commission based on the ELV-Directive [1, 2]. Importantly, the Eurostat EoL vehicle data includes both passenger cars (M1) and light commercial vehicles ("vans" – N1), and so represents a ceiling of the number of ELV cars.

2.2 Flow Estimation

Using the data collected for vehicle registrations we estimate the number of vehicles deregistered (Deregs) from the passenger car stock of each country c in year t using the following equation:

$$\text{Deregs}_{t,c} = \text{Stock}_{t-1,c} + \text{New sales}_{t,c} + \text{Used_Imp}_{t,c} - \text{Stock}_{t,c} \tag{1}$$

Where Used_Imp are used imports. Using these estimates of deregistrations we then estimate the number of unreported deregistrations in each country using the following method 1:

$$\text{Unreported}_{t,c} = \text{Deregs}_{t,c} - \text{Used_Exp}_{t,c} - \text{ELV}_{t,c} \tag{2}$$

Where Used_Exp are used exports. To estimate the total number of unreported deregistrations in the EEA region we take sums across all countries for method 1:

$$\text{Unreported}_{t,\ \text{EEA}} = \sum\nolimits_c \left(\text{Deregs}_{t,c}\right) - \sum\nolimits_c \left(\text{ELV}_{t,c}\right) - \sum\nolimits_c \left(\text{Used_Exp}_{t,c}\right) \tag{3}$$

Since we suspect the used exports are under-reported, we compare the unreported deregistrations with a second method. The total number of used cars exports from European countries (Used _ $\text{Exp}_{t,\text{EEA}}$) must equal the total number of used car imports of European countries (Used _ $\text{Imp}_{t,\text{EEA}}$), minus the total number of used car imports from outside Europe (Used _ Imp _ $\text{exEEA}_{t,\text{EEA}}$) (which is likely to be small), plus the total

number of used car exports outside Europe (Used _ Exp _ exEEA$_{t,\,\mathrm{EEA}}$). This can be written as:

$$\mathrm{Used_Exp}_{t,\mathrm{EEA}} = \sum\nolimits_{c} \left(\mathrm{Used_Imp}_{t,\mathrm{c}}\right) + \Delta\mathrm{Used_Exp_exEEA}_{t,\mathrm{EEA}} \quad (4)$$

Where ΔUsed _ Exp _ exEEA$_{t,\,\mathrm{EEA}}$ is the net difference between exports of cars to countries outside the EEA and imports of cars from outside the EEA:

$$\Delta\mathrm{Used_Exp_exEEA}_{t,\mathrm{EEA}} = \mathrm{Used_Imp_exEEA}_{t,\mathrm{EEA}} + \mathrm{Used_Exp_exEEA}_{t,\mathrm{EEA}} \quad (5)$$

Substituting this into Eq. (2) of Method 1 gives an alternative "Method 2" to calculate unreported flows (Eq. 6). Instead of using estimates of used car exports, Method 2 relies primarily on used import data, which is likely to be more complete and lead to a better estimate of unreported flows. Note that Method 2 can only be used to estimate the aggregate number of unreported cars at the European (EEA) level, rather than for individual countries.

$$\mathrm{Unreported}_{t,\ \mathrm{EEA}} = \mathrm{Deregs}_{t,\mathrm{EEA}} - \mathrm{ELV}_{t,\mathrm{EEA}} - \mathrm{Used_Imp}_{t,\mathrm{EEA}} - \Delta\mathrm{Used_Exp_exEEA}_{t,\mathrm{EEA}} \quad (6)$$

Method 1 can be used to estimate unreported deregistrations for each country, to determine the scale of unreported deregistrations for each EEA state. Both methods are then used to estimate the unreported deregistrations at the EEA level, and these are compared to explore whether export data included by EUROSTAT [6] and ITF [3] are under-reported.

3 Results

Figure 1. shows the passenger car deregistrations in each EEA state with unreported cars estimated according to Method 1. The results show that the shares of cars deregistered versus those that are exported as used cars differ significantly by country. In Italy, Norway and Iceland for example, the majority of cars deregistered from the passenger car fleet each year are scrapped domestically. Conversely, in Belgium and Luxembourg most cars that leave the stock are exported as used vehicles rather than being scrapped. In some countries, such as Finland and Ireland, the number of ELVs and used exports exceeds the number of cars deregistered by a substantial margin (leading to a negative sign on unreported vehicles). One possible reason for this is if significant numbers of ELVs are imported for scrappage from other countries. Another potential explanation is that used imports are not being captured by the data sources. Either (or both) of these explanations would account for the fact that the number of ELVs is consistently higher compared with estimates of deregistrations from differences in the car registrations in each year. In other countries, in a few isolated years, unreported registrations can be large and negative. This is likely the result of jumps in accounting methods for car fleets across the statistical timeseries.

The number of unreported deregistrations differs significantly by country. Germany is by far the largest source of unreported deregistrations in Europe. This may partly occur if significant numbers of ELVs are not tracked, but a more plausible reason is used car exports are significantly under-reported.

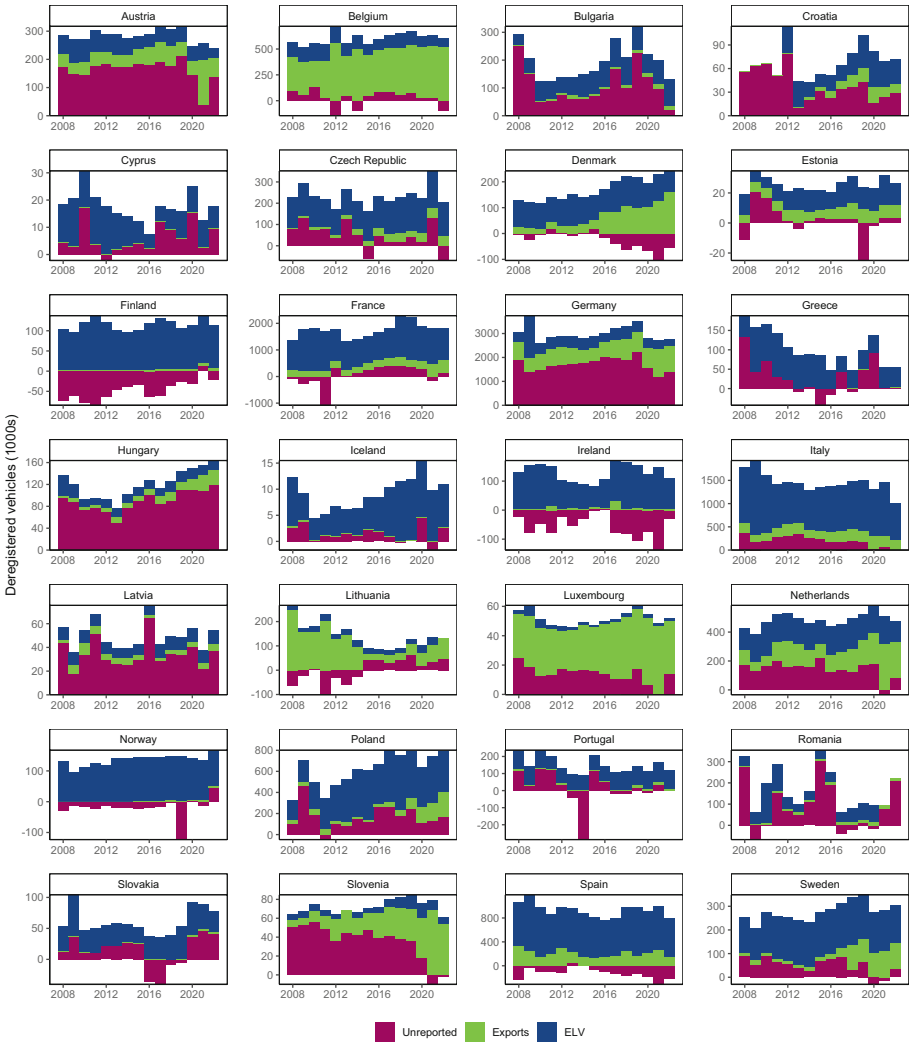


Fig. 1. Passenger car deregistrations by EEA Member State

Figure 2 shows the total EEA passenger car deregistrations with unreported vehicles estimated according to Method 1. On average, 52% of vehicles deregistered in the EEA between 2008–2022 were reported as scrapped (ELV). Using Method 1 and relying on used car export statistics, 23% of vehicles deregistered in the EEA between 2008–2022 were reported as used car exports, leaving a remaining 25% of unreported deregistered vehicles with unknown whereabouts. According to Method 1, between 2008–2022 on average 2.8 million vehicles per year were deregistered in Europe and were not reported as ELV or used exports. German unreported deregistrations accounted for 61% of this total, at 1.7 million vehicles per year on average over the same time period, with

Italy and Poland representing approximately 7% and 6% of unreported deregistrations respectively, and other countries all representing even smaller shares.

The share of imported used cars from outside the EEA is unlikely to be significantly under-reported. These findings suggest that the remaining 15% of unreported deregistered cars are likely to be traded outside of the EEA meaning the statistics on extra-EEA exports could be underestimated by a factor of four (5.5% exports outside EEA divided by 15% + 5.5%). It is unclear how many of these unreported cars are roadworthy vehicles that can be reused or undeclared ELVs.

Figure 3. shows the total EEA passenger car deregistrations with unreported vehicles estimated according to Method 2. Using more reliable estimates of used car imports in each member country and accounting for estimated net extra-EEA exports of used cars, the share of unreported vehicles can be significantly reduced from 25% using Method 1 to 15% using Method 2 over the time period considered. Used car imports in EEA Member States accounted for 29% of deregistrations between 2008–2022 and net extra-EEA exports of used cars accounted for just 3.8% (5.5% exports outside the EEA minus 1.7% imports from outside the EEA). This suggests that the estimates of used car exports in EEA national statistics underestimate the trade in used vehicles by approximately 50% (33% using Method 2 divided by 22% estimated using Method 1).

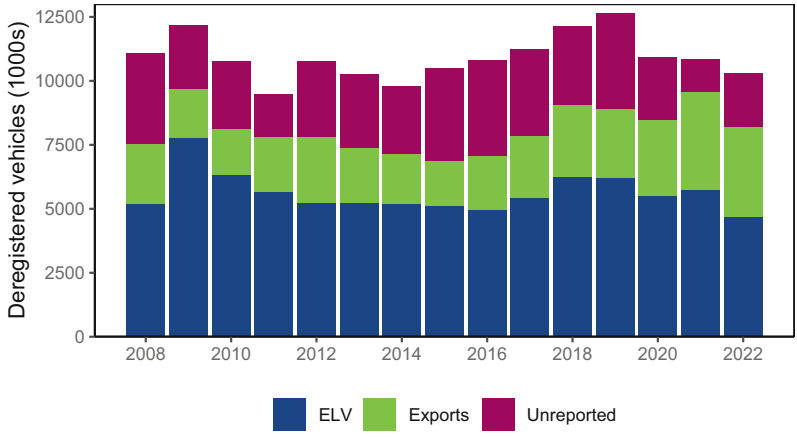


Fig. 2. Total EEA passenger car deregistrations using Method 1

The share of imported used cars from outside the EEA is unlikely to be significantly under-reported. These findings suggest that the remaining 15% of unreported deregistered cars are likely to be traded outside of the EEA meaning the statistics on extra-EEA exports could be underestimated by a factor of four (5.5% exports outside EEA divided by 15% + 5.5%). It is unclear how many of these unreported cars are roadworthy vehicles that can be reused or undeclared ELVs.

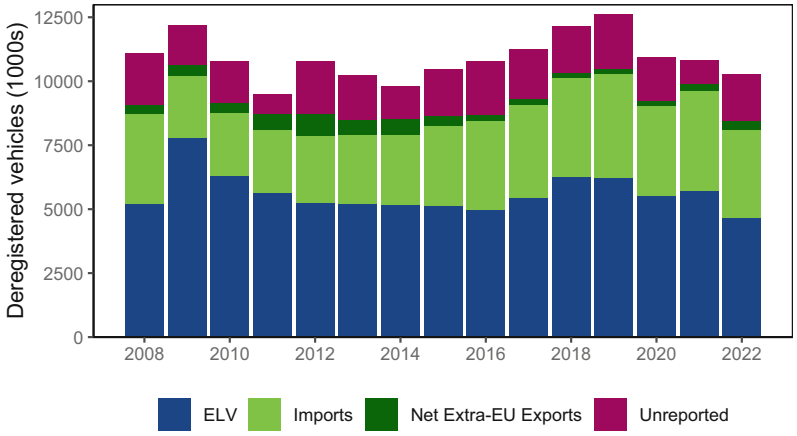


Fig. 3. Total EEA passenger car deregistrations using Method 2

4 Discussion

The findings reveal major gaps in the reporting of passenger car deregistrations across the EEA. Even with improved estimates (Method 2), millions of cars each year remain without a recorded destination. The comparison between Methods 1 and 2 highlights a systematic underestimation of used-vehicle exports. Export statistics reported by Member States appear to miss at least half of actual flows, while extra-EEA exports may be undercounted by a factor of four.

This lack of transparency undermines governments' capacity to track cross-border flows and poses significant challenges for enforcing regulations such as national transposition of the End-of-Life Vehicle (ELV) Directive, or EU-wide enforcement of a future ELV Regulation.

Germany emerges as the dominant source of unreported deregistrations, reflecting both the scale of its fleet and, potentially weaknesses in how exports are recorded. The contrast between countries that rely heavily on domestic scrappage (e.g. Italy, Norway) and those where exports dominate (e.g. Belgium, Luxembourg) shows the diversity between markets and suggests that under-reporting is unevenly distributed.

Some uncertainties remain. Negative values in certain countries point to inconsistencies in stock statistics or possible imports for dismantling. Moreover, it is not clear how many of the unreported vehicles are roadworthy versus end-of-life units circumventing dismantling regulations. Future research could usefully focus on reconciling registration data with customs records and improving reporting on extra-EEA flows.

Overall, this paper provides the first systematic quantification of unreported deregistrations across Europe and shows that the European used car market is significantly larger and less transparent than official data suggest. These findings provide policy makers with a stronger evidence base for updating the ELV Directive and designing measures that safeguard environmental standards and consumer safety.

References

1. EU Parliament: Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End-of-Life Vehicles. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611 (2000)
2. EU Parliament: Decision 2005/293/EC. https://eur-lex.europa.eu/eli/dec/2005/293 (2005)
3. ITF: New but Used: the Electric Vehicle Transition and the Global Second-Hand Car Trade. ITF Policy Papers. OECD Publishing, Paris (2023). https://doi.org/10.1787/28ee4515-en
4. Zacharof, N., Nur, J., Kourtesis, D., Krause, J., Georgios, F.: A Review of the Used Car Market in the European Union. Publications Office of the European Union, Luxembourg (2024). https://doi.org/10.2760/3237256
5. TDC: Transport Data Commons Portal. https://portal.transport-data.org/ (2025)
6. EUROSTAT: EU trade since 1988 by HS2–4-6 and CN8. https://ec.europa.eu/eurostat/databrowser/product/view/ds-045409 (2025)
7. EUROSTAT: End-of-life vehicles - reuse, recycling and recovery, totals. https://ec.europa.eu/eurostat/databrowser/view/env_waselvt/ (2025)

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Hybrid-Excited Axial-Flux Motor with Magnetic Bridge

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Abstract. Electric motors play a decisive role in achieving climate-neutral mobility, yet the use of rare-earth materials in permanent magnets raises concerns about environmental impact. This paper aims to reduce the reliance on such materials through a novel hybrid-excited synchronous motor (HESM) concept that combines permanent magnets with excitation windings on the rotor. Compared to a permanent magnet synchronous motor (PMSM), this approach requires a lower mass of rare-earth materials because the excitation winding contributes to magnetic flux generation. To investigate the magnetic behavior of the proposed machine, a numerical simulation under no-load conditions is performed. The results indicate that the concept performs as expected, reinforcing its potential as a promising approach to reduce the use of rare-earth materials in electric motors.

Keywords: Axial-flux motor · sustainability · reduction of rare-earth elements · lower material cost · hybrid excitation

1 Introduction

Electric powered vehicles do not directly produce any greenhouse gas emissions while operating because they use electricity instead of burning fuel [1,2]. Therefore, as the European Union has the objective of becoming a carbon-neutral continent by 2050 [3], emphasis should be put on the research of electric motors. A big share of motors uses permanent magnets as the sole source of rotor excitation and therefore it requires the use of rare-earth elements, which represents a critical aspect in the motor production due to its limited availability [4]. Moreover, since many applications demand a high torque-to-mass ratio, axial-flux machines

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represent a compelling alternative to conventional radial-flux machines, owing to their superior torque densities [5–7]. These machines have a short axial length relative to their outer diameter, therefore resulting in a disc-shaped geometry. In this configuration, the magnetic flux crosses the air-gap between the rotor and stator in the axial direction, whereas in radial-flux machines it flows radially. Reducing the amount of rare-earth materials in electric motor design remains a significant challenge, as these materials provide magnetic flux without having to incur in excitation losses, hence improving machine efficiency. In addition, they enable higher power densities and a simplified rotor construction [8]. However, PMSMs can exhibit lower efficiencies than electrically excited machines at high speeds, because the magnet flux cannot be directly controlled. As a result, a demagnetizing current is required to weaken the flux in high-speed, low-torque operating regions [9]. This paper proposes a hybrid-excited axial-flux motor aimed at reducing the required mass of rare-earth materials while leveraging the advantages of both excitation technologies. In the proposed topology, permanent magnets and field windings can each serve as excitation source, allowing improved controllability of the air-gap flux and enhanced overall performance. Field windings placed on the rotor side help the permanent magnets in the production of magnetic flux and for this reason they make it possible to reduce the need of rare-earth materials. Furthermore, the environmental benefits resulting from the proposed idea in this paper are substantial and they can be quantified through eco-cost values [10]. In fact, assuming no recycling or treatment at the material's end-of-life, Neodymium—a widely used material in permanent magnets for electric motors—carries an eco-cost of 622.7 eco-€/dm^3. This figure highlights that reducing the use of rare-earth materials offers substantial potential for improving the sustainability of electric motors.

2 Methodology

2.1 YASA Motor for an Active Suspension System

The proposed concept is applied in a car's active suspension system. Such systems enhance driving comfort by isolating the vehicular body to the road-caused oscillations [11]. Hereby, under feedback control, a force opposite to the road disturbances will be generated [12]. Nevertheless, it is worth noting that the proposed concept is applicable not only to suspension systems of electric vehicles but also to any other application that uses electric motors. A yokeless and segmented armature (YASA) [13] motor is used for this purpose. Therefore, the machine has a sandwich structure [14], with the stator positioned between two rotor discs carrying permanent magnets. For the present analysis, the mean radius of the machine is considered. In Table 1 a parameter set for the study object is provided.

Table 1. Parameter set of the study object

Parameter	Value
Stator outer diameter	100 mm
Inner to outer diameter ratio	65%
Stator axial length	35 mm
Number of stator slots	18
Slot axial length	28 mm
Slot width	3 mm
Number of turns	70
Magnets remanent flux density	1.26 T
Number of pole pairs	12
Permanent magnet width in the mean radius	9.77 mm
Permanent magnet thickness	3 mm
Torque	7 Nm
Rotor speed	1000 rpm
Battery voltage	800 V

2.2 Working Principle of the Hybrid-Excited Rotor

Figure 1 illustrates a lumped model of the hybrid-excited motor used in the study. The rotor is equipped with two different types of excitation, which are the permanent magnets and the field windings. Furthermore, a magnetic bridge is placed around the permanent magnet, resulting in a low-reluctance path for the flux to flow through [15]. As a result, the flux of the permanent magnets can follow two distinct paths. For low currents in the field windings, the reluctance of the magnetic bridge will be lower than the one to flow through the air-gap, hence a leakage flux will occur. Conversely, for higher currents in the field windings, more flux from the permanent magnets will be attracted to the pole in the stator.

Thanks to an additional degree of freedom compared to a PMSM, an HESM offers following advantages:

- Field strengthening: If high torques are required, a current in the rotor windings will be injected. Consequently, this will increase the magnetic flux flowing through the air-gap if no saturation occurs. This allows the use of smaller magnets while still achieving the same torque, thereby enhancing the machine's sustainability. Nevertheless, it is worth noting that this will result in Joule losses on the rotor side, although these can be kept low if adequate slot space and winding fill factors are employed.
- Field weakening: If low torques are required, zero or low currents will be injected in the rotor windings. This causes more flux to go through the magnetic bridge and therefore a weakening of the magnetic field is achieved. In contrast to a PMSM, where the flux from the permanent magnets can not be

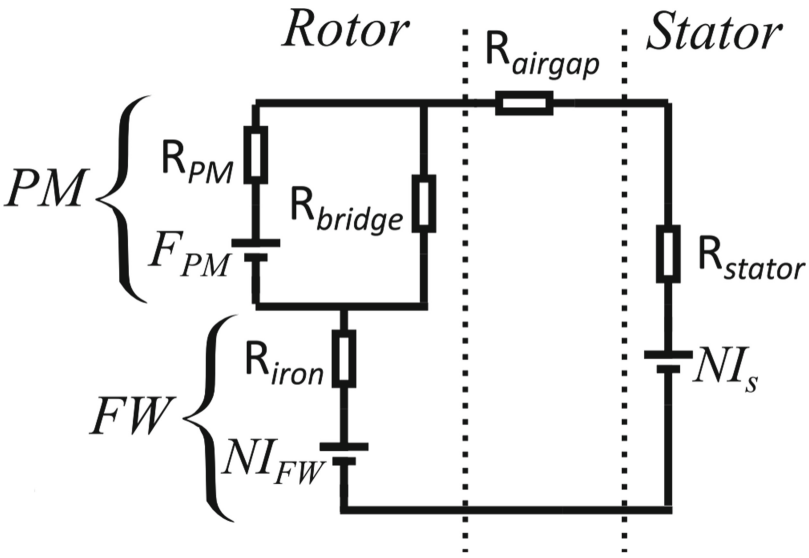


Fig. 1. Lumped model of the hybrid-excited motor [15]

controlled and therefore an injection of a demagnetizing current is required to weaken the magnetic field, the proposed configuration improves the efficiency in the field weakening region by reducing the Joule losses in the stator.

– Protection against demagnetization: Permanent magnets can lose their magnetization when exposed to strong Magnetic Motive Forces (MMF). High MMFs occur when the magnetic circuit applies a strong opposing field. This effect becomes more pronounced for high-speeds PMSMs, where field-weakening causes the production of an opposing magnetic field that increases the MMF acting against the magnet [16]. A HESM shows more robust behavior against this issue thanks to the use of a magnetic bridge. In this topology flux weakening can be achieved by injecting low or zero rotor currents instead of adding a a demagnetizing current in the stator windings, thereby avoiding high MMFs and improving the machine's safety against demagnetization. Furthermore, lower stator currents decrease winding temperatures, strengthening insulation [17] and therefore the HESM's robustness against MMFs caused by short-circuits that could demagnetize the magnets.

3 Results

3.1 Magnetic Behavior of the Hybrid-Excited Rotor

As a reference for the subsequent analysis, it is noted that the benchmark PMSM specified in Table 1 can deliver a torque of 7 Nm when a torque-producing current of 8.5 A and a permanent magnet flux of 0.1 mWb are applied. For this analysis,

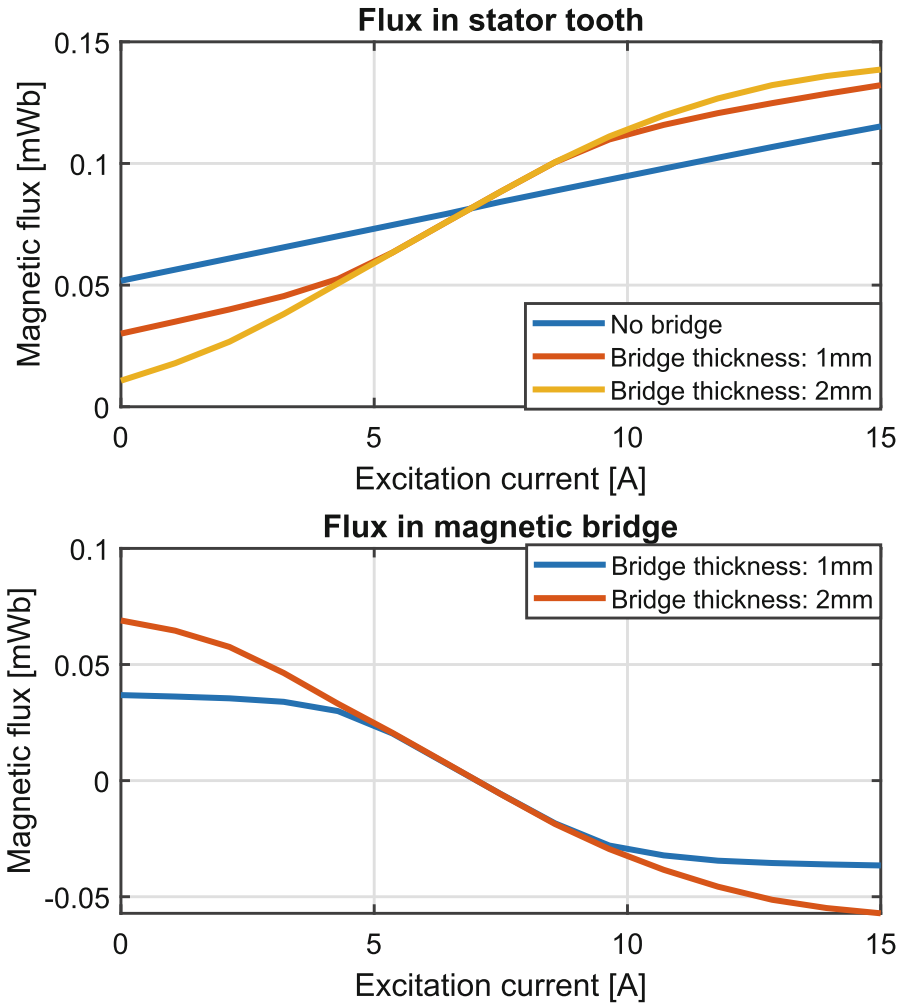


Fig. 2. Average magnetic flux in the stator tooth and magnetic bridge as a function of the excitation current.

a HESM with a permanent magnet mass that is 60% lower than that of the PMSM benchmark is considered.

Figure 2 illustrates that the magnetic flux can be effectively controlled through the rotor windings. The results also show that, even though the permanent magnets are considerably smaller than those in the original PMSM, the same flux level can be achieved for an excitation current of 8.6 A. It is worth noting that, at low excitation currents, the presence of a magnetic bridge can reduce the flux available for torque production, as a significant portion of the flux preferentially flows through the bridge rather than across the air gap. Therefore, this can represent both an advantage and disadvantage, depending on the application

of the motor. The Magnetic Bridge enables significant flux weakening with low or zero rotor excitation current, thereby maintaining high efficiency at operating points that require field weakening. Nevertheless, in low-power machines, this can reduce efficiency, as achieving a given magnetic flux requires higher rotor currents, which in turn increases rotor Joule losses. The lower plot of Fig. 2 shows that the flux flowing through the magnetic bridge decreases as the excitation current increases, leading to a desaturation of the bridge. As the rotor current increases further, a threshold is reached at which the entire flux of the permanent magnet is redirected through the rotor rather than through the magnetic bridge. For the machine under consideration, this occurs at approximately 7.3 A. Beyond this point, the torque-producing flux encounters a low-reluctance path offered by the desaturated magnetic bridge. Therefore, after this operational region has been reached, an increment in the excitation current will result in a bigger magnetic flux generation compared to a HESM with no magnetic bridge. It is worth noting that small bridges will saturate earlier than big ones, as it can be clearly seen by the line representing a magnetic bridge with a thickness of 1 mm in the lower plot of Fig. 2. Finally, the results of this magnetic analysis show that the proposed concept successfully a control of the air gap flux through the excitation windings, making it possible to achieve good efficiencies in high-speed operational regions thanks to the field weakening capability offered by the use of a Magnetic Bridge. Furthermore, the field-strengthening capability of the proposed concept is confirmed, demonstrating that the same magnetic flux as in the PMSM benchmark can be achieved despite a 60% reduction in permanent magnet mass, owing to the controllability provided by the excitation windings.

4 Conclusion

This paper considers a hybrid-excited axial-flux motor with a magnetic bridge and compares it to a permanent magnet synchronous motor under no-load conditions. For the machine investigated in this study, the combination of permanent magnets and rotor excitation under a rotor current of 8.6 A generates a magnetic flux equivalent to that of a machine relying solely on permanent magnets with 60% more magnetic material. Furthermore, efficient flux weakening is enabled through the use of a magnetic bridge. Overall, the proposed approach improves the sustainability of modern axial-flux motors by reducing dependence on rare-earth materials, leading to enhanced eco-friendliness and reduced material cost. Future research could focus on examining the mechanical behavior of this hybrid-rotor structure as well as analyzing its thermal performance relative to a conventional PMSM.

References

1. Abas, A.E.P., Yong, J., Mahlia, T.M.I., Hannan, M.A.: Techno-economic analysis and environmental impact of electric vehicle. IEEE Access **7**, 98565–98578 (2019). https://doi.org/10.1109/ACCESS.2019.2929530
2. Pipitone, E., Caltabellotta, S., Occhipinti, L.: A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context. Sustainability **13**(19), 10992 (2021). https://doi.org/10.3390/su131910992
3. Bäckstrand, K.: Towards a climate-neutral union by 2050? The European Green Deal, climate law, and green recovery. In: Routes to a Resilient European Union, pp. 39–61. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-93165-0_3
4. Cui, J., et al.: Current progress and future challenges in rare-earth-free permanent magnets. Acta Materialia **158**, 118–137 (2018). https://doi.org/10.1016/j.actamat.2018.07.049
5. Huang, S., Luo, J., Leonardi, F., Lipo, T.A.: A comparison of power density for axial flux machines based on general purpose sizing equations. IEEE Trans. Energy Conver. **14**(2), 185–192 (1999). https://doi.org/10.1109/60.766982
6. Giulii Capponi, F., De Donato, G., Caricchi, F.: Recent advances in axial-flux permanent-magnet machine technology. IEEE Trans. Ind. Appl. **48**(6), 2190–2205 (2012). https://doi.org/10.1109/TIA.2012.2226854
7. Gadiyar, N., Bohach, G., Nahin, M.M., Van de Ven, J., Severson, E.L.: Development of an integrated electro-hydraulic machine to electrify off-highway vehicles. IEEE Trans. Ind. Appl. **58**(5), 6163–6174 (2022). https://doi.org/10.1109/TIA.2022.3189609
8. Gieras, J.: Permanent Magnet Motor Technology, 3rd edn. CRC Press, Boca Raton (2009). https://doi.org/10.1201/9781420064414
9. Sepulchre, L., Fadel, M., Pietrzak-David, M., Porte, G.: MTPV flux-weakening strategy for PMSM high speed drive. IEEE Trans. Ind. Appl. **54**(6), 6081–6089 (2018). https://doi.org/10.1109/TIA.2018.2856841
10. Hendriks, C.F., Janssen, G.M.T., Vogtländer, J.: The eco-costs/value-ratio. In: Advances in Building Technology, pp. 1391–1398. Elsevier, Amsterdam (2002). https://doi.org/10.1016/B978-008044100-9/50173-X
11. Mohd Riduan, A.F., Tamaldin, N., Sudrajat, A., Ahmad, F.: Review on active suspension system. SHS Web Conf. **49**, 02008 (2018). https://doi.org/10.1051/shsconf/20184902008
12. Lee, S., Kim, W.J.: Active suspension control with direct-drive tubular linear brushless permanent-magnet motor. In: 2009 American Control Conference, pp. 5498–5503. IEEE, Piscataway (2009). https://doi.org/10.1109/ACC.2009.5160091
13. Hao, Z., Ma, Y., Wang, P., Luo, G., Chen, Y.: A review of axial-flux permanent-magnet motors: topological structures, design, optimization and control techniques. Machines **10**(12), 1178 (2022). https://doi.org/10.3390/machines10121178
14. Elena-Daniela, L., Tabacu, S.: Analysis of axial flux permanent magnet motors used for electric vehicle. In: 2024 IEEE International Conference and Exposition on Electric and Power Engineering (EPEi), pp. 415–420. IEEE, Piscataway (2024). https://doi.org/10.1109/EPEi63510.2024.10758149
15. Mörée, G., Leijon, M.: Overview of hybrid excitation in electrical machines. Energies **15**(19), 7254 (2022). https://doi.org/10.3390/en15197254
16. Mahmouditabar, F., Vahedi, A., Marignetti, F.: The demagnetization phenomenon in PM machines: principles, modeling, and design considerations. IEEE Access **11**, 47750–47773 (2023). https://doi.org/10.1109/ACCESS.2023.3274701

17. Ghassemi, M.: High power density technologies for large generators and motors for marine applications with focus on electrical insulation challenges. High Volt. **5**(1), 7–14 (2020). https://doi.org/10.1049/hve.2019.0055

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Using Intelligent Transport System Monitoring Data to Assess Pavement Durability: Evidence from Lithuania

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Abstract. Intelligent transport systems (ITS) help manage road infrastructure using data, but their impact on pavement durability has not yet been fully researched. In Lithuania, three weigh-in-motion (WIM) monitoring points have been installed on national highways: A1 Vilnius–Kaunas–Klaipėda (80.815 km), A5 Kaunas–Marijampolė–Suvalkai (92.857 km) and A6 Kaunas–Zarasai–Daugavpils (26.431 km). These stations are primarily intended for monitoring rather than control purposes. This study focuses mainly on the A5 motorway (Kaunas–Marijampolė–Suvalkai), as we have the most detailed data on it until August 2024. We examine how traffic intensity, especially heavy vehicles, and freeze-thaw cycles are related to road surface conditions, as measured by the International Roughness Index (IRI). By analyzing time series data, we create models that help us understand these relationships, but do not confirm a direct cause and effect. To assess pavement durability, we compare the observed IRI with design benchmarks, such as a 20-year service life and IRI limits set by the network. Using regression models, we calculate the remaining functional life of the pavement, showing whether it is performing better or worse than expected. The results show that even without enforcement, continuous data can help make more accurate pavement management decisions.

Keywords: Intelligent Transport Systems · Weigh-in-Motion · pavement durability · International Roughness Index · ESAL

1 Introduction

Intelligent Transport Systems (ITS) are increasingly used to measure and understand how traffic loads affect pavements. In particular, Weigh-in-Motion (WIM) and multi-functional monitoring posts provide continuous axle-load measurements and spectra that support deterioration modelling and planning even when sites are used for monitoring only rather than enforcement [1]. Functional pavement condition is commonly tracked using the International Roughness Index (IRI) alongside rutting and cracking; IRI remains the most widely adopted, comparable indicator for network-level management [2]. Forecasting IRI trends has advanced with statistical and machine-learning methods, with recent work showing strong performance from tree-based and ensemble models and growing integration into pavement management [3, 4].

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The Lithuanian road network totals about 84,000 km, comprising national, local and urban roads. Within this, state roads account for roughly 21.3 thousand km, and the motorway extends to around 1,749 km [5]. Lithuania's location on the TEN-T North Sea–Baltic corridor places it at the intersection of East-West and North-South flows, concentrating heavy-duty vehicles traffic [6]. Eurostat trend reports further indicate robust road-freight activity across the EU up to 2024, reinforcing the pressure on transit corridors [7]. In practice, higher HGV intensity accelerates functional and structural wear, raising the importance of reliable monitoring and targeted maintenance.

One of the most important factors affecting pavement condition is Average Annual Daily Traffic (AADT). It reflects the freight-vehicle loads borne by the road over its service life. The highest freight-vehicle flows occur on highways. According to Via Lietuva, since 2000 the AADT of freight vehicles has increased by 267%, from 651 veh/day (2000) to 1,735 veh/day (2024) [8]. Although changes in freight traffic on highways are not uniform, they have been rising since 2015. During road design, the pavement structure is selected according to the road class and design loads. If the design load is miscalculated and freight loads exceed what the newly designed road can carry, the pavement structure will wear out faster and distress will develop more rapidly. On Lithuanian roads, increasing freight-vehicle flows accelerate pavement deformation and degradation. Under constant and growing loads, the pavement condition loses its initial strength more quickly, forming ruts, depressions, and potholes that pose a serious risk to traffic safety—especially on wet surfaces [9]. Another important factor influencing road quality is axle load. Excessive axle loads cause larger pavement deflections. With greater deflection, a longer recovery time is required, and the damage to pavement quality may be irreversible.

Lithuania's road authority (Via Lietuva) conducts regular pavement condition surveys with laser-based vehicles (e.g., RST-type systems), supporting network-level decision-making. In the academic literature, Lithuanian researchers have developed network-level performance and planning tools, examined how repair interventions and road class influence IRI, and proposed composite condition indices calibrated to local conditions [10–12]. This provides a relevant base for linking measured loads to functional performance on national corridors.

Since 2017, three WIM monitoring locations have been operated in Lithuania on key corridors: A1 Vilnius-Kaunas-Klaipeda (80.815 km), A5 Kaunas-Marijampole-Suvalkai (92.857 km), and A6 Kaunas-Zarasai-Daugavpils (26.431 km) (Fig. 1). In this study all three sites were acknowledged but perform a deep-dive analysis on A5 (Kaunas-Marijampolė-Suvalkai) because its dataset is the most consistent up to August 2024 and the site is planned for removal as the new road opens. WIM was treated strictly as a monitoring input and estimate associations, not causal effects, following methods outlined by Bernal and co-authors [13], where associations are interpreted in observational studies without causal attribution. This approach allows for an understanding of relationships without attributing direct causality due to the observational nature of the data. To interpret durability in planning terms, observed IRI trajectories were benchmarked against design expectations (20-year service life in Lithuanian practice) and data-driven IRI thresholds derived from observed distributions, aligning with recent Lithuanian and international practice that combines condition indicators with planning models [10, 11].

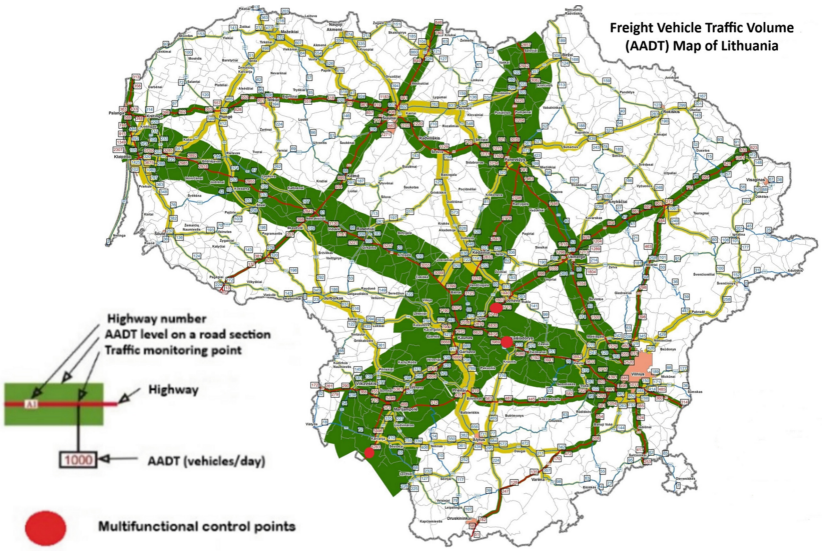


Fig. 1. Map of freight vehicle traffic volume (AADT) in Lithuania in 2024 and location of multifunctional control points [8]

This study presents a monitoring-based assessment of a heavily used road corridor, showing how continuous axle-load and climate data can support pavement deterioration modeling and transparent, reproducible workflows. The approach can be applied to other Lithuanian corridors as longer datasets become available.

The main aims were to: quantify IRI progression using an annual interrupted time-series framework, relate changes to observed loading and freeze–thaw exposure from a WIM site, and express results through a remaining-life (RFL) benchmark based on a 20-year horizon and data-driven thresholds.

Reproducibility was prioritized by using minimal, auditable inputs and a unified dataset for all analyses. Although based on a single section, the study provides a clear proof-of-concept workflow that can be extended as more consistent monitoring data become available. And combining it with longitudinal IRI measurements. As more monitoring points are added over time, the model can be refined and validated across a broader range of corridors. This will allow for more robust regional predictions and facilitate the scaling of pavement management strategies across the national road network.

2 Methodology

2.1 Study Scope and Design

This study focuses on a single Weigh-in-Motion (WIM) monitoring site located on the A5 Kaunas-Marijampole-Suvalkai road at km 92.857, using annual data from 2014 to August 2024. While three WIM monitoring locations exist along highways A1, A5, and A6, we chose the A5 site because it offers the most complete and consistent dataset.

All three sites are used solely for monitoring purposes, so the data is interpreted as associations, not causal effects resulting from enforcement actions.

To analyze the data, we apply a compact interrupted time-series analysis (ITSA) at an annual frequency, with 2017 serving as the breakpoint when multifunctional monitoring began on highways. The model includes a linear time term (to capture pre-trend), a post-2017 indicator (which reflects a level change), and a time*post-2017 interaction term (representing the slope change). ITSA is a transparent method for evaluating changes in trends when randomization is not feasible [13]. Since our analysis relies on a small annual panel, we report robust standard errors (HAC/Newey-West) and also assess the model's sensitivity using the Prais-Winsten AR (1) method, which is common in longitudinal data analysis to address potential autocorrelation [14, 15].

The functional condition of the pavement through the IRI is tracked, focusing on the annual change (ΔIRI), which reflects the rate of deterioration. Traffic loading is quantified using WIM-derived ESAL (Equivalent Single Axle Load), which includes both total and heavy vehicle components. We also account for the annual count of overloaded vehicles (available from 2019) and freeze-thaw cycles, a climatic factor that affects pavement integrity. These variables have been shown to be strongly related to roughness in previous studies, which use simplified models to link traffic and climate to pavement performance [2, 3, 10, 11].

For interpretation purposes (rather than hypothesis testing), the observed IRI trajectories were compared with both a 20-year design-life benchmark and a data-driven IRI threshold (network P90). This comparison helps us assess whether the section's deterioration is occurring faster or slower than expected based on planning models [10, 11].

It should be noted that the A5 corridor has undergone significant reconstruction work, which may have led to changes in traffic flow and axle load distribution, particularly in the period following December 2023. This could potentially influence the observed ESAL values and their relationship with pavement deterioration. Therefore, while the data from this section is comprehensive, care must be taken when interpreting results in the context of potential post-reconstruction traffic changes.

2.2 Data and Variables

The IRI mean (m/km) from national laser surveys is used as the functional indicator; it remains the most widely used, comparable network level metric [2, 3].

We compute the annual change based on the data presented in Table 1:

$$\Delta IRI_t = IRI_t - IRI_{t-1} \tag{1}$$

where IRI_t - IRI in year t (from laser surveys), IRI_{t-1} – IRI in the previous year, ΔIRI_t - year-over-year IRI change, which captures the deterioration rate and fits segmented regressions [13]. We retain IRI_{min}, IRI_{max} and IRI measurement count for data quality checks.

From A5 WIM, we aggregate axle-class records to annual totals and compute ESAL using the standard fourth-power load equivalency, linking measured axle weights to

Table 1. Pavement condition and traffic load data for A5 corridor 2014–2024

Year	IRI (m/km)	ΔIRI (m/km/y)	IRI measurement count	ESAL (total)	ESAL (heavy)	Overloaded vehicles	Freeze-thaw
2014	1,146	–	200	8765	5383	–	40
2015	–	–		8798	5130	–	43
2016	1,012	–	206	9718	5220	–	42
2017	1,288	0,276	203	10143	5438	–	37
2018	1,140	-0,148	205	9982	5530	–	45
2019	1,150	0,010	200	9965	5450	294770	47
2020	1,188	0,038	206	8034	5285	400030	49
2021	1,196	0,008	211	8848	5741	487040	46
2022	1,204	0,008	206	11430	6591	590900	44
2023	1,246	0,041	206	12369	6614	643790	50
2024	1,219	-0,027	200	12145	6283	460020	48

structural damage potential. We also track annual overloaded-vehicle counts (2019–2024) as a descriptive stressor, noting that roughness, speed, and sensor setup may affect WIM accuracy. To aid interpretation, we define a burn rate (BR):

$$BR_t = \frac{ESAL_t}{ESAL_{proj}/L_{proj}} \tag{2}$$

where BR_t is burn rate of design traffic in period t (ratio of actual to design ESAL); $ESAL_t$ is observed annual ESAL; $ESAL_{proj}$ – projected ESAL over the design service life and L_{proj} – projected design service life (use 20 years in Lithuanian practice).

For planning level interpretation, it was compared observed trajectories with 20-year design life used in Lithuanian practice for national roads, a data-driven IRI threshold equal to P90 of the observed network IRI distribution (A1/A5/A6). We use a data-driven roughness threshold IRI_{crit} equal to the P90 of the A1/A5/A6 network IRI distribution (recent period). P90 provides a transparent, auditable standard that flags the upper tail of observed functional condition without over-sensitivity to outliers. Sensitivity checks use P85 and P95. The 20-year benchmark follows Lithuanian practice for national roads; the implied annual design ESAL is $ESAL_{proj}/L_{proj}$, consistent with PMS design documentation. Using the recent-period empirical slope b (2019–2024) from $IRI_t = a + b\,t$, it was derived the remaining functional life:

$$RL_t^{emp} = \frac{IRI_{crit} - IRI_t}{\max(b, \varepsilon)} \tag{3}$$

where b is the recent-period linear slope of IRI_t and the deviation from project:

$$\Delta RL_t = RL_t^{emp} - \left(L_{proj} - t - t_0\right) \tag{4}$$

where $L_{proj} = 20$; y and t_0 is the first reliable baseline year. Positive ΔRL_t suggests slower than project roughness growth (functionally "ahead" of the simple 20-year line). This follows the Lithuanian PMS tradition of linking traffic inputs and functional indicators in strategic models [10, 11].

2.3 Statistical Analysis

It was summarised annual series and compute Spearman correlations between ΔRL_t (or ΔIRI_t) and ESAL, ESAL (heavy), overloaded vehicle count, freeze-thaw to check expected directions (e.g., more overloads ↔ shorter functional remainder) without over interpreting significance under small n [11].

Two linked families are estimated using OLS with HAC (Newey–West) and AR(1) sensitivity [15]. Given the small annual sample, HAC standard errors are reported, confirmed with Prais–Winsten AR(1), and validated via leave-one-out tests. Spearman correlations are treated as descriptive, with bootstrapped confidence intervals reported where informative.

Loading model (BR):

$$BR_t = \beta_0 + \beta_1 TIME_t + \beta_2 POST_t + \beta_3 (TIME * POST)_t + \gamma' Z_t + u_t, \quad (5)$$

where Z_t includes ESAL (heavy) and freeze-thaw. A negative β_3 would mean a slower design load consumption trajectory after 2017.

Deterioration model (ΔIRI_t):

$$\Delta IRI_t = \alpha_0 + \alpha_1 POST_t + \alpha_2 (TIME * POST)_t + \alpha_3 BR_t + \delta' Z_t + e_t \quad (6)$$

with Z_t as above. A positive α_3 supports the expected load roughness link [3].

3 Results

A linear fit to 2019–2024 indicates a most positive trend of b = 0.015 m/km ·year (95% CI [0.004, 0.026]) in IRI. With $\boldsymbol{IRI_{2024}} \approx 1.219$ m/km and $\boldsymbol{IRI_{crit}}$ **= 1,635** m/km (P90), the empirical remaining functional life is $\boldsymbol{RLM^{emp}_{2024}} \approx$ **27.6** years. Against a straight line 20-year benchmark from $\boldsymbol{t_0}$, $\boldsymbol{\Delta RL_{2024} > 0}$ suggest the section is functionally "ahead" by the IRI criterion within the observation window (Fig. 2).

Using the recent deterioration slope and the P90 threshold, the estimated remaining functional life (RFL) from the 2024 condition is approximately 27.6 years, indicating performance above a linear 20-year benchmark based on the IRI criterion.

Yearly associations between ΔIRI and explanatory variables are weak and statistically non-significant, reflecting the limited sample size (n = 6–8). Specifically, the correlations were: ΔIRI vs. ESAL total ($\rho = 0.07$, $p = 0.87$), ESAL heavy ($\rho = -0.24$, $p = 0.57$), overloaded vehicles ($\rho = 0.14$, $p = 0.79$), and freeze–thaw cycles ($\rho = 0.10$, $p = 0.82$). These results are interpreted as indicative rather than causal, although the observed directions are broadly consistent with engineering expectations.

The relatively low post-reconstruction IRI values likely reflect short-term condition improvements rather than long-term structural performance. Therefore, continued monitoring is needed to refine RFL estimates and validate long-term deterioration trends.

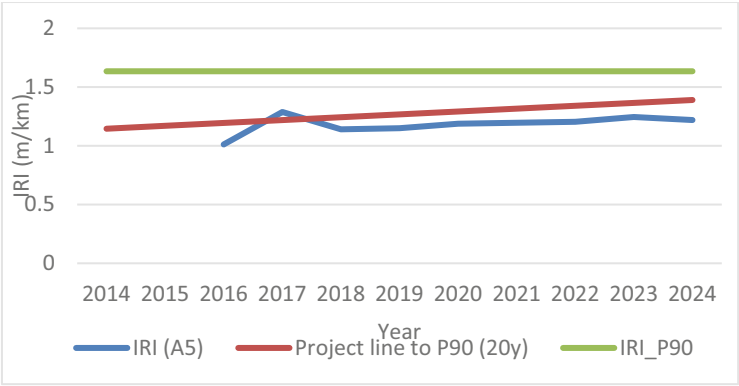


Fig. 2. Evolution of IRI on A5 with a 20-year project line to the network P90 threshold.

4 Conclusions

The A5 section exhibits slow IRI growth (≈ 0.015 m/km·yr.; 95% CI [0.004, 0.026]) and remains well below the network P90 threshold, suggesting that IRI is unlikely to be the primary trigger for intervention within the observed period.

Alignment with planning targets is positive: using the P90 threshold and a linear 20-year benchmark, the remaining functional life from 2024 is approximately 27.6 years, indicating performance ahead of a simple planning trajectory.

Associations between ΔIRI, traffic loading, and freeze–thaw cycles are directionally consistent but statistically limited due to the small sample size and are therefore treated as indicative rather than causal.

Intervention timing is likely driven by rutting, cracking, structural capacity, and drainage rather than IRI alone. Continued multi-parameter monitoring is recommended. Future work should expand to additional corridors (e.g., A1, A6), include rutting and cracking indicators, use higher resolution data, and apply multivariate models to improve remaining life estimates.

References

1. Wojtala, R., Sinelec, A., Zajączkowski, P.: Weigh-in-motion site for type approval of vehicle mass and axle loads with enforcement capability. Sensors. **23**(22), 9290 (2023). https://doi.org/10.3390/s23229290
2. Hettiarachchi, C., Yuan, J., Amirkhanian, S., Xiao, F.: Measurement of pavement unevenness and evaluation through the IRI parameter – an overview. Measurement. **206**, 112284 (2023). https://doi.org/10.1016/j.measurement.2022.112284
3. Kaloop, R.O., El-Badawy, S.M., Hu, J.W., Abd El-Hakim, R.T.: International roughness index prediction for flexible pavements using novel machine learning techniques. Eng. Appl. Artif. Intell. **122**, 106007 (2023). https://doi.org/10.1016/j.engappai.2023.106007
4. Tamagusko, T., Ferreira, A.: Pavement performance prediction using machine learning: supervised learning with tree-based algorithms. Transp. Res. Procedia. **82**, 2521–2531 (2025). https://doi.org/10.1016/j.trpro.2024.12.202

5. Ministry of Transport and Communications of the Republic of Lithuania (2025). https://sumin.lrv.lt/en/sector-activities/roads-and-road-transport-1/about-the-sector/. Accessed 15 Oct 2025
6. European Commission: North Sea–Baltic Corridor. (2025). https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t/north-sea-baltic-corridor_en. Accessed 15 Oct 2025
7. Eurostat: Road freight transport statistics—Statistics Explained. European Commission. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_by_journey_characteristics. Accessed 15 Oct 2025
8. Via Lietuva: Traffic intensity statistics. https://vialietuva.lt/eismo-intensyvumas (2025). Accessed 15 Oct 2025
9. Sivilevičius, H., Vansauskas, V.: Research and evaluation of ruts in the asphalt pavement on Lithuanian highways. J. Civil Eng. Manage. **19**(5), 609–621 (2013). https://doi.org/10.3846/13923730.2013.817481
10. Jurkevičius, M., Puodžiukas, V., Laurinavičius, A.: Implementation of road performance calculation models used in strategic planning systems for Lithuania conditions. Baltic J. Road Bridge Eng. **15**(3), 146–156 (2020). https://doi.org/10.7250/bjrbe.2020-15.489
11. Paplauskas, P., Vaitkus, A.: Dependency of pavement roughness level on the type of road works. Baltic J. Road Bridge Eng. **17**(2), 552 (2022). https://doi.org/10.7250/bjrbe.2022-17.552
12. Paplauskas, P.: Model for assessing the rate of deterioration of asphalt pavement condition on state roads. Doctoral dissertation, Vilnius Tech, Vilnius (2024). https://doi.org/10.20334/2024-027-M
13. Bernal, J.L., Cummins, S., Gasparrini, A.: Interrupted time series regression for the evaluation of public health interventions: a tutorial. Int. J. Epidemiol. **46**(1), 348–355 (2017). https://doi.org/10.1093/ije/dyw098
14. Newey, W.K., West, K.D.: A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica. **55**(3), 703–708 (1987). https://doi.org/10.2307/1913610
15. Prais, S.J., Winsten, C.B.: Trend estimators and serial correlation. Cowles Commission Discussion Paper 383 (1954)

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Market Positioning for a New Compact Battery Electric Vehicle: Addressing Market Gaps in L6e and L7e Segments

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Abstract. ZEV-UP project introduces a new battery electric vehicle as an innovative alternative in the L6e and L7e market segments. This study presents a comparative market positioning analysis of ZEV-UP variants against competitors, highlighting originality, advantages, and areas for improvement. ZEV-UP offers three variants: two 2-seaters, one for passengers (Control Model 1 - CM1) and one for commercial use (CM3), and a 4-seater passenger vehicle (CM2). Each features optimized ergonomics, driver interface positioning, and enhanced roominess, balancing affordability with advanced functionality. The study evaluates eleven key attributes, emphasizing ergonomics, human-machine interaction, drive comfort, and energy efficiency. Findings highlight ZEV-UP's superior ingress/egress comfort, spacious first-row seating, and a cost-effective, user-friendly dashboard. A major differentiator is the ZEV-UP's integration of 5G-based teleoperation technology, enabling remote operation via a drive-by-wire system. This feature enhances safety and convenience, particularly in urban and shared mobility applications. Additional assessments include climatic comfort, noise, vibration, and harshness characteristics, as well as durability and regulatory compliance. ZEV-UP prioritizes natural ventilation, flexible noise isolation, and automotive industry best practices. Overall, ZEV-UP vehicles achieve a balance between affordability, ergonomics, and technological innovation. This study underscores the importance of market feedback, regulatory alignment, and continuous innovation in advancing urban electric mobility.

Keywords: Electromobility · Benchmarking · Battery Electric-Vehicle

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1 Introduction

Compact electric vehicles (EVs), in the L6e and L7e categories, offer numerous advantages, including reduced environmental impact, lower energy consumption, and improved manoeuvrability in urban areas. When focusing on Battery Electric Vehicles (BEVs), which are fully electric and powered solely by rechargeable batteries, the advantages are further enhanced through a vehicle with a small and light design making them ideal for addressing congestion, last-mile transportation challenges, and the growing demand for more efficient mobility solutions in dense urban environments.

As the automotive industry shifts towards more sustainable solutions, market penetration, consumer acceptance, and effective pricing strategies for maximizing the global footprint of BEVs, help companies adapt to competition and market dynamism [1, 2]. A recent study [3] demonstrated that strong policy interventions and strategic market entry can incentivize producers to offer more affordable BEVs, expanding the market through forward-looking strategies over myopic approaches [4].

Consumers remain central to EV adoption: studies identify range anxiety, battery costs, and vehicle attributes as primary determinants of purchase decisions [5, 6]. Mitigating these barriers through technological advancements and strategic market positioning has been shown to enhance overall market acceptance [7]. Additionally, the availability and accessibility of fast-charging infrastructure significantly impact consumer willingness to transition to EVs [8]. Investments in dynamic wireless charging (DWC) can further extend the driving range of BEVs by reducing reliance on large onboard batteries and minimizing the need for frequent stationary charging stops. Such investments may also lower societal costs [9] by improving energy distribution efficiency, alleviating stress on electricity grids, and reducing the need for costly grid expansions. Moreover, decreasing battery capacity requirements can mitigate environmental externalities associated with battery production, including resource extraction and carbon-intensive manufacturing processes [10]. Improved charging accessibility also supports electrified public transportation, lowering emissions, enhancing urban air quality, and reducing pollution-related health costs.

From an economic perspective, local production and tax exemptions foster adoption by reducing costs and improving affordability; such measures can therefore play an important role in strengthening the competitiveness of BEVs within evolving mobility markets [4].

Despite these developments, important gaps remain in the development, adoption, and positioning of compact EVs, particularly in terms of infrastructure compatibility, regulatory frameworks, and consumer awareness.

ZEV-UP aims to address these challenges by developing a new prototype of a small BEV in the L6e and L7e categories, optimizing vehicle design, enhancing performance, and ensuring market readiness by considering key factors such as consumer needs, urban mobility patterns, and policy frameworks. By bridging existing market gaps, ZEV-UP contributes to the broader goal of expanding the sustainable mobility landscape and fostering the adoption of compact EVs in urban environments.

2 Methodology

ZEV-UP's market positioning applies the V-Cycle methodology, a strategic approach widely used in the automotive industry to manage complex product development [11, 12]. Its structured framework aligns development phases with corresponding verification phases, ensuring that each stage is thoroughly validated before progressing.

The method connects development (from requirements to subsystem design) with validation (from component to full-vehicle testing), enabling systematic verification at every phase (Table 1): 1) System definition: vehicle requirements are decomposed into eleven key attributes and subsystem objectives; 2) Validation: subsystems are tested independently before full-vehicle integration to confirm design targets.

Table 1. Vehicle-system level targets interface matrix (UNB: Underbody, CHS: Chassis, PWT: Power-train, EES: Electrical/Electronic Systems, INT: Interior, UPB: Upper-body, HVAC: Heating/Ventilation/Air Conditioning, DOC: Doors/Closures).

Attributes	UNB	CHS	PWT	EES	INT	UPB	HVAC	DOC
Accommodation and Usage	X	X	X	X	X	X		X
Weather Comfort and Performance				X	X	X	X	X
Durability and Reliability	X	X	X	X	X	X	X	X
Human-Machine Interface				X	X			
Noise, Vibration and Harshness	X	X	X		X	X		X
Perceived Quality	X	X		X	X	X		X
Performance and Economy	X	X	X	X		X		X
Safety and Security	X	X	X	X	X	X		X
Sustainability	X	X	X	X	X	X	X	X
Vehicle Dynamics	X	X	X	X		X		
Weight	X	X	X	X	X	X	X	X

The eleven attributes cover cost, performance, range, size, mass, capacity, comfort/safety and perceived technology content, and are normalised and aggregated in a transparent multi-attribute index. This approach was chosen over alternative methodologies for its feasibility in terms of cost and time, its comparability with similar studies, and because it avoids ad-hoc single-metric comparisons by making assumptions about trade-offs explicit and replicable across L6–L7 BEVs.

By structuring vehicle design into these distinct systems, the methodology fosters effective collaboration across engineering domains while maintaining a mission-oriented approach that optimizes both technical performance and user experience.

3 Market Positioning and Product Definition

3.1 Competitive Benchmarking

The comparative assessment of ZEV-UP vehicles with existing compact EVs on the market (Table 2) is done around several key positioning criteria, including pricing, range, battery capacity, and interior and exterior design features.

Table 2. Competitive Benchmarking.

Aspect	Citroën Ami	Microlino	Tazzari Minimax	XEV Yoyo	ZEV-UP
Regulatory class	L6	L6 / L7	L6 / L7	L7	L6 / L7
Min. price (€)	7,990	17,990	17,988	16,590	11,500-14,500
Max. speed (km/h)	45	45 / 90	45 / 80	80	60 / 80
Range (km)	75	91–230	112–162	150	100–150
Battery cap. (kWh)	5.5	6–14.4	7.8–11.2	10.4	6.6–19.8
Battery type	Fixed	Fixed	Fixed	Swappable	Swappable (modular)
Dim. (m) (L × W × H)	2.41 × 1.39 × 1.52	2.52 × 1.47 × 1.50	2.52 × 1.47 × 1.51	2.51 × 1.47 × 1.56	Configurable
Max. weight (kg)	700	613–630	≈750	836	758–1100
Chassis	Box section + plastic panels	Self-supporting steel/aluminum	Steel frame + safety cell	Steel frame + plastic panels	Aluminum rolling chassis + composite body
Seating layout	2	2–4	2	2	2
Boot cap.	63	230	240–400	160	200–1500
Touch screen	No	Optional	Yes	Yes	Yes
Heating / AC	Yes / No	Yes / No	Yes / Yes	Yes/Yes	Yes / Yes

Three variants of vehicles are going to be developed in ZEV-UP project to meet diverse market expectations and usage scenarios, sharing over 60% of components to enhance efficiency and scalability. CM1 is a two-seater optimized for essential mobility; CM2, a four-seater variant, targets daily family use; and CM3, also a two-seater, is designed for commercial applications with expanded cargo space.

Price analysis demonstrated that, while some two-seater EVs are available at entry-level prices between €5,000 and €7,990. CM1, priced at 11.500 (including battery),

offers a competitive alternative that balances affordability with a richer set of features and equipment. CM2's four-seat configuration addresses a gap in the L6e/L7e market and is estimated at €14,500 (with 11.0 kWh battery). Finally, the CM3 commercial variant, priced at €14,000 (with 11.0 kWh battery), is more affordable than most comparable vehicles, which often reach €17,000 to €18,000. A modular battery system lets users tailor costs: the <7.0 kWh pack costs €3,000, and the <11.0 kWh pack €4,000. Price data were taken from manufacturers' official websites and, when needed, official price lists or authorised dealers, using the lowest list price for the Italian/EU market during the collection period.

Comparisons with the above-mentioned vehicles reveal that many BEVs currently on the market are designed for short-range usage, with the majority offering ranges within the 0–100 km bracket. ZEV-UP vehicles propose a modular battery strategy applicable across all vehicle variants. Three battery pack levels are offered, all sharing identical physical dimensions, enabling fast battery swaps for shared, commercial use.

Design strongly shapes user perception, affecting aesthetics, safety, functionality, and comfort. The ZEV-UP models are positioned in alignment with this trend. The design strategy for ZEV-UP aims to: 1) Reinforce the product identity as an innovative, forward-looking solution for urban mobility; and 2) deliver an affordable yet premium vehicle, avoiding low-cost stigma.

The ZEV-UP models exhibit advanced exterior design features align with current BEVs market trends. They feature panoramic roofs—solar-equipped in CM2 and CM3—and removable framed doors, combining practicality and visual appeal. A differentiator is the integrated battery swap capability via a single, floor-mounted pack, enabling replacement and operational flexibility, particularly in shared or commercial use cases.

In interior design and on-board facilities, ZEV-UP vehicles stand out from competitors. Storage capacity surpasses most vehicles in the segment (CM1: 500 L, CM2: 200 to 1,000 L, and CM3: 1,500 L), ensuring adaptability for personal and commercial use. Multimedia equipment positions ZEV-UP in the high-end range, with a Thin Film Transistor touchscreen, Bluetooth, and an optional connectivity module enabling remote control, monitoring, data recording, and diagnostics via mobile app or fleet platform.

3.2 Product Definition

Converting benchmarking knowledge into engineering specifications requires a system-level approach that define ZEV-UP's position in the L6e/L7e segments. Accommodation and ergonomics interact with the human-machine interface, providing the basis of noise, vibration, and harshness optimisation, which determines perceived quality. Energy efficiency and dynamic performance need to complement safety and security concerns. Sustainability considerations cut across all the systems, especially affecting vehicle dynamics and weight optimisation strategies.

The accommodation and usage specifications address critical gaps identified in competitor vehicles. The first-row design ensures easy ingress/egress while maintaining headroom and shoulder room. This ergonomic foundation extends to the second row, where the CM3 variant's Euro pallet capacity demonstrates the vehicle's adaptability to commercial applications without compromising the compact exterior dimensions. Track widths ensure stability during the dynamic manoeuvres enabled by torque vectoring,

while modular cargo volumes across variants accommodate personal and commercial loads through removable seating configurations.

These space considerations directly influence the weather comfort and performance systems, where the HVAC (heating, ventilation, and air conditioning) system enables rapid cabin cooling. Thermal management requirements are balanced with vibration targets through a tuned suspension system, ensuring ride comfort and structural rigidity demanded for long-term durability.

The aluminium rolling chassis and composite body of the vehicle support advanced human-machine interface innovations. The 7" Thin Film Transistor touchscreen and smartphone connectivity exemplify a user-oriented design, while the 5G teleoperation system enables remote assistance, fleet tracking and diagnosing via mobile interface, supporting both individual and commercial use cases.

This attention to perceptual quality extends to the perceived quality attributes, where a premium aesthetic is achieved despite cost-optimized materials. Manufacturing tolerances permit limited non-structural defects, with zero tolerance for structural issues that could compromise the specified vehicle lifespan. These material choices directly support performance and economy objectives, where WLTP (Worldwide Harmonized Light Vehicles Test Procedure) energy consumption targets representing a 10% improvement over comparable vehicles.

The safety and security systems build upon this architecture through energy-absorbing structures designed for collision protection, complemented by three-point seatbelts and a modular bumper system. The ADAS (Advanced Driver Assistance Systems) suite—including Forward Collision Warning, Lane Departure Warning, and Blind Spot Information System—shares the same sensor array for teleoperation, creating a synergistic relationship between active safety and connectivity. Sustainability considerations include recycled material content and corrosion-resistant structures, reducing lifecycle impacts while maintaining structural integrity under full load conditions. Weight is addressed through optimised chassis and composite body panels that preserve crashworthiness and NVH (Noise, Vibration, and Harshness) performance. The integration of these attributes results in a common vehicle architecture addressing identified market gaps. The modular battery system with fast swappability and adaptable range and speed configurations demonstrates how accommodation requirements influence performance, durability and perceived quality, ensuring ZEV-UP's positioning as a versatile and future-ready urban mobility solution.

4 Discussion

ZEV-UP is developed within a highly regulated environment, in whichswappable architectures and battery module technologies currently lack standardized authorization platforms (UNECE R100). Teleoperation legislation is currently limited only to parking manoeuvres (UNECE R79), and hence, dynamic driving applications are currently placed within a regulatory grey zone. Controlled environment pilot projects can bring forward the clarification of said requirements while showing the safety advantages of these applications within shared mobility scenarios.

Technological trade-offs are reliance on standardized battery interfaces and infrastructure density swapping, and these can put a damper on private user adoption. The

cooldown ability of the HVAC system is adequate for the climates of Europe but can mandate phase-change materials in extreme heat markets such as the Gulf region. Barriers to consumer adoption remain where perceived safety of light structures is concerned, although ZEV-UP understeer tuning and 3-point seatbelts eliminate these fears through structural rigidity optimizations.

The circular economy challenges centre on composite panel recyclability and battery degradation tracking, requiring partnerships with specialized recyclers and blockchain-based health certificates. Conversely, the business model opportunities are significant: the CM3's 1.5m^3 cargo capacity and panoramic roof suit urban logistics and tourism, while the 5G telemetry data could enable traffic optimization and usage-based insurance models. A "ZEV-UP Mobility Platform" bundling leasing, swapping, and teleoperation could validate demand through B2B fleet deployments before scaling to private users. From a sustainability perspective, the present work focuses on vehicle mass, size and energy-use implications; a full cradle-to-grave Life-Cycle Assessment (LCA) of the ZEV-UP architectures is being developed within the project and will be reported separately to quantify their net environmental benefit.

5 Conclusions

ZEV-UP represents a paradigm shift in the L6-L7compact EV segment, integrating modularity, connectivity, and sustainability. In terms of compact EV market, ZEV-UP variants address three main gaps, the user-centric design providing class-leading ergonomics and large storage for multipurpose, offering comfort and utility, the integration of innovation such as in-wheel motors, 5G teleoperation and battery swapping place ZEV-UP on the bridge between conventional EVs and autonomous vehicles, and the reducing one important adoption barriers, related to the battery, by providing BaaS models. By addressing eleven key attributes, ZEV-UP sets a new benchmark for micro urban mobility, offering practical, efficient, and future-ready solution. The next phase will focus on prototype validation, regulatory certification, and pilot programs, ensuring that ZEV-UP is market-ready and scalable for the evolving demands of urban transportation.

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References

1. Wang, Z.: A Comparative Analysis of Product Positioning Strategies in the Global Electric Vehicle Market: Insights from Leading Brands and Emerging Markets. AEMPS. **84**, 288–296 (2024). https://doi.org/10.54254/2754-1169/84/20240823
2. Duan, A.: Research on Product Positioning of New Energy Vehicles-Taking Tesla and Build Your Dream as Examples. AEMPS. **84**, 280–287 (2024). https://doi.org/10.54254/2754-1169/84/20240822

3. Choi, H., Koo, Y.: New technology product introduction strategy with considerations for consumer-targeted policy intervention and new market entrant. Technol. Forecast. Soc. Chang. **186** (2023). https://doi.org/10.1016/j.techfore.2022.122126
4. Ogunkunbi, G.A., Al-Zibaree, H.K.Y., Meszaros, F.: Modeling and evaluation of market incentives for battery electric vehicles. Sustainability. **14**, 4234 (2022). https://doi.org/10.3390/su14074234
5. Jensen, A.F., Cherchi, E., Mabit, S.L., Ortúzar, J.D.D.: Predicting the potential market for electric vehicles. Transp. Sci. **51**, 427–440 (2017). https://doi.org/10.1287/trsc.2015.0659
6. Hidrue, M.K., Parsons, G.R.: Is there a near-term market for vehicle-to-grid electric vehicles? Appl. Energy. **151**, 67–76 (2015)
7. Cano, Z.P. et al.: Batteries and fuel cells for emerging electric vehicle markets. Nat. Energy. **3**, 279–289 (2018). https://doi.org/10.1038/s41560-018-0108-1
8. Morrissey, P., Weldon, P., O'Mahony, M.: Future standard and fast charging infrastructure planning: an analysis of electric vehicle charging behaviour. Energy Policy. **89**, 257–270 (2016). https://doi.org/10.1016/j.enpol.2015.12.001
9. Liu, Q. et al.: Dynamic wireless power transfer system for electric-powered connected and autonomous vehicle on urban road network. IET Intell. Transp. Syst. **15**, 1153–1166 (2021). https://doi.org/10.1049/itr2.12087
10. Liu, S., Wang, D.Z.W., Tian, Q., Lin, Y.H.: Optimal configuration of dynamic wireless charging facilities considering electric vehicle battery capacity. Transp. Res. Part E Logist. Transp. Rev. **181**, 103376 (2024). https://doi.org/10.1016/j.tre.2023.103376
11. Zhidkikh, N., Smolyaninov, A., Deniskin, Y., Polity, V., Mangushev, I.: Project management model of motor vehicle development with consideration of built-in quality concept requirements. E3S Web Conf. **376**, 01100 (2023). https://doi.org/10.1051/e3sconf/202337601100
12. Anjum, S.K., Wolff, C.: Agile Principles in Automotive Software Development: Analysis of Potential Levers. In: 2021 IEEE European Technology and Engineering Management Summit (E-TEMS), pp. 141–147 (2021). https://doi.org/10.1109/E-TEMS51171.2021.9524860

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New Insights into the Investigation on Additive Manufacturing for Its Application on Railway Wheels

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Abstract. The present work continues the investigation into the potential of Direct Energy Deposition-Laser Beam (DED-LB) for its application on railway wheels. The aim of the work is to study this technique in order to extend the service life of the wheels, as well as trying to improve its performance. Moreover, this would be particularly interesting in cases of severe and localized flange wear, avoiding high amount of material to be wasted during the turning. To ensure the relevance of the results, the samples were directly extracted from a worn ER9 wheel and cladded with three different materials. Their functionality was analysed in terms of hardness, residual stress, and a Ball-on-Disc device is employed to study their wear and friction behaviour. The results show that DED-LB could be used as a feasible technique to create superficial coatings on railway wheels, this would involve an exceptionally favourable impact on the society, contributing to the development of an industry that is environmentally sustainable which would additionally reduce the maintenance costs and enhance the efficiency of railway operations.

Keywords: Green and sustainable industry · Metal Additive Manufacturing · Railway wheels · Wear

1 Introduction

This work is the continuation on the study on the use of Metal Additive Manufacturing (MAM) for its function on railway wheel reprofiling [1]. The main objective is to study the use of this procedure trying to increase the lifetime of the wheel. The wheel wear management is crucial for reducing maintenance expenses and enhancing the productivity of railway industry. The issue is that the current method for the reprofiling of used wheels is a turning procedure that reinstates the initial design profile [2], which requires a high volume of material to be rejected. Moreover, this discarding is larger when the wear occurs predominantly in the flange. A graphical representation of this issue is detailed in Fig. 1, which shows that the reprofiling depth for restoring a worn flange is considerably greater than that for a worn tread, indeed, it can be more than twice that of the tread. However, with the possibility of adding a very few quantity of

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material by MAM, it would be possible to avoid a considerable amount of material to be wasted.

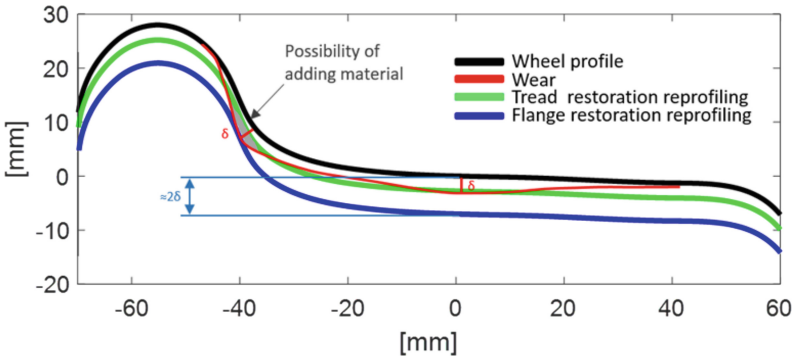


Fig. 1. Necessary diameter reduction for different locations of wear

Moreover, the wear can also implicate to turn remaining wheels even if they could be considered as safe, given that the wheels must meet the requirements relating to the difference in their diameters [3–5]. Finally, after numerous reprofiling procedures the minimum diameter of the wheel is achieved [6], indicating that the service life is over, and the wheel must be discarded and replaced [5]. What is more, the replacement can be up to ten times more expensive that the reconditioning [7]. Therefore, the investigation has been concentrated on reducing maintenance expenses and enhancing the efficiency of railway operation. Consequently, the research has concentrated on utilising the MAM for railway wheels reprofiling, this technique has already been shown to create protective Fe-based coatings in lower and middle rails R200 and R260 [8], ultra hard rails R400HT [9], and bainitic rails [10]. Moreover, it has been demonstrated that steel coatings can effectively reduce the wear of the standard rail R260 in almost 90% [11]. Additionally, other works have explored simultaneously the utilisation of a large variety of Fe-based materials, Meng et al. [12] demonstrated that Fe-based coatings significantly enhance wear resistance while simultaneously reducing plastic deformation and surface degradation. Fasihi et al. [13] examined the performance of an innovative Fe-based alloy developed through the combination of different commercial steels. Their findings confirmed that the alloy successfully integrated the characteristics of its source materials, resulting in a substantial improvement of both wear and fatigue resistance. Similarly, Xie et al. [14] analysed the performance of various Fe-based alloys and reported that, in addition to decreasing rail wear, the coatings also contributed to slowing down crack propagation. However, in the case of wheels the investigation is still too weak, due to the high mechanical performance they must have. Nevertheless, MAM would be particularly beneficial for them, as it would conduct to a reduction in the amount of material removed in the conventional machining process, to an extended service life of wheels, and a lower wheel replacing frequency. This involves an exceptionally favourable impact on society, contributing to the development of an industry that is environmentally sustainable and which would additionally reduce the maintenance costs and enhance the efficiency of

railway operations. Thus, this study is intended to serve as the initial phase of the investigation in which the European research programme could hypothetically lean on in the future for applying MAM in the railway industry.

2 Methodology

2.1 Materials

A worn wheel used in passenger transportation was acquired to be employed as substrate material this study. This wheel is made of high strength steel, ER9, which is the most strength grade according to the standard UNE-EN 13262 [15]. To prepare the specimens, the wheel was firstly machined to extract the plate and the hub, and to obtain the tread. Then, some cuts were made in the rim to obtain a plenty of segments from the tread. Lastly, the rolling surface was removed to obtain planar surfaces, and these were ground to remove roughness. Three powders are employed in this work as filler materials. These were selected according to their potential wear resistance, as well as their economical and commercial availability, and chemical interaction capability. The selected standardized steels are: AISI 4140, an economic low-allow steel, with similar composition to that the wheel, and which is commonly used in when low wear is necessary, like gears and crankshafts; AISI 52100, a particular steel fabricated for bearings, and therefor, with excellent properties against wear and Rolling Contact Fatigue (RCF); and AISI H13, a versatile and affordable material employed to resist wear in hot-work and cold-work tooling applications. All the materials were atomized by inert gas, their particle distribution is in the range $-105 + 45$ μm, and their chemical composition is shown in Table 1.

Table 1. Chemical composition of materials (in %wt.). Fe balance

Material	C	Mn	Cr	Si	Mo	S	P	Al	Ni
Wheel ER9	0.6	0.8	0.3	0.4	0.08	0.015	0.02		0.3
AISI 4140	0.4	0.75–1	0.8–1.1	0.15–0.35	0.15–0.25	<0.04	<0.035		
AISI 52100	0.95	0.41	1.49	0.2		0.004	<0.01	0.01	
AISI H13	0.3–0.4	0.2–0.4	4.75–5.5	0.8–1.2	1.25–1.75				

2.2 DED-LB Equipment and Procedures

In order to carry out the manufactured parts, an own built-up DEB-LB equipment was used, this apparatus employs 1 kW fibre laser with of 1,070 nm wavelength, the powder is guided by a Sulzer Metco Twin 10-C powder, and the drag gas, as well as protection

gas, to create shielding atmosphere and avoid oxidation, was Argon. Then, an adjustment of the laser parameters for the recommended values of clad height dilution coefficient [16] was performed for each material. The distance between was regulated to acquire a uniform height in layers, avoiding excessive overlap. The coatings were manufactured in perpendicular layers, to improve properties in both directions, and as many layers as necessary to get a total height above 1 mm. The parameters are summarized in Table 2.

Table 2. DED-LB parameters

Material	Power [W]	Scanning Speed [m/min]	Feed Rate [g/min]	Pass [mm]	No. Layers
AISI 4140	700	450	3.3	1.00	2
AISI 52100	800	450	3.0	1.20	2
AISI H13	600	450	3.5	1.15	3

2.3 Analyses and Experiments

Hardness. After manufacturing, the roughness of the manufacturing process was eliminated by grinding, and hardness test were done. For this purpose, 10 measurements with a diamond spheroconical indenter were performed on the surface using a Rockwell C scale tester (Tecmicro), following the procedures of the standards [17].

Residual Stress. The microstructure of the specimens was examined by X-Ray Diffraction (D8 Discover, Bruker) technique, and the residual stresses generated during the manufacturing were measured using the neutron diffraction technique.

Tribological Tests. The specimens were polished using coarse and fine grained abrasive sanding papers, to achieve a minimum surface roughness. The tribological tests were performed using a pin-on-disc device (Microtest), being the pin a 6 mm diameter WC 94/Co 6 ball, following the procedures of standards [18]. The applied pressure was 2070 MPa, the operating velocity was 400 mm/s on a track diameter of 25 mm for a total of 20,000 cycles. All tests were performed at ambient temperature and humidity. Afterwards, the wear tracks were examined throughout an Optical Microscope (DCM 3D, Leica), in order to obtain the wear profiles and quantify material loss.

3 Results and Discussion

3.1 Hardness

Table 3 summarises the hardness measurements of all materials. Firstly, it is clearly visible that all three coated parts present a major rise contrasted to that of the wheel, 27.8 ± 0.8 HRC, which correlates with the value (255 HB) of the standard [15]. AISI 4140 has the lowest value and a large deviation, 53.8 ± 4.9 HRC. This deviation could suggest irregularities in the material, affecting its strength in decisive circumstances.

In contrast, AISI 52100 and AISI H13 offered lower deviation, 66.2 ± 1.3 HRC and 59.3 ± 1.3 HRC respectively. Moreover, these values are considerably greater than that of the wheel material, indicating that these could be more suitable for applications requiring a superior resistance. However, for this specific application, an extremely high hardness is not always desired, since it could facilitate the deterioration of the rail. Trying to control this issue is essential for ensuring a consistent functionality. In this case, AISI H13 is considered as the most appropriate option because of its trade-off between average and deviation.

Table 3. Hardness measurements of the specimens [HRC]

Material	Average	SD.
Wheel ER9	27.8	±0.8
AISI 4140	53.8	±4.9
AISI 52100	66.2	±1.3
AISI H13	59.3	±1.3

3.2 Residual Stresses

Afterwards, X-Ray Diffraction (XRD) analyses were done to measure the surface residual stresses. When using MAM, it is very likely to acquire tensile residual stresses, because of the material undergoing rapid melting and subsequent solidification, resulting in material contraction. However, the three materials showed compressive biaxal + shear stress state. AISI 4140 showed the higher values, − making this material a very suitable candidate. AISI 52100 exhibited also favourable result in the major principal stress, but with a considerable difference with the second one, which indicates that its properties may be affected depending on the direction. Finally, AISI H13, exhibited the lowest compressive result, but with the lowest difference between both major stresses. A summary of the results is shown in Table 4. To conclude, the generated stress state in three materials is an outstanding result, since compressive stresses increase the resistance of the wheel against RCF, helping to slow the crack propagation.

Table 4. Generated residual stresses during manufacturing [MPa]

Material	σ_1	σ_2
AISI 4140	−405.9	−368.9
AISI 52100	−220.5	−97.2
AISI H13	−62.9	−38.2

3.3 Friction

Figure 2 shows the measured Coefficient of Friction (CoF) of four materials during the test. Upon initial observation, it is concluded that AISI H13 exhibited an extremely high value, a constant value of 0.6 during the whole test, suggesting a high amount of material loss. Otherwise, both AISI 4140 and AISI 52100 presented almost identical performance to that of the reference wheel, with an average coefficient of 0.4. Nonetheless, minor discrepancies remain evident, the wheel presented a uniform rising predisposition, whereas AISI 4140 and AISI 52100 begin to fall after the barer of 1000 m, making these two materials to end with even at slightly lower value. In conclusion, the excellent performance of AISI 4140 and AISI 52100 point to the viability of using MAM for wheel applications and its indispensable friction behaviour.

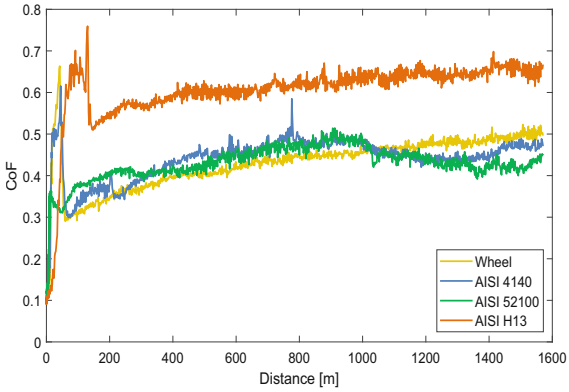


Fig. 2. Measured Coefficient of Friction in ball on disc device

3.4 Wear

The developed wear tracks are shown in Fig. 3. At first glance, it is observed that AISI H13 presented a huge amount of material loss, as anticipated before. Indeed, its depth is just below 20 μm, which is about four times that of the wheel. Contrariwise, AISI 52100 has a thin and profound hole, whose cause is believed to be on debris stuck in the ball which make a groove on contact surface. Nevertheless, this behaviour might be originated because of the controlled atmosphere of the laboratory, while it is less probably to appear on a real track, where the drag forces would avoid it. Finally, the profile of AISI 4140 is practically identical to that of the wheel, but with a lower depth. This points out that AISI 4140 not only matches the wear mechanism of the wheel, but can even improve its behaviour.

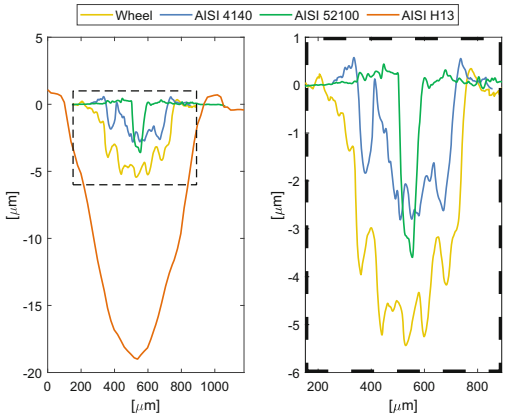


Fig. 3. Measured wear profiles after the test

4 Conclusions

In this work DED-LB was studied to analyse the feasibility of introducing MAM to railway wheel reconditioning. Thus, different coatings were performed on a used railway wheel with three different filler materials. It is evident that more exhaustive work needs to be done before this technique can be implemented into the industry, nevertheless, promising conclusions can be achieved from this study.

To summarize, the results show that these materials can lead to an enhanced functionality of the wheel in the mechanical performance analysed here, demonstrating that this technique could effectively be used as a viable technique to use on railway wheels. Moreover, this technique would be of special interest for railway exploitations that suffer from wear in the flange, such as tramways, subways and commuter train lines that commonly have moderate and sharp curves, or freight transportation trains, whose wear is noticeably higher than other transport. This would conduct to a reduction in the amount of material removed in the conventional machining process, as well as to an extended service life of wheels, and thus, lower wheel replacing frequency, while having strong environmental benefits. This involves an exceptionally favourable impact on the society, contributing to the development of a circular economy, that is, an industry that is environmentally sustainable which would additionally reduce the maintenance costs and enhance the efficiency of railway operations. The path toward implementing DED-LB on actual railway wheels operating under real track conditions remains long and complex. Nevertheless, this research paves for the development of a novel reprofiling procedure for worn railway wheels, offering promising technical and economic advantages.

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References

1. Hernandez-Martinez, J., Santamaria, J., Arrizubieta, J.I., Correa, N.: Experimental evaluation of novel alloy powders for extending service life of railway wheels worn by use. Wear. **570**, 205945 (2025). https://doi.org/10.1016/j.wear.2025.205945
2. European Standard UNE-EN 13715:2021: Railway applications – wheelsets and bogies – wheels – tread profile (2021)
3. International Union of Railways UIC 510–2: Trailing stock – wheels and wheelsets – conditions concerning the use of wheels of various diameters on the same axle (2004)
4. European Standard UNE-EN 13260:2021: Railway applications – wheelsets and bogies – wheelsets – product requirements (2021)
5. European Standard UNE-EN 15313:2017: Railway applications – in-service wheelset operation requirements – in-service and off-vehicle wheelset maintenance – product requirements (2017)
6. European Standard UNE-EN 13979:2017: Railway applications – wheelsets and bogies – monobloc wheels – technical approval procedure – part 1: forged and rolled wheels (2007)
7. Åhrén, T., Waara, P., Larsson-Kraik, P.O.: Technical and economic evaluation of maintenance for rail and wheels on Malmbanan. In: International Heavy Haul Conference, pp. 5.86–5.87, Dallas, Texas (2001)
8. Lu, P., et al.: Laser cladding of rail: the effects of depositing material on lower rail grades. Wear. **438–439**, 203045 (2019). https://doi.org/10.1016/j.wear.2019.203045
9. Roy, T. et al.: Effect of deposition material and heat treatment on wear and rolling contact fatigue of laser cladded rails. Wear. **412–413**, 69–81 (2018). https://doi.org/10.1016/j.wear.2018.07.001
10. Zhang, B., He, B., Wang, H.: Microstructural investigation and mechanical performance of laser cladding repaired bainite steel with AerMet100 steel. Surf. Coat. Technol. **440**, 128498 (2022). https://doi.org/10.1016/j.surfcoat.2022.128498
11. Lewis, S.R. et al.: Improving rail wear and RCF performance using laser cladding. Wear. **366-367**, 268–278 (2016). https://doi.org/10.1016/j.wear.2016.05.011
12. Meng, L., et al.: Laser-induction hybrid cladding of different coatings on rail surface: microstructure, wear properties and contact fatigue behaviors. Appl. Surf. Sci. **566**, 150678 (2021). https://doi.org/10.1016/j.apsusc.2021.150678
13. Fasihi, P., Abrahams, R., Mutton, P., Yan, W.: Tribological properties of a new alloy laser cladded on hypereutectoid rails. J. Tribol. **143**(5), 051110 (2021). https://doi.org/10.1115/1.4050896
14. Xie, T., et al.: Investigation on the rolling contact fatigue Behaviors of different laser cladding materials on the damaged rail. J. Tribol. **143**(5), 051108 (2021). https://doi.org/10.1115/1.4050690
15. European Standard UNE-EN 13262:2021: Railway applications – wheelsets and bogies – wheels – product requirements (2021)

16. Urresti, A., Murua, O., Arrizubieta, J.I., Lamikiz, A.: In-situ monitoring of the DED-LB process for defect detection. Procedia CIRP. **124**, 314–317 (2024). https://doi.org/10.1016/j.procir.2024.08.125
17. ASTM International ASTM E18-15: Standard test methods for Rockwell hardness of metallic materials (2015)
18. ASTM International ASTM G99-17: Standard test method for wear testing with a pin-on-disk apparatus (2017)

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The E-Scooter Paradox: Governing Micromobility for Urban Sustainability. Environmental Impacts and Policy Implications from Hamburg's Suburban Implementation

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Abstract. Despite meeting sustainability criteria in theory, shared e-kick scooters face widespread criticism regarding their environmental benefits and urban integration. This study examines the potential of e-scooters as first - and last-mile connections in suburban areas through a demonstration project in Hamburg, Germany. Using vehicle data, user surveys, and life cycle assessment methodology, we analyzed 175,381 vehicle-kilometers across two suburban districts. Results show that 23% of trips were intermodal, with 26% replacing car trips. Under conservative assumptions, the deployment resulted in net additional emissions of 4,272 kg CO_2e due to high embedded emissions from vehicle production. However, a sensitivity analysis reveals that achieving 37% car trip substitution or reducing LCA emissions to 42.6 g CO_2e/km would result in net-zero emissions. The study demonstrates that improved vehicle durability, increased modal shift from private cars, and integration with public transport can enable e-scooters to contribute meaningfully to sustainable urban mobility systems, notably in sub-urban environments.

Keywords: E-scooters · intermodal transport · life cycle assessment · urban mobility · first-last mile

1 Introduction

Shared electric kick-scooters embody all characteristics of sustainable vehicles: they are small-sized, light, space-efficient, electric, locally emission-free, and shared rather than privately owned. Yet, they are widely criticized by the public, policymakers, mobility practitioners, and researchers alike as unsustainable, resource-intensive, and intrusive in urban spaces. This paradox has triggered a debate on whether e-scooters represent a meaningful contribution to sustainable urban mobility or a distraction from more effective transport solutions.

Life cycle assessments (LCAs) indicate that the sustainability of e-scooters depends on their design, production, maintenance, operation, and the transport modes they replace. E-scooters are therefore not inherently sustainable or unsustainable; their net

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impact is context-dependent. While LCAs provide valuable insights into environmental effects on a product level, they rarely contextualize e-scooters as part of intermodal travel with combination with mass transport.

The introduction of e-scooters has been business-driven, with operators deploying large fleets with little coordination with local authorities. Cities were largely unprepared, lacking effective policies mechanisms to regulate their operation. Accordingly, this study addresses two objectives: first, to evaluate the environmental impacts of shared e-scooter services based on a real-life demonstration in suburban contexts using a service-level perspective; and second, to derive evidence-based policy options for cities to address critical impacts of privately operated mobility services.

2 Literature Review

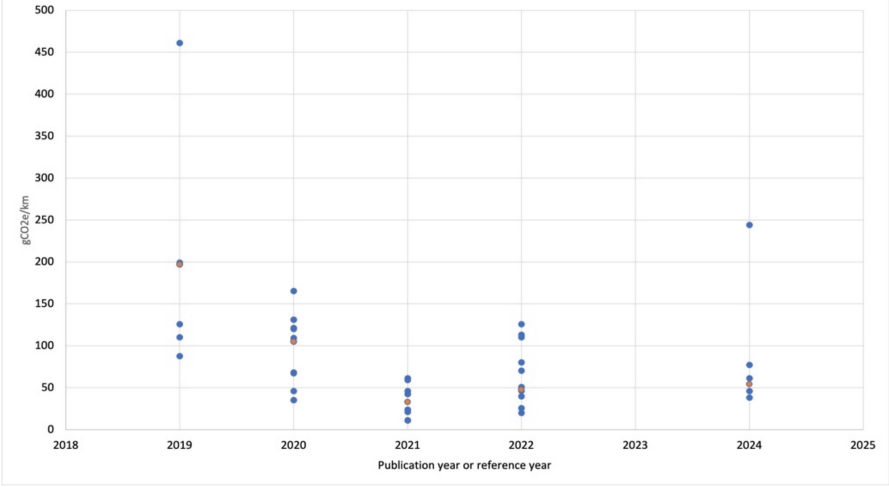


Fig. 1. Distribution of GHG emissions of shared electric kick scooters (gCO2e/vehicle km) in studies by publication or reference year (median Values per year highlighted in red)

2.1 Life Cycle GHG Emissions of e-Scooters

A consistent finding across LCA studies is that the majority of energy use and greenhouse gas emissions originate from vehicle and battery production, rather than from the actual use phase. Although e-scooters consume significantly less energy per kilometre during operation than most other motorised modes, their total emissions per vehicle-kilometre rise substantially once embedded emissions are included. This effect is amplified considering the short operational lifetime of e-scooters. Assumptions in LCA studies range from less than six months to up to two years [1]. Accordingly, LCA-based GHG emissions vary widely across studies, from below 20 gCO_2e to up to more than 450 gCO_2e

per vehicle kilometre. Differences in assumptions about production methods, lifetime, and servicing logistics largely explain this variability, with tendentially declining GHG emission factors in more recent studies analyzing second and third generation e-scooters (Fig. 1) [2–8].

2.2 Modal Substitution Patterns

Shared e-scooter services are commonly concentrated in dense urban cores already well served by walking, cycling, and public transport, while peripheral areas are often excluded. With average trip lengths under two kilometres, e-scooters frequently substitute for walking, cycling, or public transport rather than private vehicles. As car trips are typically longer, their substitution potential is limited, and in some contexts e-scooters may increase overall energy use and GHG emissions [6, 9, 10]. When integrated with public transport for first- and last-mile travel, however, e-scooters can reduce car dependency and emissions. With the exemption of few studies [6, 11, 12], this complementary role remains largely underexplored.

3 Methodology

3.1 Demonstration Activity

The Hamburg demonstration aimed to investigate whether shared e-scooters can effectively serve as first - and last-mile connection to public transport. The activity focused on two suburban districts, Lokstedt and Langenhorn, which are located 8 to 12 km from the city centre. Each of the selected areas has two subway stations with comparatively weak public transport connectivity to the surrounding neighbourhoods. The assumption was that a hybrid sharing scheme for e-scooters, with designated parking spots at subway stations and free floating in the surrounding area, would offer flexible connectivity to public transport, encouraging intermodal travel and increasing public transport's competitiveness with private car use.

To facilitate intermodal use, designated parking spaces were established at these stations. The infrastructure followed a minimalist approach, consisting of ground markings and a traffic sign to indicate the parking areas.

3.2 Data Collection

The research design combined qualitative and quantitative methods, drawing on surveys, vehicle data, and information supplied by the subcontracted e-scooter operator. The vehicle data collected included the number of scooters available during the demonstration period, the origins and destinations of trips, total trip counts, average trip distances, and the share of trips starting or ending at subway stations. To complement these data, a user survey of approximately 5,500 TIER app users in the project area achieved 121 responses. The survey provided insights into the share of intermodal trips, substitution patterns with other modes of transport, and the extent of induced demand.

The evaluation also referred to data sourced from literature, notably for GHG emissions per e-scooter kilometer. For typical trip distances in Hamburg, data from the

national mobility survey 'Mobilität in Deutschland' and its regional report for the Hamburg Metropolitan Region were used [13]. Information about well-to-wheel emissions of the car fleet were sourced from the German Environmental Agency [14].

4 Methodology

4.1 Travel Patterns and Modal Substitution

During the one-year project period, 175,381 vehicle-kilometers were traveled on e-scooters in the demonstration areas. Average trip length of scooter trips was 1.7 km, while trips to and from public transport stations were shorter with 0.9 km on average. The online user survey revealed that, depending on the trip purpose, only 21 to 42% of users used the shared scooter for point-to-point trips, and between 31 and 41% in combination with other means of transport, except walking. Between 17 to 28% of respondents indicated that they used shared e-scooters in combination with public transport (Fig. 2).

To validate the survey results, vehicle data were analyzed to determine the proportion of e-scooter trips that originated or terminated at the four subway stations. Given the absence of major attractions in the vicinity of these stations, we assume that the vast majority of these trips were part of intermodal journeys. The spatial analysis showed that 23% of e-scooter trips either started or ended at subway stations, which is consistent with the range of the survey results. The survey also found that 26% of e-scooter trips replaced car trips, while the remainder primarily substituted walking, cycling, and public transport. Two percent of trips were induced, meaning they would not have been done in absence of the e-scooter service.

4.2 Environmental Impact Assessment and Sensitivity Analysis

Building on this information, a conservative baseline scenario was developed. This scenario considered both the additional emissions from the implementation and use of e-scooters, and the avoided emissions from shifted car trips. The baseline scenario applied a simplified life cycle analysis (LCA, focusing only on CO2e emissions) perspective, assuming all e-scooters were newly produced rather than relocated. An average emission factor of 67 gCO_2e per vehicle-km was used, representing the median of studies assessed. The consulted studies include assessments of early models with short lifetimes and GHG-intensive servicing. Since the demonstration employed newer models with longer lifetimes, swappable batteries, and electric service vehicles, this value represents a very conservative assumption.

For substituted car trips, the scenario assumes that car stocks remained unchanged. Accordingly, only well-to-wheel emissions of direct fuel consumption were considered, excluding dynamic effects such as long-term reductions in car ownership. Moreover, the baseline scenario was restricted to those e-scooter trips that are intermodal (26% of all e-scooter trips, based on the survey and vehicle data). Out of those, 23% replaced car trips (survey data). The scenario further assumed an average distance of 5.6 km per car trip, derived from the mobility survey for the Hamburg metropolitan area [13], which indicated a typical distance for Hamburg of 4 km for commuting and 8 km for leisure trips, with a distribution of 40/60%.

Using the pessimistic baseline assumptions resulted in net additional emissions of 4,272 kgCO_2e over the demonstration period. This baseline scenario was then used for a sensitivity analysis for key variables required to achieve GHG emission break-even.

4.3 Sensitivity Analysis

To assess the implications of the pessimistic baseline scenario, we modified the underlying assumptions to identify threshold values for the share of shifted car trips and the emissions per e-scooter-kilometre required to reach a zero net effect on GHG emissions.

In the first alternative scenario, the restriction to intermodal trips was relaxed by also accounting for the substitution of car trips by all other e-scooter trips observed during the demonstration period, including those not associated with intermodal travel chains. For these trips, an average e-scooter trip distance of 1.7 km was assumed, based on the collected vehicle data, and the corresponding car trip distances were adjusted accordingly. Under this scenario, the analysis indicated GHG emission reductions of 3,144 kg CO_2e over the demonstration period.

A second sensitivity analysis demonstrated that, if 36% of intermodal e-scooter trips replaced car trips, no additional GHG emissions would occur. Replacement rates above this threshold would result in net reductions of transport-related GHG emissions. The assessed substitution rate of private car trips was higher in this suburban/intermodal setting than in most earlier studies, but not sufficient to achieve a zero net effect on emissions.

In a third calculation, the sensitivity to variations in the average length of substituted car trips was assessed. Assuming an emission factor of 164 g CO_2e/km, an average car trip distance of 8.8 km was identified as the break-even point for a zero net-effect on GHG emissions. This value is considered feasible given the location of the demonstration sites.

A final sensitivity analysis considered the greenhouse gas emissions associated with e-scooters themselves. The analysis found that an emission factor of 42.6 gCO_2e/km would correspond to a zero net effect on GHG emissions. This value lies well within the range of more recent LCA studies, particularly those analyzing second and third generation e-scooters, as those deployed in the Hamburg case study. In a study for Paris, De Bortoli and Christoforou found that emissions below 56 gCO2e/km would be required to be climate positive [15].

5 Discussion and Policy Recommendations

5.1 General Findings

The scenario analysis indicates that, contingent upon the underlying assumptions, the deployment of shared e-scooters in urban peripheries and their integration with public transport systems may either mitigate greenhouse gas (GHG) emissions or generate additional life-cycle emissions. With the exception of the car trip substitution rate, all estimated threshold values required to achieve net-zero emission effects fall within the range reported in previous studies or appear realistically attainable under current technological and operational conditions. Given that these parameters operate concurrently,

and considering that several may exceed the conservative baseline assumptions adopted in this study, it is plausible that the introduction of shared e-scooters has contributed to a reduction in transport-related GHG emissions. Key leverage points include extending vehicle service life, improving operational efficiency, and implementing measures that increase the substitution of car trips.

5.2 Vehicle Lifetime Enhancement

Despite improvements in e-scooter durability, premature withdrawals due to vandalism remain common. City administrations play a central role in addressing this issue by regulating parking through geo-fencing and designating no-parking zones near water bodies, bridges, and steep slopes. Providers, in turn, are responsible for implementing these measures and maintaining compliance. The introduction of dedicated parking spaces or docking stations, coordinated by municipalities in partnership with operators, can reduce street clutter, limit vandalism and misuse, and thereby extend vehicle lifetimes.

5.3 Operational Efficiency

During operation, the largest share of GHG emissions arises from servicing and relocating shared vehicles. Early e-scooters with fixed batteries required collection for charging, often using diesel vans [2]. Newer models with swappable batteries enable decentralised charging with smaller service vehicles, such as e-cargo bikes, reducing operational impacts. Station-based systems have also been shown to generate lower emissions than free-floating schemes [16, 17]. Additional reductions can be achieved through charging docks integrated into racks, complemented by renewable energy or second-life vehicle batteries in mobility hubs [18].

Urban administrations can substantially influence these impacts through licensing and tendering. Service requirements should exclude diesel vans for servicing, and promote low-emission fleets such as e-cargo bikes instead. Environmental performance criteria can be weighted heavily in operator selection, as illustrated by Paris's 2020 tender, which allocated 40% of the evaluation score to environmental performance [19].

5.4 Integrated Mobility Hub Development

Physical integration through mobility hubs at public transport stations and digital integration of shared mobility services into public transport apps can strengthen intermodal connectivity while easing parking management. Hamburg's ITS strategy highlights the linkage of public transport, shared mobility, and hub expansion as key measures for reducing GHG emissions. Intermodal e-scooter use can also be fostered by demand-management policies that discourage private car use, such as stricter parking regulations, congestion pricing, and cost contributions for car users in central areas.

6 Conclusion

The study demonstrates that the environmental impact of shared e-scooters is highly context-dependent and not inherently sustainable or unsustainable. Life cycle assessments consistently show that the majority of energy use and greenhouse gas emissions

originate from the vehicle and battery production, rather than the actual use phase. Emissions are amplified by the short operational lifetime of e-scooters. Furthermore, during the operation phase, a significant share of emissions arises from servicing and relocating shared vehicles.

The scenario analysis highlighted the sensitivity of the environmental impact to key assumptions. While a conservative baseline scenario resulted in net additional emissions, sensitivity analyses revealed that a net-zero effect could be achieved by either increasing the share of trips that replace car trips, or reducing the e-scooter's LCA emission factor.

Despite the business-driven and profit-oriented nature of e-scooter operators, cities have opportunities to govern these micro-mobility services in order to enhance integration, to complement public transport and to avoid negative impacts. Cities can influence key factors and through licensing and tendering requirements, the provision of mobility hubs, the integration of shared mobility into public transport apps, and through complementary measures that discourage private car use in inner cities.

References

1. Kazmaier, M., Taefi, T.T., Hettesheimer, T.: Techno-economical and ecological potential of electric scooters: a life cycle analysis. Eur. J. Transp. Infrastruct. Res. **20**(4), 233–251 (2020)
2. dena: E-Scooter-Sharing – eine ganzheitliche Bilanz. Potenziale von E-Scootern für eine nachhaltigere, urbane Mobilität (2021). https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/dena-STUDIE_E-Scooter-Sharing.pdf. Accessed 4 May 2026
3. Hollingsworth, J., Copeland, B., Johnson, J.X.: Are e-scooters polluters? The environmental impacts of shared dockless electric scooters. Environ. Res. Lett. **14**, 084031 (2019)
4. Holmgren, K., Einarson Lindvall, E., Rosell, J.: Life cycle assessment of shared dockless stand-up E-scooters in Sweden. J. Sustain. Dev. Energy Water Environ. Syst. **12**, 1–18 (2024)
5. ITF: Greener Micromobility. OECD Publishing, Paris (2024)
6. Krauss, K., Gnann, T., Burgert, T., Axhausen, K.W.: Faster, greener, scooter? An assessment of shared e-scooter usage based on real-world driving data. Transp. Res. A Policy Pract. **181**, 103997 (2024)
7. Bozzi, A.D., Aguilera, A.: Shared E-scooters: a review of uses, health and environmental impacts, and policy implications of a new micro-mobility service. Sustainability. **13**, 8676 (2021)
8. Severengiz, S., Finke, S., Schelte, N.: Screening LCA E-Scooter Sharing Update (2021). https://www.hochschule-bochum.de/en/sustainable-technologies-lab/overview/screening-lca-e-scooter-sharing-update/. Accessed 4 May 2026
9. Yan, X., Yang, W., Zhang, X., Xu, Y., Bejleri, I., Zhao, X.: A spatiotemporal analysis of e-scooters' relationships with transit and station-based bikeshare. Transp. Res. Part D: Transp. Environ. **101**, 103088 (2021)
10. Ziedan, A., Darling, W., Brakewood, C., Erhardt, G., Watkins, K.: The impacts of shared e-scooters on bus ridership. Transp. Res. A Policy Pract. **153**, 20–34 (2021)
11. Luo, H., Zhang, Z., Gkritza, K., Cai, H.: Are shared electric scooters competing with buses? A case study in Indianapolis. Transp. Res. Part D: Transp. Environ. **97**, 102877 (2021)
12. Gebhardt, L., Ehrenberger, S., Wolf, C., Cyganski, R.: Can shared E-scooters reduce CO2 emissions by substituting car trips in Germany? Transp. Res. Part D: Transp. Environ. **109**, 103328 (2022)
13. infas, DLR, IVT, infas 360: Mobilität in Deutschland - MiD. Regionalbericht Stadt Hamburg (2020)

14. Umweltbundesamt: Vergleich der durchschnittlichen Treibhausgas-Emissionen einzelner Verkehrsmittel im Personenverkehr (2023)
15. De Bortoli, A., Christoforou, Z.: Consequential LCA for territorial and multimodal transportation policies: method and application to the free-floating e-scooter disruption in Paris. J. Clean. Prod. **273**, 122898 (2020)
16. Finke, S., Schelte, N., Severengiz, S., Fortkort, M., Kähler, F.: Can battery swapping stations make micro-mobility more environmentally sustainable? E3S Web Conf. **349**, 02007 (2022)
17. Sun, S., Ertz, M.: Can shared micromobility programs reduce greenhouse gas emissions: evidence from urban transportation big data. Sustain. Cities Soc. **85**, 104045 (2022)
18. Rubenis, A., Celms, A., Adrian, L., Garkevics, M.: Sustainability of shared e-Scooter Services in Riga. Environ. Clim. Technol. **28**, 20240063 (2024)
19. City of Paris: Appel à candidatures pour le remisage sur le domaine public de flottes d'engins de déplacement personnel motorisés en libre-service sans station d'attache (2019). https://cdn.paris.fr/paris/2019/12/19/638d1f516fc9be79d7a7b3c80f1b6871.pdf. Accessed 4 May 2026

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Correlation Between American and European Micro-deval Test Methods for Fine Aggregates

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Abstract. This study investigates the correlation between the American and European micro-Deval test methods for evaluating the abrasion resistance of fine aggregates. Fine aggregate types examined include diabase, limestone, calcarenite and recycled materials. While both ASTM D7428 and EN 1097-1:2023 Annex E use the micro-Deval device, the two standards differ in methodology and evaluation criteria. The ASTM method determines the Abrasion Resistance Value, whereas the European method evaluates the Friability Coefficient.

Comparative tests were conducted at the Central Laboratory of the Cyprus Public Works Department, and the results were analysed to establish statistical correlations. A moderate to strong relationship between the two parameters was observed, allowing the derivation of conversion relationships between the two methods. Based on the results, threshold values are proposed to support the local adoption of the Friability Coefficient for evaluating fine aggregates.

Keywords: Micro-Deval · fine aggregates · Friability Coefficient · durability

1 Introduction

This study investigates the correlation between micro-Deval testing results for fine aggregates obtained using ASTM D7428 [1] and EN 1097–1:2023 Annex E [2]. Typical Cypriot fine aggregates of diabase, limestone and calcarenite types were examined, as well as recycled fine aggregates. Samples were subjected to parallel testing under both standards, and the results were analysed to determine statistical correlations and establish practical threshold values for local applications.

The first publication of the European standard for micro-Deval testing, EN 1097–1:1996 [3], applied only to coarse aggregates, as it did not include a methodology for testing fine aggregates. Consequently, European countries relied on national specifications, such as NF P 18–576 [4] and BS 7533–3 [5] for measuring the abrasion resistance of sands. In Cyprus, the Public Works Department adopted the American standard ASTM D7428, published in 2008, and incorporated it into its Technical Specifications [6] to assess the quality of fine aggregates used in bituminous mixtures.

The 2023 edition of EN 1097–1 introduced two methodologies for testing fine aggregates, enabling the transition of the Cyprus Public Works Department from the ASTM

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procedure to a formal European method. This development created the need to establish a correlation between the two approaches. To the authors' knowledge, no previous study has established a correlation between the ASTM D7428 Abrasion Resistance Value and the EN 1097–1 Annex E Friability Coefficient for fine aggregates.

2 Background

The micro-Deval test evaluates the resistance of aggregates to wear by abrasion under wet conditions (Fig. 1). ASTM D7428 [1] and EN 1097–1:2023 Annex E [2] use similar micro-Deval devices that differ a little in drum dimensions, with the ASTM version being 16–23 mm longer than the European equivalent. The standards also specify slightly different steel ball dimensions, with ASTM requiring a diameter of 9.5 ± 0.5 mm and the European method 10 ± 0.5 mm. However, the two standards differ more significantly in testing conditions, particularly in the mass of steel load and water, which influences their evaluation criteria.

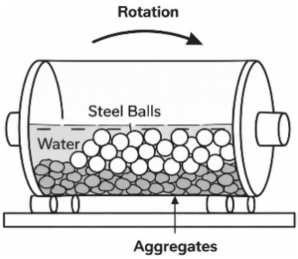


Fig. 1. Schematic representation of the micro-Deval test

The methodology described in EN 1097–1 Annex E is based on earlier French practice, as reflected in documents such as Sétra guide for earthworks [7], and is also described in the national standard NF P 18–576 [4]. It is incorporated in the French aggregate specification NF P 18–545 [8] and determines the Friability Coefficient as the percentage of material passing the 0.1 mm sieve after testing. In contrast, ASTM D7428 determines the Abrasion Resistance Value, using lower water content and a smaller steel load. The MOT Ontario method LS-619 [9] is closely aligned with ASTM D7428, with the addition of a pre-soaking stage.

Another approach for fine aggregates is described in BS 7533–3 [5] based on earlier work by Lilley and Dowson [10]. A variation of that method is described in the UK Defence Estates Specification for Concrete Block Paving [11], where performance-based thresholds are defined.

Table 1 summarises the main differences between the three methodologies for fine aggregates, including aggregate grading, water content, steel load and evaluation method.

Table 1. Methodologies for testing fine aggregates in the micro-Deval device

Description	Units	ASTM D7428	EN 1097–1 Annex E	BS 7533–3
Aggregate load	grams	500	500	230
Water	ml	750	2 500	2 000
Total steel load	g	1 250	2 500	
Rotation	min	15	15	60
Gradation for test	mm	0.075 to 4.75	0.2 to 2 (or 4)	
End control sieve	mm	0.075	0.1	0.063
Result		% Loss	% Loss	D_{10} [(a)]
Indic. Limit Asphalt		20–25[(b)]	40–45[(c)]	
Indic. Limit Bedding		8		10%[(d)]
Steel Load				
Diam. 9,5 or 10 mm	grams	1 250	1 015–1 135	
Diam. 18 mm	grams		21 spheres, mass 440–500	
Diam. 25 mm		–	–	2 spheres
Diam. 30 mm	grams	–	9 spheres, mass 925–985	
Notes:	[(a)] D_{10} The sieve through which 10% of the material passes after the end of the test [(b)] Values from ASTM D7428 and Rogers et al. [(c)] Values for asphalt fine aggregates NF P 18–545 [(d)] BS 7533 requires D_{10} on the 0.1 mm sieve			

3 Significance of the Micro-deval Test

The micro-Deval test is widely used as an indicator of aggregate durability for coarse and fine aggregates, with studies demonstrating good correlation between test results and construction performance, including work on Cypriot aggregates by Fournari and Ioannou [12] and Fournari [13], as well as broader studies such as Rogers et al. [14] and Jayawickrama et al. [15].

Since 2018, a slightly modified version of ASTM D7428 has been applied by the Public Works Department to assess the quality of asphalt fine aggregates. The test addresses several limitations of the Magnesium Sulphate Soundness test, which was previously used, including long testing times. Micro-Deval testing also provides a suitable method for evaluating recycled materials since it is not affected by cementitious fractions, as reported for the Magnesium Sulfate Soundness test [16–18], because the result is a purely mechanical measure of wear.

Establishing a correlation between the ASTM D7428 and the EN 1097–1:2023 Annex E methods is essential to enable efficient transition to the European standard. The accumulated data on local materials from the application of the American standard

would thus provide a basis for establishing threshold values for the Friability Coefficient for each type of fine aggregates.

4 Methodology for Establishing a Correlation

A total of 94 fine aggregate samples (diabase, limestone, calcarenite and recycled materials) were tested, as summarised in Table 3. Each sample was divided into two specimens, the first of which was tested according to ASTM D7428 [1] and the second to the corresponding methodology of EN 1097–1:2023 Annex E [2].

For ease of comparison, the grading requirements of ASTM D7428, reproduced in Table 2, were used for both specimens. The ASTM procedure, applied to the first specimen, had minor modifications consisting of an overnight pre-saturation period and the use of EN 1097–1 apparatus. The second specimen was tested according to EN 1097–1 Annex E, using the increased water volume and steel load defined in the standard.

Table 2. Nominal particle size distribution of specimens

Passing sieve	Retained sieve	Nominal Mass [(a)]
4,75 mm	2,36 mm	50 g
2,36 mm	1,18 mm	125 g
1,18 mm	0,6 mm	125 g
0,6 mm	0,3 mm	100 g
0,3 mm	0,150 mm	75 g
0,150 mm	0,075 mm	25 g [(b)]
Total		500 ± 5
Notes:	[(a)] When the mass of a fraction was not sufficient, mass from the closer available fraction was used [(b)] The mass of this fraction was excluded from the calculation of total initial mass for the second specimen	

A key difference between the two procedures is the control sieve definition. In EN 1097–1 Annex E, the initial grading excludes material below 0,2 mm, while the final loss is measured on the 0,1 mm sieve, creating a gap in the evaluated fraction. In contrast, ASTM D7428 uses the same sieve (0,075 mm) for both initial grading and final measurement. To ensure comparability, the EN results were adjusted by excluding the fraction below 0,150 mm from the initial mass and recalculating the percentage loss accordingly.

Regression analysis was performed to evaluate correlations between the Abrasion Resistance Value and the Friability Coefficient and to support the derivation of practical threshold values.

The results of the Abrasion Resistance Value and the adjusted Friability Coefficient are presented in Fig. 2, where the relationship between the two methods is illustrated.

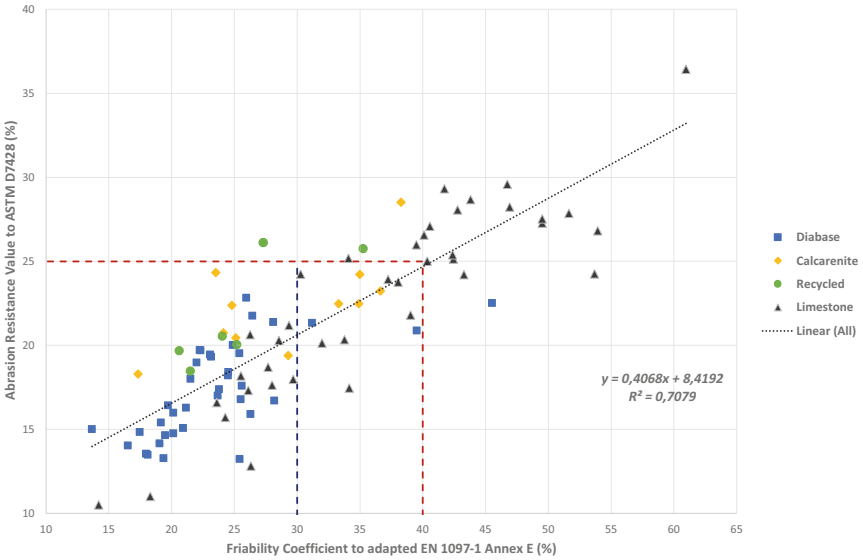


Fig. 2. Relationship between Abrasion Resistance Value (ASTM D7428) and Friability Coefficient (EN 1097–1 Annex E) for tested aggregates

5 Results

The Friability Coefficient consistently showed higher losses than the Abrasion Resistance Value, reflecting the more severe testing conditions of the EN 1097–1 Annex E [2] procedure. The relationship between the two parameters is presented in Fig. 2, and the corresponding regression analysis is summarised in Table 3.

Moderate to strong correlations were observed across all aggregate types, with R^2 values ranging from approximately 0,46 to 0,80. These results indicate that both methods evaluate similar degradation mechanisms despite differences in testing conditions. The overall dataset showed a relatively strong correlation ($R^2 \approx 0{,}71$), described by the regression equation Eq. 1:

$$y = 0,41x + 8,42 \tag{1}$$

More consistent correlations were observed for crushed limestone aggregates, allowing the transposition of threshold values between the two methods. It is noteworthy that the observed relationship suggests that an Abrasion Resistance Value limit of 25% as

defined in ASTM D7428 [1] corresponds, based on the derived regression, to Friability Coefficient value of 40%, which aligns with the limits specified in NF P 18–545 [8].

Table 3. Statistical analysis of the results

Type	Comments	Number of tests	Regression equation	R^2
Diabase	Hard, crushed	37	y = 0,32 x + 9,75	0,47
Calcarenite	Natural (washed), rounded	11	y = 0,28 x + 14,23	0,46
Recycled	From demolition waste, with friable inclusions	7	y = 0,55 x + 8,14	0,61
Limestone	Soft, crushed	39	y = 0,47 x + 5,45	0,80
All tests		94	y = 0,41 x + 8,42	0,71

Table 4. Conversion of Abrasion Resistance Value Limits to Friability Coefficient

Application	Abrasion Resistance Value Limit	Equivalent Friability Coefficient Limit
Granular sub-base	35	(a)
Granular base	30	53
Open graded base course	25	30[(b)]-40
Structural concrete	20	25[(b)]-28
Concrete pavement	20	25[(b)]-28
AC base course & sec. road surf. course	25	30[(a)]-40
AC premium surf. course (manufactured sand)	15	(a)
AC premium surface course (natural sand)	20	25[(b)]-28
Asphaltic concrete (all traffic levels)	15	(a)
Bedding & joint sands (>1,5 M ESALs)	8	(a)
Notes:	[(a)] Values out of graph limits [(b)] Possible threshold only for crushed, hard aggregates	

Recycled aggregates exhibited a stronger response under the Friability test, indicating increased sensitivity to friable inclusions, although the limited number of samples introduces uncertainty. In contrast, diabase and calcarenite aggregates showed greater variability and weaker correlation. However, the graph indicates that if a Friability Coefficient threshold limit of 30% is imposed for diabase fine aggregates, almost all samples with Abrasion Resistance Values of less than 25%, which is the current limit set by the

Public Works Department for asphalt aggregates, will be included. Similarly, a Friability Coefficient threshold limit of 40% for calcarenite fine aggregates will allow the use of materials exhibiting Abrasion Resistance Value limit of 25%. In any case, additional investigation is suggested before establishing definite threshold limits.

The derived regression relationships allow the conversion of existing Abrasion Resistance Value limits, included in ASTM D7428, into equivalent Friability Coefficient thresholds, as presented in Table 4.

6 Conclusions

This study examined the correlation between the micro-Deval test procedures defined in ASTM D7428 and EN 1097–1 Annex E for fine aggregates. The results show a moderate to strong correlation between the Abrasion Resistance Value and the Friability Coefficient, depending on aggregate type.

Consistent correlations between the two methods were observed for limestone aggregates, allowing the conversion of threshold values. Possible threshold limits were identified for diabase and calcarenite aggregates despite weaker correlations; however, further investigation is required. The Friability Coefficient test appears particularly sensitive to friable inclusions in recycled aggregates, indicating its suitability for the assessment of recycled materials.

The derived regression relationships enable the determination of equivalent Friability Coefficient limits from existing Abrasion Resistance Value thresholds, supporting the transition to the European standard for local applications. Further work is recommended to expand the dataset, extend the study, and refine the proposed limits.

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References

1. ASTM: D 7428–15: Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the micro-Deval Apparatus. ASTM International, West Conshohocken (2015)
2. CEN (European Committee for Standardization): EN 1097–1:2023: Tests for Mechanical and Physical Properties of Aggregates - Determination of the Resistance to Wear (micro-Deval). CEN, Brussels (2023)
3. CEN (European Committee for Standardization): EN 1097–1:1996: Tests for Mechanical and Physical Properties of Aggregates - Determination of the Resistance to Wear (micro-Deval). CEN, Brussels (1996)
4. AFNOR (Association Française de Normalisation): NF P 18–576: Granulats - Mesure du coefficient de friabilité des sables. AFNOR, Saint-Denis (2013)
5. BSI (British Standards Institution): BS 7533–3:2005+A1: 2009 Pavements Constructed with Clay, Natural Stone or Concrete Pavers. Code of Practice for Laying Precast Concrete Paving Blocks and Clay Pavers for Flexible Pavements. BSI, London (2009)

6. Public Works Department: Volume C. In: Standard Technical Specifications and Measurement Method (for Road and Civil Engineering Works). [in Greek]. Public Works Department, Nicosia (2020)
7. Sétra (Service d'études Techniques des Routes et Autoroutes): Design and Execution of Earthworks: Section 3: Test Procedures. Sétra, Sourdun (2007)
8. AFNOR (Association Française de Normalisation): NF P 18–545: Aggregates - Defining Elements, Conformity and Coding. AFNOR, Saint-Denis (2011)
9. Ministry of Transportation Ontario: Test Method LS-619: Method of Test for the Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. Ministry of Transportation Ontario, Toronto (2001)
10. Lilley, A.A., Dowson, A.J.: Laying course sand for concrete block paving. In: Proceedings of the 3rd International Conference on Concrete Block Paving, Rome, pp. 457–462 (1988)
11. Defence Estates: Specification 35: Concrete Block Paving for Airfields. TSO, London (2005)
12. Fournari, R., Ioannou, I.: Correlations between the properties of crushed fine aggregates. Minerals. **9**, 86 (2019). https://doi.org/10.3390/min9020086
13. Fournari, R.: Study of physical-mechanical properties of fine-grained aggregates and investigation of their effect on the properties of mortars and concrete [in Greek]. (2017)
14. Rogers, C., Lane, B., Senior, S.: The micro-Deval abrasion test for coarse and fine aggregate in asphalt pavement. Report, Downsview (2003)
15. Jayawickrama, P.W., Hossain, M.S., Phillips, F.: Micro-Deval test for the assessment of bituminous aggregate durability. J. ASTM Int. **4**, 1–13 (2007). https://doi.org/10.1520/jai100519
16. CEN (European Committee for Standardization): prEN 17555–1: Draft standard: Aggregates for construction works - Part 1: Characteristics. CEN, Brussels (2021)
17. Collins, R.J., Nixon, P.J.: Implications of the harmonisation of construction product standards for the use of recycled and secondary aggregates. Report, Oxon (2003)
18. BRE (Building Research Establishment): Digest 433: Recycled Aggregates. BRE, Watford (1998)

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Rethinking the Driver Cabin for Affordable Lightweight Battery Trains

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Abstract. Despite fully autonomous trains being a promising solution, train drivers may still be required for decades. Driver cabins for passenger trains are expensive (in terms of construction and maintenance) and take up significant space. The purpose of the project is to challenge the traditional way of designing cabins and to provide affordable solutions for new light battery-powered trains. These new rolling stock units aim to preserve or even reopen former heavy rail tracks at a moderate cost. The paper summarizes the research process and design thinking steps, from concepts to full-size, TSI - and standards-compliant mock-ups. The first round was conducted by Shift2Rail PIVOT between 2017 and 2019, using the C-K (Concept-Knowledge) theory to explore how new technologies could support train drivers. The second phase, from 2020 to 2022, led to three innovative prospective designs with detailed 3D renderings, still under the supervision of Europe's Rail. The third phase, conducted by the SNCF Group with several industrial partners, involved three successive full-size mock-ups to develop a functional cabin that could be produced and certified within three years. This cabin drastically reduces size and cost without compromising ergonomics or comfort, thanks to a high level of digitalization of its functional elements.

Keywords: Lightweight battery trains · Driver cabin design · Digitalization · Design thinking · Cost-efficient solutions

1 Introduction

Public transportation, especially rail services, is experiencing exponential growth in demand. Simultaneously, increasing requirements for environmental performance and cost reduction are making traditional railway models less suitable for serving rural areas.

The conventional procurement system—based on competitive tenders for new rolling stock and governed by a multitude of standards—tends to hinder innovation. Railway operators, constrained by limited time, industrial expertise, and resources, are often unable to develop highly innovative specifications. Manufacturers, in turn, respond with proven solutions to minimize costs and lead times, lest they be excluded from consideration.

To address these challenges, a European initiative was conducted from 2017 to 2022 (under Shift2Rail and later Europe's Rail) to foster the emergence of innovative concepts.

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Observing a lack of offerings for lightweight trains, the SNCF Group chose to collaborate with various industrial partners to build upon these efforts and define realistic, disruptive specifications tailored to address this unmet need.

This article outlines the research methodology employed across the different phases, presents the key findings, and discusses short-term perspectives, synthesizing eight years of research and development. The focus is placed on the example of driver cabins, although similar approaches were applied to other train components.

2 Methodology

The research was conducted in successive phases, progressing from unconstrained ideation to the development of components ready for short-term industrialization. Each phase brought together industrial and academic partners interested in the nature of the work and benefited from complementary European or French funding, supplementing the contributions of each participant.

A key feature of the process was its ability to capitalize on insights from earlier phases without being bound by them. Notably, SNCF retained the freedom to form a new consortium at each stage. Partners, for their part, avoided long-term commitments lacking visibility on final outcomes and return on investment.

We present a chronological analysis of the methodology adopted at each stage and the resulting outputs, highlighting the overall coherence and effectiveness achieved over the eight-year period.

3 Three Main Phases

3.1 2017–2019, Shift2Rail – Reinventing the Driver Cabin

Within the broader European Shift2Rail PIVOT framework, the "Modular Interiors" Work Package explored both passenger areas and driver cabins. The objective was to develop more compact, modular, and adaptable spaces by 2030. The work was led by SNCF Group, in collaboration with DB Group, ALSTOM, SIEMENS, and VIRTUAL VEHICLE.

The C-K theory (Concept-Knowledge [1, 2]) was chosen for its capacity to broaden the solution space by overcoming representational biases linked to existing systems. At this stage, no standards or regulations were considered.

This approach enabled exploration of voice and gesture control, haptic-feedback touchscreens, 3D sound design, and virtual or augmented reality. Recent automotive and aerospace cockpit concepts—such as those developed by THALES—were particularly influential.

We then cross-referenced these elements with an analysis of the minimum technical functions required and ergonomic principles specific to train driving, to identify viable concepts. Ergonomic principles related to rail driving activity were comforted with academic knowledge [3–10].

This initial phase enabled the identification of a range of solutions not yet implemented onboard trains but potentially capable of meeting operational needs, regardless

of their level of technological maturity. Particularly recent innovations, such as gesture control with contactless haptic feedback via ultrasonic transducers, were considered for further study without being limited by potential challenges related to adaptation to the railway environment. For comparison, BOSCH showcased a concept car equipped with this type of technology for infotainment system control at CES 2017.

3.2 2020–2022, Europe's Rail – From Concept to Design

In a second phase of European research, the proposed solutions were evaluated in 2021 by a large panel of train drivers through a survey conducted in collaboration with the CARBODIN program (Car Body Shells, Doors and Interiors). For CARBODIN specific results, see [11, 12]. A total of 1,762 respondents from 15 European countries helped narrow the options to innovative technologies acceptable to current drivers—ensuring a smooth transition with existing personnel.

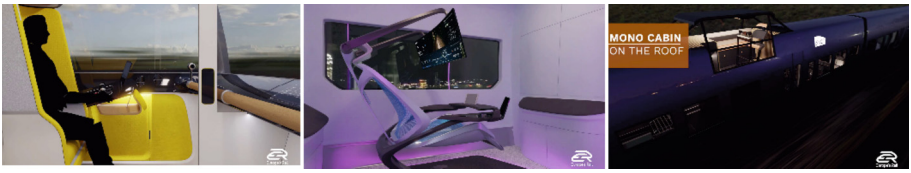
Unsurprisingly, physical controls were confirmed as essential for safety-critical functions (e.g., traction, braking, doors). However, drivers demonstrated a strong openness to digitalization and touch-based controls, provided that the reliability of these systems matches that of current technologies. They also expressed interest in alternative interfaces for secondary functions (such as climate control and windshield wipers), as well as in modernized, contextual sound environments inspired by automotive design.

These insights enabled SNCF Voyageurs, with design firms L'Agence Pigment and Use.Design, to translate selected elements into three innovative cabin concepts (Fig. 1). The primary concern was reducing surface area, weight, and manufacturing cost while maintaining ergonomic workspaces. Two of the concepts therefore feature a single cabin per train. All three are disruptive and remain exploratory, with no immediate production plans. They were presented at the INNOTRANS trade fair in Berlin in September 2022.

"Modular Cocoon". A cabin under 4 m^2—60% smaller than conventional train cabins—designed mainly for semi-automated operation (GOA2). It is reminiscent of a compact office space, with short manual driving phases performed standing. Information is projected onto the windshield as a large Head Up Display.

"Techno Chair". A more futuristic concept featuring a bidirectional cabin with a rotating seat that can be placed anywhere in the train. The driver views the track via screens fed by external cameras, with augmented reality overlays displaying speed and technical status. Though technologically feasible, regulatory barriers remain. This onboard teleoperation avoids transmission and latency issues faced by remote driving systems under study in several countries. It could increase passenger capacity and free up train extremities for other uses (passenger space or technical zones also suited for crash absorption). The cabin becomes a standardized module, no longer custom-built for each train.

"Panoramic Cabin". Designed for lightweight, short trains without pantographs, this single cabin with a rotating seat is positioned centrally and elevated, offering panoramic track views. This layout echoes past designs (e.g., Renault/ANF/De Dietrich X3800 railcar, produced in 251 units and in service until 1988), now reimagined with modern naval-inspired features and camera-based blind spot visualization.



(a) (b) (c)

Fig. 1. (a) Modular Cocoon (b) Techno Chair (c) Panoramic Cabin

3.3 2023–2025, Toward a Production-Ready Driver Cabin

Project Context. SNCF Group has committed to revitalizing regional rail lines across France by offering credible alternatives to road transport. Through several lightweight train initiatives, the group aims to provide solutions that circumvent the limitations of conventional heavy rolling stock. Avoiding unnecessary overcapacity not only reduces acquisition and operational costs but also enables lighter infrastructure maintenance—due to reduced axle loads—and may even eliminate the need for infrastructure renewal.

A gap in the market is evident: manufacturers' catalogues lack rolling stock under 50 m in length, 100 t in weight, and 120 seated passengers. In response to a French Government national call for projects under the "France 2030″ initiative, led by ADEME, SNCF formed two industrial consortia to develop DRAISY and TELLi, designed to complement the regional train offering. These projects rely heavily on battery technology to avoid costly overhead line installations and eliminate fossil fuel usage.

DRAISY is a lightweight, battery-only train weighing 20 t and measuring 14 m, capable of reaching 100 km/h and accommodating 80 passengers (30 seated). It is being developed by SNCF Group, LOHR, SFERIS, STATIONS-E, and the RAILENIUM technological research institute. The aim is to develop and achieve certification for a demonstrator vehicle by 2028. It is not addressed further here.

TELLi is a hybrid catenary/battery train, 30 m long and weighing 50 t, with 150 passengers (74 seated), a 200 km range, and a top speed of 120 km/h. With an axle load of just 12 t, it will be among the lightest battery-powered trains on the market. It features compact cabins at both ends, allowing for panoramic passenger spaces at the front and rear. The consortium includes 11 partners with complementary expertise: SNCF Group, CAF, ALSTOM, WABTEC, HITACHI, CAPGEMINI, TEXELIS, EKTAKOM, IRT RAILENIUM, FERROCAMPUS, and CEREMA.

TELLi incorporates all the functions of a conventional train: it must be interoperable and capable of accessing major urban stations, thus complying with numerous technical interoperability specifications and standards. It is also highly innovative, particularly in terms of its low mass and battery management. Finally, it must appeal to future drivers and passengers.

Development work for DRAISY and TELLi was conducted in parallel, following similar processes and leveraging synergies wherever possible. For clarity, this article focuses on the development of the TELLi driver's cabin. The objective for TELLi was to evolve the concepts and designs from previous European research into a complete specification by the end of 2025, enabling industrial production within three years and demonstrated through a full-scale mock-up.

Architectural Choices. Although single-cabin concepts were attractive, they were excluded due to regulatory approval challenges within the targeted timeframe (certain standards would need to evolve beforehand). It was therefore decided to implement compact cabins at both ends of the train.

Engineering and driving experts from SNCF Group reviewed all functional requirements to maximize digitalization and reduce the number of physical interfaces by 30% compared to conventional cabins. However, certain safety-critical actions (traction, braking, door control) still require physical buttons or manipulators for ergonomic and operational safety reasons.

A study was conducted on next-generation human-machine interfaces (HMIs), focusing on larger, thinner screens. These offer improved readability for drivers and allow for a greater number of icons and functions—an inherent benefit of digitalization. Additionally, the slim profile of modern screens enables inclinations previously impossible with older railway equipment.

As the driver cabin is a workspace, ensuring comfort is essential. The design firm Zamak was involved in this phase to enhance ergonomics and comfort. Several layout options were explored, resulting in an innovative, functional, and comfortable proposal modelled in 3D CAD (Fig. 2).



Fig. 2. From "Modular Cocoon" concept to TELLi final cabin design (SNCF Voyageurs SA)

Head-Up Display (HUD) Integration. The anticipated operating conditions for lightweight trains—on minimal infrastructure with limited signalling and numerous level crossings—could increase the cognitive load on drivers for environmental monitoring. The emergence of high-safety, rail-compliant head-up display (HUD) technologies prompted consideration of an optional HUD system, activatable at the driver's discretion.

The implications and operational conditions of such systems extend beyond the scope of this article and have been studied by IRT RAILENIUM [13].

Three-Step Iterative Prototyping. Three iterative prototyping stages were conducted through workshops involving experts in train driving, cabin layout, ergonomics, electronic systems, and design (fig. 3).

Cardboard Full-Scale Mock-Up. A robust, low-cost, and rapidly produced cardboard mock-up was built to simulate tactile feedback and provide a tangible alternative to virtual reality. Ergonomic refinements were made in real time through cuts and additions

during workshops—an agility not easily afforded by VR. The mock-up also validated the integration of all technical functions: each screen and 3D-printed physical control button was positioned considering its underside footprint and optimized layout logic.

Wooden Full-Scale Mock-Up. Following the definition phase, a wooden mock-up confirmed the final ergonomics and placement of all functions. This more rigid model defined the cabin wall volumes and console envelope limits. It was evaluated using a representative seat to verify seating comfort and precise positioning of all controls, ensuring ergonomic postures: primary controls accessible without changing seat position, main screens within direct line of sight, and easy installation, exit, and emergency evacuation.

Final Welded Prototype. A full-scale welded prototype based on finalized 3D renderings reproduced the complete cabin's design, comfort, and spatial footprint. Installed in a showroom (Saintes city, France) alongside other interior space mock-ups, it also serves as a valuable communication tool for potential buyers.



Fig. 3. Preliminary CAD/Cardboard mock-up/Wooden mock-up/ Final CAD/Final mock-up (SNCF Voyageurs SA)

This mock-up validated the project team's vision and demonstrated that, despite their compact size, these cabins meet the needs of future lightweight train drivers. Driving experts confirmed the consistency of the new design with current train standards: despite a 30% reduction in physical controls due to digitalization and a smaller footprint, the overall layout and operational principles remain consistent with recent driver desks (those in accordance with UIC 612 guidelines and EN 16186 standards). As a result, driver training and adaptation to this new cabin are expected to be straightforward and rapid.

4 Conclusions

The need for lightweight battery-powered trains is well established as a means to revitalize rural capillary rail lines. However, manufacturers currently lack such rolling stock in their catalogues and are unable to offer them through conventional tendering processes. They do not possess the necessary expertise in train operation to reinvent the driver cabin space, nor the financial capacity to bear the industrial risk of such projects alone.

The role of European and national institutions is therefore critical in enabling these developments. By contributing its engineering and operational expertise, SNCF Group has leveraged successive projects initiated since 2017 to define radically innovative rolling stock that could be industrially produced by 2028 at significantly reduced costs. The next steps will depend on the willingness of transport authorities to place orders for these trains.

Through the example of the TELLi driver's cabin, we have demonstrated how a purely conceptual ideation process can lead to the emergence of innovative designs, and how these designs can be transformed into short-term realizable projects. In this case, a 66% reduction in cabin footprint was accomplished, enabling the addition of eight extra seats. For a very lightweight train with a capacity of 30 to 70 seats, this is a decisive factor for operational profitability.

The combination of industrial capabilities, the expertise of a major railway operator, and the leverage of public funding enabled to offer future-oriented solutions for more sustainable, safer, and cost-effective transport—solutions that none of the stakeholders could have accomplished alone.

In a society facing significant budgetary constraints, these results underscore the importance of a medium - and long-term vision supported by sustained investment in research and development. Based on the deliverables of European programs Shift2Rail and Europe's Rail, funded by the French Government as part of the France 2030 program implemented by ADEME, benefiting from consortia bringing together leading industrial players and top research institutes, SNCF Group's commitment to serving all territories has resulted in concrete, industrially viable proposals that can be realized within the next years.

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References

1. Hatchuel, A., Weil, B., Le Masson, P.: Towards an ontology of design: lessons from C–K design theory and Forcing. Res. Eng. Des. **24**(2), 147–163 (2012). https://doi.org/10.1007/s00163-012-0144-y

2. Sharif Ullah, A.M.M., Rashid, M.M., Tamaki, J.: On some unique features of C–K theory of design. CIRP J. Manuf. Sci. Technol. **5**(1), 55–66 (2012). https://doi.org/10.1016/j.cirpj.2011.09.001
3. Naweed, A.: Investigations into the skills of modern and traditional train driving. Appl. Ergon. **45**(3), 462–470 (2014). https://doi.org/10.1016/j.apergo.2013.06.006
4. Nneji, V.C., Cummings, M.L., Stimpson, A.J.: Predicting locomotive crew performance in rail operations with human and automation assistance. IEEE Trans. Hum. Mach. Syst. **49**, 22–32 (2019)
5. Rose, J.A., Bearman, C.: Making effective use of task analysis to identify human factors issues in new rail technology. Appl. Ergon. **43**(3), 614–624 (2012). https://doi.org/10.1016/j.apergo.2011.09.005
6. Fan, J., Smith, A.P.: A preliminary review of fatigue among rail staff. Front. Psychol. **9** (2018). https://doi.org/10.3389/fpsyg.2018.00634
7. Karvonen, H., Aaltonen, I., Wahlström, M., Salo, L., Savioja, P., Norros, L.: Hidden roles of the train driver: a challenge for metro automation. Interact. Comput. **23**(4), 289–298 (2011). https://doi.org/10.1016/j.intcom.2011.04.008
8. Wilson, J.R., Norris, B.J.: Rail human factors: past, present and future. Appl. Ergon. **36**, 649–660 (2005)
9. Kecklund, L., Mowitz, A., Dimgard, M.: Human factors engineering in train cab design—prospects and problems. In: Cacciabue, P.C., Hjälmdahl, M., Luedtke, A., Riccioli, C. (eds.) Human Modelling in Assisted Transportation, pp. 327–333. Springer, Milan (2011). https://doi.org/10.1007/978-88-470-1821-1_35
10. Li, Y.: On human factors in the design of locomotive cab: an investigation on driver's cognitive and behavioral characteristics. DEStech Trans. Soc. Sci. Educ. Hum. Sci. (2017). https://doi.org/10.12783/dtssehs/apme2016/8144
11. Gandini, L.M., Ricci, S., Vanderhaegen, F., Enjalbert, S.: State of the art of HMI in transport industries. Research Report,. Université Polytechnique Hauts-de-France (2020)
12. Enjalbert, S., Gandini, L.M., Pereda Baños, A., Ricci, S., Vanderhaegen, F.: Human–machine interface in transport systems: an industrial overview for more extended rail applications. Machines. **9**(2), 36 (2021). https://doi.org/10.3390/machines9020036
13. Bernard, C.I., Gadmer, Q.: Understanding the railway driving activity to design HUD: recommendations and specificities for future light trains. Cogn. Tech. Work. (2025). https://doi.org/10.1007/s10111-025-00830-9

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From Electrification on Component-Level to Software-Defined Vehicles: The Role of Modular Smart Corner Systems in Next-Generation Electric Vehicle Architecture

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Abstract. The transition to software-defined vehicles (SDVs) necessitates a paradigm shift in both control strategies and vehicle architecture. The EU-funded *SmartCorners* project addresses this challenge by developing integrated smart corner systems (SCS), which combine in-wheel motor (IWM) propulsion, brake-by-wire, active suspension actuator, and steer-by-wire functionality in a single module. These SCS are embedded within a highly adaptable skateboard chassis architecture, enabling scalable deployment across diverse vehicle platforms. The *SmartCorners* project targets to demonstrate significant advancements, including improvement in real-world driving range, reduction of component and system costs, an increasement in interior volume, and a development time drop of the EV systems enabled by digital-twin-based design methodologies. Beyond these performance gains, *SmartCorners* establishes the foundational principles of modularity, adaptability, and software integration that underpin the evolution toward SDVs. These achievements highlight a critical bridge between electrified component innovation and the holistic software-defined mobility systems of the future.

Keywords: Electric Mobility · SDVs · Smart Corner Systems · Control Strategies · Vehicle Architecture

1 Introduction

The arising era of SDVs is revolving around the mechatronics design on vehicle-level, requiring seamless integration of purely mechanical systems, embedded electronics, and information processing to launch increasingly complex systems, while achieving safety, performance, and cost targets [1, 2]. This transition toward SDV architectures is leading to increased autonomy, connectivity, safety and security functionalities, novel driving

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experiences, and new business models for original equipment manufacturers (OEMs) [3]. As SDVs need well-aligned software and electronics it is essential to address the topics of reliability, cybersecurity, interoperability, and standardisation together with its backbone, the information and communication technology (ICT) [4]. Besides technological in-vehicle advancements the entire mobility ecosystem will be transformed by the ongoing digitalisation and the trend toward connected, cooperative and automated mobility (CCAM).

In the EU-funded SmartCorners project—focusing on user-centred optimal design of EV with smart e-corners—artificial intelligence (AI)-based approaches and machine learning (ML) methods provide a great contribution to the four ambitious project objectives, including: (a) accelerated design and testing methodologies of adaptable, efficient, right-sized, flexible and user-centric SCS based on in-wheel powertrains, (b) new series of scalable and flexible SCS for next-generation EVs, (c) predictive, user-centric, AI - and model-based control solutions for SCS equipped EVs, and (d) holistic thermal and passenger comfort management. In SmartCorners AI and/or ML are utilized for structural health monitoring and force estimation, proactive vehicle motion control, control of the thermal management, control strategies of operating conditions, identification of trends and patterns like of usage, user behaviours, routes, weather conditions, fault mitigation, and the model predictive control framework, among others.

This paper provides a technological deep dive dedicated to the SCS investigated in SmartCorners. Finally, in the conclusion section, the SCS' benefits, business opportunities, and market impact are addressed.

2 Methodology/Results

EVs offer different possibilities and configurations, mainly dependent on the location of the electric traction motor. Within the SmartCorners project, a new modular SCS is proposed, merging traction, braking, suspension, and steering. In detail, the IWM can both drive and brake the vehicle, while active suspension and steering actuators focus on handling and comfort performance. In particular, the suspension actuator plays a key role to counteract the negative impact of adding the IWM mass to the unsprung mass both in terms of vibrations transmissibility and road holding. Additionally, the brake-by-wire covers the braking functionalities in all the scenarios where the regenerative braking is not anymore sufficient for the safe stop of the vehicle. All those systems are arranged as compact, preassembled unit called SCS that can be mounted directly onto the vehicle frame. In the end, a concept of a modular four-wheel drive (4WD) battery electric vehicle (BEV) is proposed by equipping a skateboard-like flat vehicle chassis, so-called "skateboard platform", with four SCS at its corners. The integration of the SCS on the skateboard platform reduces assembly/disassembly time and frees up space. In fact, due to this compact and modular design, less components and complex assembly/disassembly operations are needed, hence the interior space for passengers and luggage is expected to increase by 15% and 20%, respectively.

Figure 1 showcases the proposed SCS; it takes advantage of the suspension subframe of the reference demo-vehicle and then it fits to its body-in-white (BIW). Indeed, the project firstly targets the retrofit integration of the SCS into a demo-vehicle, i.e., an

Alfa Romeo Stelvio, to demonstrate its potentiality as an add-on feature for vehicles already on the market. Then, the concept is optimally deployed on a custom-designed skateboard platform. However, a limited number of changes to the vehicle's BIW are required, thus the skateboard platform of battery electric vehicles (BEVs) is intended to propose an optimal solution. The proposed suspension architecture is a low-type double wishbone with virtual steering axis. Together with the removal of the usual linear damper and coil spring, this configuration allows to get rid of any stiff structural component at higher points of the vehicle body, which are critical for pedestrian impact scenarios. The knuckle is an aluminium component custom designed to fix the suspension arms, wheel hub, steering link, and IWM. The upper control arm (blue arm in Fig. 1) of the suspension is manufactured through a Sheet Moulding Compression (SMC) process, as it is made of a composite material based on vinyl-ester resin filled with 50% chopped carbon fibres. The piezoresistive properties of this composite material allow the integration of conductive electrodes for real-time stress-state monitoring. The latter is not only fundamental for passengers' safety but also enables predictive maintenance strategies by warning the vehicle owner before any significant damage occurs. Reduction of the vehicle downtimes is particularly important for commercial vehicles since companies can schedule the use and repair of their fleet to avoid any service interruption. The two lower arms are aluminium components, and the rear arm (yellow arm) integrates flanges to allow the connection of the push/pull-rod of the active suspension actuator (ASA) and for a torsional spring, replacing the usual coil spring as illustrated in Fig. 2. To completely avoid clash possibilities during suspension travel and steering, the ASA is located inward with respect to the main rail of the skateboard platform, as the internal combustion engine removal frees up space in the original engine compartment. The ASA is flanged to the main rail, and a bell-crank element transmits the motion of the rear lower control arm to the ASA shaft. The ASA is a custom-designed rotary actuator made up of a planetary speed and a rotary brushless three-phase electric machine [5]. The torque-control of the electric machine permits the force-control of the suspension. A primary push/pull-rod connects the suspension arm to the bell-crank component and a secondary rod the bell-crank to the ASA crank lever. The latter rod is also produced in composite material as its piezoresistive properties allows force sensing, hence force-feedback for control purposes. In the end, a by-wire actuator controls both steering and toe angle as it acts directly on the single corner module. It integrates three critical components: a linear actuator, i.e., a rack-pinion mechanism, to control the steering link, two redundant power-sourced rotary devices to drive the system with self-sensing capabilities, and a control unit. The rotary device deploys a motor and a geartrain to reach the targeted forces. The intelligent corner design allows for independent control of torque, camber angle, and toe angle for each corner, resulting in an over-actuated EV.

With respect to conventional powertrain systems, the IWMs used in SCS demonstrate a superior torque response rate, which is attributed to the following two reasons. Firstly, the rotational inertia (which quantifies the object's rotational resistance) between rotor and tire is reduced thanks to the omission of both shaft and gearbox from the system. This direct linkage between motor and tyre facilitates more rapid torque regulation, increasing vehicle responsiveness, which is an advantage from the vehicle dynamics point of view. Secondly, the IWMs facilitate the immediate wheel torque sign change,

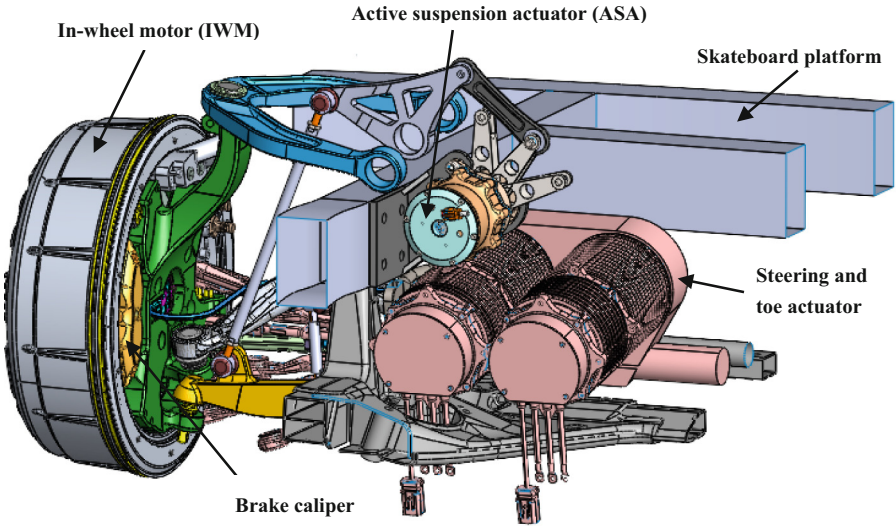


Fig. 1. Smart Corner System (SCS)

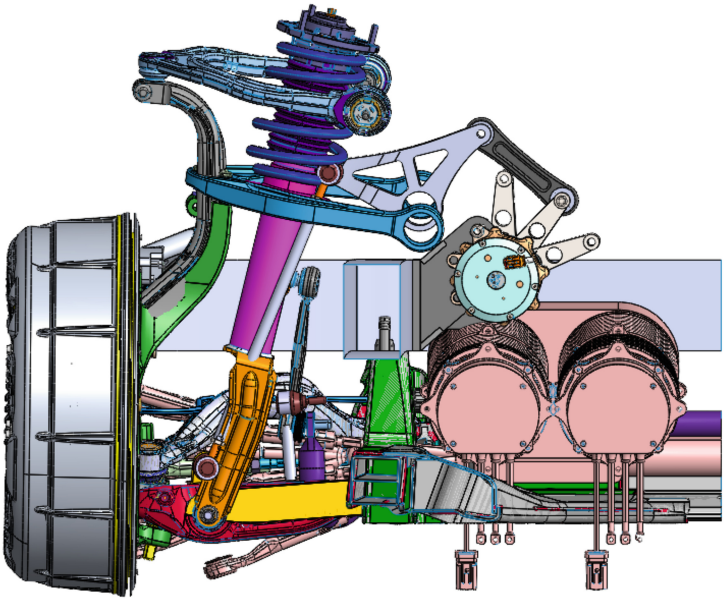


Fig. 2. Comparison between the normal production front suspension and the proposed SCS

enhancing agility and the control capabilities of the EVs, being crucial for functions that require high frequency torque oscillations. Another advantage from the SCS architecture is evolving from the synergy between IWM and the geometric characteristic of the suspension; by regulating the motor torque, the IWM not only generates a longitudinal

force, but also a vertical one, which can work in harmony with the one generated by the suspension system. With a controlled modulation of these forces, the IWM can actively increase passenger comfort, as shown at the top of Fig. 3 [6]. An additional advantage of using SCS on a 4-wheel drive layout, is the possibility to independently control the torque on the 4 wheels, implementing Torque Vectoring (TV) algorithms [7]. Several advantages are enabled by TV control strategies, and some examples are reported herewith. The difference between the wheel torques generates an additional yaw moment, which helps to counteract understeer and oversteer condition, improving safety even in critical condition. Moreover, with the application of differentiated torques, the vehicle behaves more agilely and responsively in cornering condition, e.g. by increasing the torques on the outer wheels, and reducing the torques on the inner wheel. TV algorithms are very effective at improving lateral dynamics, as shown at the bottom of Fig. 3, where the benefits of TV in terms of yaw rate reference tracking are compared between the performance of a benchmarking controller (proportional integrative—PI) with a nonlinear model predictive controller (NMPC). TV algorithms are also very effective for longitudinal dynamics control; in particular, they allow maximizing the traction force during acceleration when there are differences in grip between the wheels, sending the torque only to the wheel(s) with traction, reducing unnecessary wheel slip, and improving the ability to transfer torque to the ground. Thinking about the economy of the EV, which is a crucial aspect, the IWMs allow easy management of the regenerative braking, maximizing the energy recovery while driving and increasing vehicle autonomy. Another very effective application of the TV control algorithms is the emergency braking. In this case, usually the TV is not the primary braking system, but with independent wheel torque control, it can enhance longitudinal stability and safety during very strong braking. Specifically on split road friction coefficient surfaces, e.g., left wheels on asphalt, right wheels on ice, TV allows applying different braking forces on each side of the car that counteract the yaw unbalance generated from the road conditions. These strategies, combined with already existing safety logics (e.g., ABS, ESC), make EVs more stable and fun to drive.

The control algorithms that act on IWMs and active kinematic actuators, e.g., 4-wheel steering applications, allow a user-centric vehicle based on the driver's preferences, with the option of choosing between different driving modes (e.g., sport, comfort, and energy-efficient). Furthermore, with the independent control of the actuators, manoeuvres that require greater agility—such as on-the-spot steering and crab walking—can be done. In terms of vehicle dynamics control during extreme manoeuvres, predictive TV and active kinematics algorithms increase vehicle stability and safety by adjusting the vehicle's yaw moment during the manoeuvre. To enhance the innovation level of SCS control algorithms, the integration of an advanced sensor system enables the design of AI-based control architectures that learn, adapt, and react in real-time depending on variable vehicle and environmental conditions. These architectures are not only applicable to conventional vehicle but are also fully applicable to autonomous vehicles [8], where road preview, path tracking, and automatic thermal comfort control [9] become key components. The main advantages resulting from the utilization of AI-based control strategies are the following:

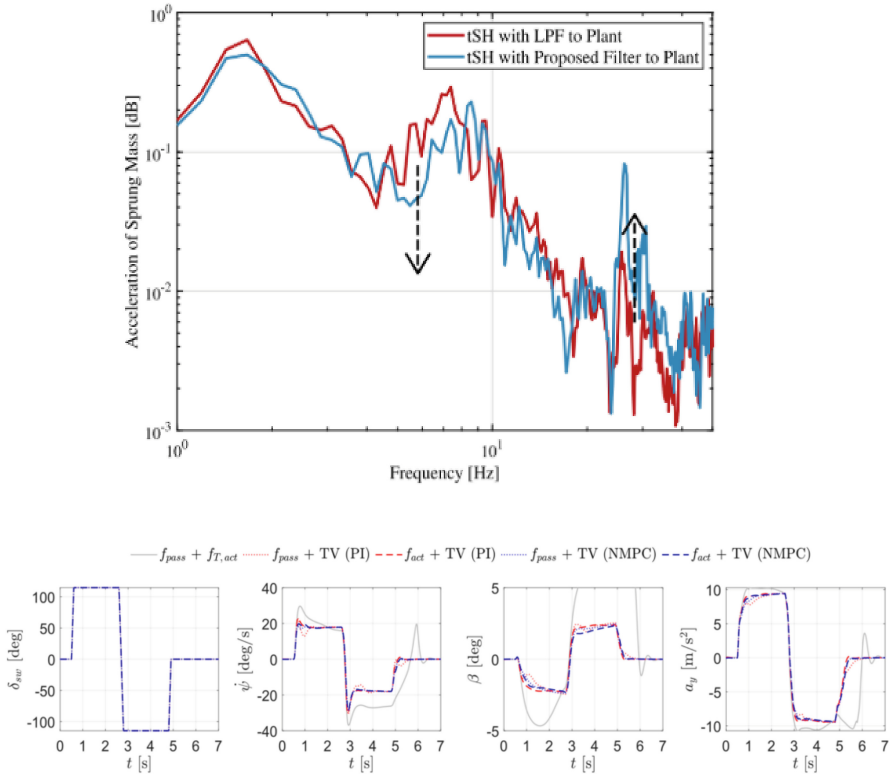


Fig. 3. Benefits coming from different IWM control applications: (top) Passenger comfort [6], (bottom) Vehicle's dynamics control [7]

- Compared to traditional controllers with fixed gain, AI algorithms can be trained on large datasets that include many extreme or rare conditions, allowing the system to better react to conditions not previously modelled, improving the robustness and safety of the control strategies.
- With respect to traditional predictive controllers, AI-based algorithms (such as Neural Network Model Predictive Controllers) have a reduced computational cost, which makes them real-time implementable for achieving high performance in terms of vehicle dynamics control.
- The real-time capability of the AI-based predictive algorithm, in combination with the advanced sensor system, allows the dynamic adaptation of the vehicle states to variable external conditions, e.g., changes in load, wear, road conditions, and temperature, to maintain a high level of passenger comfort.

At the same time, the design of energy-oriented controllers allows reducing the power lost during the manoeuvres, exploiting the possibility of having regenerated power from the IWMs during the braking phase, increasing the autonomy of the EV. In the end, the SCS introduces different degrees of global vehicle motion control.

3 Conclusion

Rigorous electrification on component-level and intelligent material selection led to the development of the presented modular and scalable SCS, which contains multiple vehicle functionalities and technological capabilities, namely (a) the IWM enabling traction and braking control, (b) the electro-mechanical brake-by-wire, supporting the IWM during hard braking manoeuvres, (c) the ASA providing optimal control of the vertical dynamics, (d) the steering actuator, ensuring precise control of the wheel toe angle, (e) AI/ML-based data-driven control strategies for the aforementioned functionalities, (f) digital twinning, supporting the SCS development, (g) virtual sensing, and (h) consideration of user-centric vehicle settings. These developments result in an SDV-ready SCS, able to boost the vehicle's performance, safety, and occupant's comfort, while simplifying EV development as well as the SCS repair, maintenance, and recycling processes. The SCS design presented in this paper is optimised to retrofit the Alfa Romeo Stelvio. Thus, SCS optimised for skateboard platforms will look different to achieve minimal packaging requirements, leading to increased passenger compartment space, greater cargo space, and more freedom in the design process of any kind of vehicle.

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References

1. Bello, L.L., Mariani, R., Mubeen, S., Saponara, S.: Recent advances and trends in on-board embedded and networked automotive systems. IEEE Trans. Industr. Inform. **15**(2), 1038–1051 (2019). https://doi.org/10.1109/tii.2018.2879544
2. Macher, G., Stolz, M., Armengaud, E., Kreiner, C.: Filling the gap between automotive systems, safety, and software engineering. e & i Elektrotech. Informationstech. **132**(3), 142–148 (2015). https://doi.org/10.1007/s00502-015-0301-x
3. Bazzi, A., Shaout, A., Ma, D.: MT-SOTA: a merkle-tree-based approach for secure software updates over the air in automotive systems. Appl. Sci. **13**(16), 9397 (2023). https://doi.org/10.3390/app13169397
4. Vdović, H., Babić, J., Podobnik, V.: Automotive software in connected and autonomous electric vehicles: a review. IEEE Access. **7**, 166365–166379 (2019). https://doi.org/10.1109/access.2019.2953568
5. Galluzzi, R., Circosta, S., Amati, N., Tonoli, A.: Rotary regenerative shock absorbers for automotive suspensions. Mechatronics. **77**, 102580 (2021). https://doi.org/10.1016/j.mechatronics.2021.102580
6. Suzuki, T., Mae, M., Takeuchi, T., Fujimoto, H., Katsuyama, E.: Model-based filter Design for Triple Skyhook Control of in-wheel motor vehicles for ride comfort. IEEJ J. Ind. Appl. **10**(3), 310–316 (2021). https://doi.org/10.1541/ieejjia.20004677
7. Dalboni, M., Tavernini, D., Montanaro, U., Soldati, A., Concari, C., Dhaens, M.: Nonlinear model predictive control for integrated energy-efficient torque-vectoring and anti-roll moment distribution. IEEE/ASME Trans. Mechatron. **26**(3), 1212–1224 (2021). https://doi.org/10.1109/TMECH.2021.3073476

8. Vaskov, S., Quirynen, R., Menner, M., Berntorp, K.: Friction-adaptive stochastic nonlinear model predictive control for autonomous vehicles. Veh. Syst. Dyn. **62**(5), 1–25 (2023). https://doi.org/10.1080/00423114.2023.2219791
9. Brusey, J., Hintea, D., Gaura, E., Beloe, N.: Reinforcement learning-based thermal comfort control for vehicle cabins. Mechatronics. **50**, 413–421 (2018). https://doi.org/10.1016/j.mechatronics.2017.04.010

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Operational Tools for Assessing Environmental Impacts and Benefits in Linear Infrastructure: A Systematic Review

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Abstract. The environmental implications of linear infrastructure —such as roads, railways, and pipelines— require robust tools for assessing impacts and benefits. This study presents a systematic review of tools and methods used in high-impact publications between 2021 and 2024, focusing on case studies that evaluate environmental performance across the entire infrastructure project life cycle: planning, design, construction, operation, maintenance, and end-of-life. The review analyzes 102 peer-reviewed articles and strategic documents. Tools are classified by type (e.g., solutions, services, corporate frameworks), life cycle coverage, goal definition, system boundaries, data quality, and assessment methodology. Results show a fragmented but evolving landscape. Impact assessments are heavily concentrated in construction (69%) and operation phases (78%), while maintenance (53%) and end-of-life stages (37%) remain underrepresented. Spatial modeling, ecological indicators, and Life Cycle Assessment (LCA) are among the most frequently applied approaches (45%, 32% and 27%, respectively). However, structured evaluation of environmental benefits is rare: 70% of studies include no assessment of ecological gains, and none incorporate economic valuation. Comparative evidence indicates that many of these limitations —particularly methodological fragmentation, weak life cycle coverage, and the lack of integration between spatial and technical approaches— have persisted for more than a decade, despite sustained attention in the literature.

Keywords: Linear infrastructure · Environmental impact assessment · Life cycle analysis · Sustainability tools · Spatial and ecological modeling

1 Introduction

The development of linear infrastructure—understood as systems that extend longitudinally across the territory, such as energy, telecommunications, supply, and transport networks—is fundamental to the functioning of modern societies. Yet, their construction

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and operation generate specific environmental impacts, largely resulting from continuous land take and the spatial fragmentation they create. A substantial share of linear infrastructure is dedicated to transport, which stands out for the magnitude and persistence of its ecological effects: it alters habitats, disrupts ecological connectivity, increases wildlife mortality, and modifies ecosystem processes at multiple scales. This prominence has positioned linear transport infrastructure at the center of international policy agendas, which increasingly call for the integration of ecological considerations across all stages of the infrastructure life cycle. The European Union's Biodiversity Strategy for 2030 and the Kunming-Montreal Global Biodiversity Framework have set ambitious goals for ecosystem restoration and biodiversity conservation, placing unprecedented pressure on transport planners to adopt more environmentally responsive approaches. However, the use of operational tools capable of systematically assessing both the impacts and potential benefits of such infrastructure remains fragmented and unevenly standardized.

This systematic review addresses a critical knowledge gap by characterizing the current state of operational tools used for environmental impact assessment of linear infrastructure. The analysis aims to identify methodological patterns, assess the integration of ecological criteria, and provide evidence-based recommendations for developing more robust and standardized assessment frameworks.

2 Methodology

A comprehensive literature review was conducted covering peer-reviewed publications between January 2021 and December 2024. The selection process followed two main screening stages: (1) initial screening of titles and abstracts to eliminate irrelevant topics, and (2) full-text screening based on specific inclusion criteria: relevance to linear infrastructure, inclusion of environmental impact assessment, and use of structured tools or operational frameworks.

The review was structured around six analytical dimensions derived from established Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) frameworks: (1) nature of the assessed activity; (2) life cycle phase addressed; (3) system boundaries and scoping; (4) inventory data quality and transparency; (5) impact assessment methodologies; and (6) benefit assessment approaches and baseline criteria.

The final sample consisted of 102 case studies. Classification across the six analytical dimensions was carried out independently by multiple reviewers, and any discrepancies were resolved through discussion and consensus.

3 Results

Table 1 summarizes the distribution of categories across all dimensions. Note that in some cases a single study is counted more than once when multiple methods, phases or data types were reported.

Table 1. Summary of methodological features and assessment categories identified across the 102 reviewed studies. Note: In some categories, a single study may be counted more than once when multiple methods, phases, or data types were reported

Dimension	Category	Mentions
Type of tool	Specific solutions	53 (52%)
	Plans or strategies	41 (40)
	Services	10 (10)
	Corporate frameworks	8 (8)
Life cycle phase	Operation	80 (78)
	Construction	70 (69)
	Maintenance	54 (53)
	Planning/Design	43 (42)
	End-of-Life	38 (37)
System boundaries	Partial empirical scoping (non-LCA)	50 (49)
	Strategic or territorial scoping	28 (27)
	Defined system boundaries (LCA methodology)	24 (24)
Inventory data category	Field data collection	51 (50)
	Spatial analysis	44 (43)
	Statistical & predictive modeling	35 (34)
	Other	23 (23)
	Stakeholder & qualitative data	23 (23)
	Laboratory & experimental data	18 (18)
Impact assessment category	Spatial analysis/GIS	46 (45)
	Simulation/Predictive models	35 (34)
	Ecological indicators/Bioindicators	33 (32)
	Life Cycle Assessment	28 (27)
	Qualitative/Narrative assessment	26 (25)
	None/Not specified	22 (22)
	Stakeholder-based/Perception analysis	15 (15)
	Multi-Criteria Decision Analysis (MCDA)	8 (8)
	Economic valuation/monetization	6 (6)
Benefit assessment method	Qualitative/descriptive Evaluation	11 (11)
	Scenario Comparison/Policy Options	4 (4)
	Quantitative Ecological Gains	3 (3)
	Stakeholder-defined or Perception-based	2 (2)

(*continued*)

Table 1. (*continued*)

Dimension	Category	Mentions
	Cost-effectiveness analysis	1 (1)
	Economic valuation/monetization	0 (0)

3.1 Study Characteristics and Tool Typologies

The reviewed studies covered a broad geographic range, with Europe (n = 49) and Asia (n = 28) accounting for the largest shares. Most case studies focused on transport-related infrastructure, particularly roads (47%) and railways (32%), with fewer studies addressing multimodal corridors or other linear systems such as pipelines and transmission lines.

In terms of assessed activity, specific technical solutions represented the largest category (52%, n = 53), followed by strategic plans or frameworks (40%, n = 41). Service-oriented approaches (10%, n = 10) and corporate or institutional frameworks (8%, n = 8) appeared less frequently. This distribution indicates that the literature is more strongly oriented toward project-level or operational applications than toward standardized or system-wide assessment frameworks.

3.2 Life Cycle Coverage, System Boundaries, and Inventory Data

Life cycle coverage was clearly uneven. The operational phase was most frequently addressed (78%, n = 80), followed by construction (69%, n = 70), while maintenance (53%, n = 54), planning/design (42%, n = 43), and especially end-of-life (37%, n = 38) were less consistently included. This pattern suggests that full life cycle assessment remains uncommon, particularly for later or less visible project stages.

System boundaries also varied substantially. Nearly half of the studies (49%, n = 50) relied on partial empirical scoping rather than formalized life cycle boundaries, while 27% (n = 28) adopted strategic or territorial definitions. Only 24% (n = 24) applied clearly defined LCA-based system boundaries. This confirms the coexistence of multiple scoping logics, often with limited comparability across studies.

Inventory data were similarly heterogeneous. Field data collection was the most frequent source (50%, n = 51), followed by spatial analysis (43%, n = 44) and statistical or predictive modeling (34%, n = 35). Stakeholder-based and qualitative inputs (23%, n = 23), other non-standardized data (23%, n = 23), and laboratory or experimental data (18%, n = 18) were less common. Overall, the results point to considerable variation in data quality, transparency, and reproducibility.

3.3 Assessment Methodologies and Benefit Evaluation

Assessment methods were highly diverse. Spatial analysis and GIS-based approaches were the most frequently used (45%, n = 46), followed by simulation or predictive modeling (34%, n = 35), ecological indicators or bioindicators (32%, n = 33), and formal

LCA methodologies (27%, n = 28), typically based on ReCiPe, IPCC, or CML Baseline characterization methods. Qualitative or narrative assessments were also frequent (25%, n = 26), whereas multi-criteria decision analysis (8%, n = 8) and economic valuation or monetization (6%, n = 6) remained limited. Notably, 22% (n = 22) of the reviewed studies did not report a clearly structured impact assessment method.

Benefit assessment was the least developed dimension. Most studies (70%, n = 71) did not include any structured evaluation of environmental benefits. Among those that did, qualitative or descriptive approaches predominated (11%, n = 11), while scenario comparison (4%, n = 4), quantitative ecological gain metrics (3%, n = 3), stakeholder-defined benefits (2%, n = 2), and cost-effectiveness analysis (1%, n = 1) were only marginally represented. No study applied formal economic valuation to biodiversity or ecosystem gains. Across the sample, benefit-related baselines and evaluation criteria were often absent or only implicitly defined.

Taken together, these findings confirm that current environmental assessment practices for linear infrastructure remain fragmented, with stronger development in impact characterization than in integrated life cycle coverage or structured benefit evaluation.

4 Discussion and Conclusions

4.1 Methodological Fragmentation and Integration Challenges

The reviewed literature reveals considerable methodological pluralism in the environmental assessment of linear infrastructure. This diversity reflects legitimate differences in objectives, scales, and disciplinary traditions, but it also generates significant challenges for integration and comparability. The coexistence of highly formalized approaches such as LCA alongside spatial ecological models and qualitative strategic frameworks complicates knowledge synthesis and limits the transferability of results across contexts.

A consistent pattern is the concentration of assessments on the construction and operation phases, while maintenance and especially end-of-life remain underrepresented. This imbalance does not necessarily reflect the actual distribution of impacts, but rather the availability of data and institutional priorities. Maintenance activities generate recurrent environmental burdens over long time horizons, and decommissioning or restoration phases present relevant opportunities for reducing long-term ecological footprints. A comprehensive assessment of biodiversity impacts therefore requires addressing all life cycle stages and considering cumulative and interactive effects.

A further structural gap persists between spatial ecological approaches, focused on landscape connectivity and habitat quality, and technically oriented studies based on material flows and standardized indicators. Both offer complementary capacities: spatial analyses capture ecological processes and configurations at territorial scales, whereas LCA provides comparable metrics of specific environmental pressures. However, the former rarely include construction impacts or material flows, and the latter scarcely represent habitat fragmentation or biological connectivity. Integrating both paradigms remains a key challenge, for example through hybrid frameworks that combine ecological risk assessment with inventory structures compatible with LCA.

Data-related limitations further constrain methodological robustness. Although field-based studies provide high spatial and temporal resolution, transparency and reproducibility remain uneven. The limited presence of experimental data constrains parameter precision, while the low incorporation of participatory or local knowledge limits the integration of socioecological dimensions. More systematic integration of empirical monitoring, spatial modeling, experimental approaches, and stakeholder-based knowledge would help consolidate a more robust evidence base.

The most critical gap identified is the lack of structured benefit assessment. Most studies do not quantify ecological improvements associated with interventions, even when trade-offs between impacts and environmental gains are central to decision-making. Qualitative approaches predominate, and when benefits are quantified, they often lack clear baselines or standardized metrics. In addition, no studies incorporate economic valuation, despite growing policy interest in ecosystem services and natural capital. Developing consistent gain metrics, counterfactual scenarios, and explicit baseline definitions remains an unresolved challenge.

4.2 Comparative Evidence and Structural Implications

Many of the limitations identified in this review have been documented in earlier studies and remain largely unresolved. Methodological fragmentation, weak integration between spatial and technical approaches, and imbalances across life cycle phases have been highlighted in previous reviews [1–3] and are confirmed by our findings. Similarly, life cycle coverage gaps are consistent with the limitations identified by Chester and Horvath [4], particularly regarding the underrepresentation of non-operational phases such as maintenance and end-of-life.

Shortcomings in validation and experimental design, previously identified by van der Grift et al. [5] and Rytwinski et al. [6], also persist. Issues related to scope definition, transparency, and the limited treatment of cumulative impacts align with the findings of Lechner et al. [7], while the gap between strategic planning and measurable implementation outcomes reflects observations by Bigard et al. [8]. Although connectivity modeling has become more widespread, concerns regarding validation raised by Clauzel et al. [9] remain relevant.

At the same time, some incremental progress is evident. The use of spatial analysis has increased, strategic approaches have expanded—particularly in European contexts—and emerging digital tools are beginning to support more integrated assessments. However, these advances have not resolved the core structural limitations identified more than a decade ago.

An important emerging finding of this review is the systematic absence of benefit assessment: 70% of studies do not quantify ecological gains, and none include economic valuation. Together with geographic imbalances, taxonomic biases, and the lack of coherent operational standards, this reinforces the interpretation that fragmentation is structural rather than circumstantial. Incremental methodological improvements appear insufficient to overcome these limitations.

Three main directions emerge for future research and practice. First, rather than pursuing full methodological integration, the development of “translation protocols”

between different assessment paradigms may offer a more feasible path toward interoperability. Second, addressing persistent gaps in monitoring, validation, and data transparency will likely require institutional and regulatory support, not only methodological refinement. Third, advancing benefit assessment requires a shift from impact minimization toward ecological enhancement, supported by explicit baselines, standardized gain metrics, and scenario-based evaluation approaches.

Overall, this systematic review of 102 studies (2021–2024) confirms that environmental assessment of linear infrastructure remains methodologically diverse but fundamentally fragmented. This fragmentation limits comparability, synthesis, and the development of decision-support tools aligned with current biodiversity and sustainability policy objectives.

Aligning infrastructure development with these objectives will require transformative changes beyond incremental methodological advances. Without improved standardization, institutional embedding, and enhanced data practices, environmental assessment risks remaining analytically sophisticated but operationally limited.

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Data availability. All case studies presented will be available upon request.

References

1. Karlson, M., Mörtberg, U., Balfors, B.: Road ecology in environmental impact assessment. Environ. Impact Assess. Rev. **48**, 10–19 (2014). https://doi.org/10.1016/J.EIAR.2014.04.002
2. Teixeira, R.F.M., De Souza, D.M., Curran, M.P., et al.: Towards consensus on land use impacts on biodiversity in LCA: UNEP/SETAC life cycle initiative preliminary recommendations based on expert contributions. J. Clean. Prod. **112**, 4283–4287 (2016). https://doi.org/10.1016/J.JCLEPRO.2015.07.118
3. Curran, M., De Baan, L., De Schryver, A.M., et al.: Toward meaningful end points of biodiversity in life cycle assessment. Environ. Sci. Technol. **45**, 70–79 (2011). https://doi.org/10.1021/ES101444K
4. Chester, M.V., Horvath, A.: Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. **4**, 024008 (2009). https://doi.org/10.1088/1748-9326/4/2/024008
5. van der Grift, E.A., van der Ree, R., Fahrig, L., et al.: Evaluating the effectiveness of road mitigation measures. Biodivers. Conserv. **22**, 425–448 (2013). https://doi.org/10.1007/S10531-012-0421-0
6. Rytwinski, T., Soanes, K., Jaeger, J.A.G., et al.: How effective is road mitigation at reducing road-kill? A meta-analysis. PLoS One. **11**, e0166941 (2016). https://doi.org/10.1371/JOURNAL.PONE.0166941

7. Lechner, A.M., Doerr, V., Harris, R.M.B., et al.: A framework for incorporating fine-scale dispersal behaviour into biodiversity conservation planning. Landsc. Urban Plan. **141**, 11–23 (2015). https://doi.org/10.1016/J.LANDURBPLAN.2015.04.008
8. Bigard, C., Pioch, S., Thompson, J.D.: The inclusion of biodiversity in environmental impact assessment: policy-related progress limited by gaps and semantic confusion. J. Environ. Manag. **200**, 35–45 (2017). https://doi.org/10.1016/J.JENVMAN.2017.05.057
9. Clauzel, C., Girardet, X., Foltête, J.C.: Impact assessment of a high-speed railway line on species distribution: application to the European tree frog (Hyla arborea) in Franche-Comté. J. Environ. Manag. **127**, 125–134 (2013). https://doi.org/10.1016/J.JENVMAN.2013.04.018

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Towards Nature-Positive Transport: Embedding Biodiversity and Societal Considerations in Railways Infrastructure Planning and Policy

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Abstract. The rail sector, with its capacity to drive intermodal integration, is well-positioned to lead the transition toward scalable and sustainable transport solutions across Europe in connection with other transport modes and sectors. Despite broad recognition of the importance of biodiversity-sensitive infrastructure in national and international frameworks, implementation remains limited [3]. Key barriers include fragmented regulatory frameworks, insufficient cross-sectoral coordination, and the inadequate incorporation of biodiversity considerations into infrastructure planning, construction and operation as highlighted by initiatives such as the BISON project. In response, this study—conducted within the EU-Rail SYMBIOSIS project—analyses the societal impacts, regulatory challenges, and interdependencies between rail and energy infrastructure in relation to biodiversity and climate objectives. Using a robust methodology based on literature review and stakeholder consultation, an inclusive framework is being developed to improve environmental and cumulative impact assessments and enhance environmental evaluation procedures across the infrastructure life cycle. The work also examines the alignment of EU policies with international environmental goals and investigates the consequences of the Corporate Sustainability Reporting Directive on biodiversity matters' governance and accountability. Evidence-based recommendations are formulated to integrate biodiversity and climate priorities into procurement practices and regulatory mechanisms. The outcomes aim to support a more resilient, integrated, environmentally and socially responsible approach to transport infrastructure planning and implementation across Europe.

Keywords: Sustainable transport infrastructure · Societal challenges · Environmental impacts · Biodiversity · Nature-positive policies

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1 Introduction

The transition to sustainable transport is central to addressing biodiversity loss, climate change, pollution, and social equity. Transport is the only EU sector where greenhouse gas emissions have increased since 1990, growing at an average annual rate of 1.7% until 2022 [10]. In contrast, rail has reduced its emissions and remains the lowest-emitting motorised mode, combining high capacity with energy efficiency and low-carbon performance. Despite accounting for around 11% of freight and 7% of passengers, it produces less than 0.4% of transport-related emissions [12, 13].

However, these benefits are accompanied by important challenges. Rail infrastructure can lead to habitat loss and fragmentation, wildlife collisions, and the spread of invasive species, while also disrupting communities and, in some cases, exacerbating social inequalities if not properly planned.

Although awareness of biodiversity integration in transport planning is increasing, implementation in the rail sector remains limited. Key barriers include the lack of standardised guidelines, limited expertise and data availability, insufficient integration of biodiversity within climate-focused strategies, weak multidisciplinary coordination, and constrained resources and monitoring frameworks. Addressing these challenges requires coordinated action among policymakers, infrastructure managers, and biodiversity experts, supported by clear standards, adequate resources, and robust monitoring systems. A holistic approach—integrating environmental, economic, and social dimensions—is essential across the infrastructure lifecycle.

In this context, EU-Rail promotes digitalisation, interoperability, and sustainability in line with the goal of reducing transport emissions by 90% by 2050. Initiatives such as Rail4EARTH support system resilience and efficiency [11], while the EU-funded SYMBIOSIS project focuses on integrating biodiversity into infrastructure planning and management. As a Coordination and Support Action, SYMBIOSIS brings together a multidisciplinary consortium to address the societal and environmental challenges of sustainable transport, aiming to embed biodiversity considerations throughout the infrastructure lifecycle and align environmental, operational, and societal objectives.

2 Methodology

SYMBIOSIS adopts a mixed-methods, participatory framework to assess societal and biodiversity challenges related to railway infrastructure planning and policy, while integrating these considerations into its development. The research combines a systematic literature review with iterative stakeholder consultations, synthesising academic studies, technical reports, and policy documents on transport ecology, infrastructure planning, ecosystem services, and socio-economic impacts to establish the conceptual basis and identify evidence gaps. In parallel, stakeholder engagement—through questionnaires, semi-structured interviews, workshops, conference sessions, and online surveys—captures experiential knowledge, priorities, and constraints from actors involved in or affected by railway infrastructure.

A structured stakeholder mapping process ensures representative and targeted engagement across key groups, including transport operators and infrastructure managers, energy sector actors, policymakers and regulators, civil society, international experts, and industry and supply chain stakeholders.

The framework evaluates three interconnected dimensions: (i) societal impacts, analysed through qualitative data, social indicators, and case studies to assess distributional effects and governance challenges; (ii) environmental impacts, focusing on biodiversity and ecosystem services through literature review, GIS-based analyses of habitat fragmentation and connectivity, and relevant impact metrics; and (iii) regulatory interdependencies, examined by mapping legal frameworks, policy instruments, and institutional roles to identify gaps, inconsistencies, and synergies across sectors.

To further support biodiversity integration, the project examines sustainability reporting and procurement practices. This includes analysing disclosures in the transport sector to identify reporting gaps, drawing on frameworks such as the Corporate Sustainability Reporting Directive (CSRD), and benchmarking infrastructure companies to identify best practices. Key performance indicators and procurement criteria are defined to address biodiversity-related risks and opportunities, supported by stakeholder and expert input.

Finally, findings are consolidated through multicriteria analysis (MCA) to evaluate trade-offs and co-benefits, while Social Readiness Levels (SRLs) are used to assess the maturity and societal acceptance of proposed measures, ensuring feasible and implementable solutions.

3 Navigating the Challenges: Integrated Policy and Societal Considerations for Sustainable Rail

Achieving sustainable rail infrastructure requires more than technological progress; it depends on coherent policy frameworks and a thorough understanding of societal and environmental needs. Efforts that address ecological integrity or community well-being in isolation risk falling short without integration. Governance in this area is particularly complex, as regulations overlap with domains such as trade, health, and human rights, producing a fragmented regulatory landscape that undermines consistent enforcement and hampers communication between key sectors and stakeholders [8, 23, 28].

Biodiversity governance illustrates these challenges. Habitats Directive [15] and Birds Directive [16] established the Natura 2000 network, yet inconsistent implementation continues to jeopardise its coherence [European Commission, 2015]. Similarly, Regulation (EU) 2024/1679 (TEN-T Regulation) [19], is, at the same time, lacking explicit provisions on biodiversity, relying instead on Environmental Impact Assessments (EIA) under Directive 2011/92 [17], as amended by Directive 2014/52/EU [18]. The absence of clear criteria and weak enforcement mechanisms have limited the Directive's effectiveness [26]. The EU Taxonomy Regulation (2020/852) recognises biodiversity and ecosystem restoration as core environmental objectives, but its impact relies on stronger coordination, technical capacity, and consistent integration into planning [2, 25].

Regulatory fragmentation is exacerbated by weak cooperation between institutions, limited political will, and limited funding, which frequently place a higher priority on

economic issues rather than ecological ones [20]. A lack of awareness, training, and clear criteria contributes further to such inefficiencies [1].

The Corporate Sustainability Reporting Directive (CSRD; Directive 2022/2464/EU) represents a broader effort to align economic and environmental priorities, explicitly linking biodiversity loss to financial risks and social responsibility [7, 22]. Expanding on the Non-Financial Reporting Directive, the CSRD broadens the sustainability reporting obligations to include small and medium-sized enterprises (SMEs), imposes stricter transparency requirements, and highlights the importance of accountability within supply chains. While these measures have the potential to strengthen accountability and improve data collection, they also pose increased compliance challenges, particularly for SMEs. For larger corporations, obtaining data from suppliers can lead to greater awareness and foster behavioural changes, though it can also be expensive and may offer limited immediate benefits. Recent proposals to relax certain requirements for SMEs, could jeopardize the overall effectiveness of the Directive.

Beyond broader biodiversity, sustainability governance, and regulatory inconsistencies, rail stakeholders face sector-specific challenges in balancing environmental, social, and economic objectives. While rail transport offers clear sustainability advantages—such as lower emissions per capita and high passenger capacity—it requires significant capital investment, long-term planning, and careful urban integration [12–14]. At the same time, it may generate notable environmental and social impacts, including community displacement and disruption, accessibility limitations for persons with disabilities, and environmental pressures such as pollution, noise, habitat fragmentation, and disruption of wildlife corridors. These impacts may disproportionately affect vulnerable populations, raising environmental justice concerns, while also contributing to climate and health risks, such as increased urban heat, air pollution, and exposure to extreme weather events. In addition, insufficient coordination between transport modes and spatial planning can exacerbate land-use inefficiencies, urban sprawl, cumulative biodiversity impacts, and dependence on private vehicles, underscoring the need for integrated and inclusive planning approaches.

Addressing these complex issues requires an integrated and inclusive strategy. The potential for rail to contribute to sustainable transport can be enhanced through policies that prioritize biodiversity, strengthen governance frameworks, and involve local communities throughout all phases. Encouraging mixed-use development around stations and aligning rail infrastructure expansion with consistent and careful land-use planning avoiding or mitigating the impacts on biodiversity, can contribute also to the reduction of reliance on cars, stimulate economic development, and foster resilient, nature protection and low-carbon communities.

4 Towards an Inclusive Framework for Nature-Positive Transport

The European Union has introduced various strategies aimed at creating a more sustainable and resilient transport system under the European Green Deal, notably the Sustainable and Smart Mobility Strategy and the Biodiversity Strategy for 2030. Both prioritize the need to address biodiversity in transport infrastructure considering measures to ensure the establishment and maintenance of functional ecological corridors,

integrated spatial development, and the diminishment of ecosystem-disrupting pollutants. Nonetheless, achieving such integration calls for the mobility and biodiversity sectors to work together, encouraging an all-inclusive paradigm [4–6].

To effectively promote sustainable transport that benefits both ecosystems and society, it is essential to consider landscape fragmentation across Europe, especially in connection with the Trans-European Transport Network (TEN-T). The combination of "Green" and "Grey" infrastructure has led to significant landscape fragmentation, which varies across countries—from low to very high levels [12–14] Strategic planning based on ecosystem principles [21], along with the concept of reversibility [24], are key to ensuring long-term sustainability of infrastructure projects. These strategies include monitoring cumulative impacts on habitat fragmentation, accounting for wider ecological effects beyond the immediate infrastructure line, and considering the long-term horizon [27]. Innovative tools such as AI-driven biodiversity monitoring, also applied in the collection of data to enhance Strategic Environmental Assessments (SEA) and EIAs are becoming more and more important for managing these challenges effectively during all phases of transport infrastructure development.

Importantly, incorporating social considerations is crucial for achieving an inclusive approach to sustainable transport, ensuring community engagement, addressing social equity, improving accessibility for marginalized groups, and promoting benefit-sharing with local populations (e.g., displaced communities). Such social dimensions must be integrated throughout biodiversity goals to enhance trust, resilience, and social cohesion in transport planning and implementation [7, 22].

Green sustainable procurement is a viable approach for public and private stakeholders to keep track of the effective introduction of biodiversity and social instances into companies' strategies, as findings from infrastructure companies involved in the SYMBIOSIS Project indicate. Despite the ecological impact of linear infrastructure, such as roads and railways, existing procurement frameworks often do not include explicit criteria related to biodiversity. By integrating environmental and social standards into contractual agreements, organizations could enhance their compliance with new corporate sustainability reporting requirements but also promote a broader commitment to biodiversity across their supply chains, and therefore among a wide number and variety of infrastructures' stakeholders.

The integration of ecological, social, and economic considerations can lead to the development of an inclusive, nature-positive transportation system, combined with a coherent policy framework. This holistic approach aligns with the broader goals of the European Green Deal and universal sustainable development objectives, emphasizing the importance of cross-sector cooperation and innovative, adaptive management strategies.

5 Conclusions

These represent only the first findings of the SYMBIOSIS project, yet they already point to important considerations for embedding biodiversity and societal aspects into railway infrastructure planning and policy. The analysis shows that while existing EU Directives provide a useful foundation, inconsistencies and gaps in their implementation limit effectiveness, underscoring the need for clearer guidance, standardized metrics, and stronger enforcement mechanisms.

The findings underscores the need for joint action across policy, regulation, industry, spatial planning, and research domains to realize biodiversity-affirming railway infrastructure. From the policymakers' perspective, it means the needs for articulation of coherent and legally consistent policy be accompanied by definable targets, KPIs, and resource allocation for incentives—such as grants or tax benefits—to promote nature-based solutions and sustainable procurement practices. Equally important is ensuring community engagement and equitable access throughout all stages of railway planning and development. For industry stakeholders, a shift toward sustainable procurement and investment in innovative, nature-based solutions is essential, alongside collaboration with local communities to maximize both environmental and societal value. The research community, in turn, needs to focus on the development of unified approaches and frameworks, mitigating cumulative impacts, and evaluating the effectiveness of policy and financial instruments supporting nature-positive infrastructure.

Together, these actions lay the groundwork for advancing a railway sector that is not only resilient and sustainable but also better aligned with the ecological and social needs of the future.

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References

1. Baierl, C., et al.: Development and use of the European Defragmentation Map (Deliverable D5.3). BISON – Horizon 2020 project (2023)
2. Ballesteros, M.: Transposition and Implementation of the 2014 Directive on the Assessment of the Effects of Certain Public and Private Projects on the Environment (2018)
3. BISON Project: Report on Identification of Gaps and Barriers to Expand Replicability and Application of Good Practice to Mainstream Biodiversity and Transport (Deliverable D3.2) (2022). https://bison-transport.eu/wp-content/uploads/2022/09/D3.2_Report-on-Gaps-and-Barriers.pdf
4. Convention on Biological Diversity: Mainstreaming of biodiversity in the energy and mining, infrastructure, manufacturing, and processing sectors. Decision 14/3 (2018)
5. Convention on Biological Diversity: Mainstreaming of biodiversity within and across sectors. Decision 16/13 (2024)
6. Convention on Biological Diversity: Biodiversity and climate change. Decision 16/22 (2024)
7. Dempsey, N.: Sharing the Benefits of Biodiversity: A Review of the Distribution of Benefits from Biodiversity (2013)
8. Dostál, I. et al.: State of play report on knowledge and capacity related to mainstreaming biodiversity into the transport sector. HARMON 2, Interreg Danube Region Programme (2025)
9. European Commission: The Implementation of the Natura 2000, Habitats Directive 92/43/EEC and Birds Directive 79/409/EEC. European Commission (2015)
10. European Commission: EU Transport in Figures – Statistical Pocketbook 2023. Publications Office of the European Union, Luxembourg (2023)

11. European Commission: Implementing EU law. https://ec.europa.eu/implementing-eu-law/home/en
12. European Environment Agency: Rail and Environment – The Benefits of Rail in Tackling Climate Change. EEA, Copenhagen (2021)
13. European Environment Agency: Landscape Fragmentation Pressure and Trends in Europe (2021). https://www.eea.europa.eu/data-and-maps/indicators/mobility-andurbanisation-pressure-on-ecosystems-2/assessment
14. European Environment Agency: Transport and Environment: Facing a Green and Healthy Future? EEA, Copenhagen (2021)
15. European Parliament and Council: Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (1992). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043
16. European Parliament and Council: Directive 2009/147/EC on the conservation of wild birds (2009). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147
17. European Parliament and Council: Directive 2011/92/EU on environmental impact assessment (2011). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0092
18. European Parliament and Council: Directive 2014/52/EU Amending Directive 2011/92/EU (2014). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0052
19. European Parliament and Council: Regulation (EU) 2024/1679 on the Trans-European Transport Network (TEN-T) (2024). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1679
20. Georgiadis, L., et al.: Recommendations for policy/strategy harmonization (Deliverable D5.2). BISON – Horizon 2020 project (2023)
21. Georgiadis, L., et al.: A Global Strategy for Ecologically Sustainable Transport and Other Linear Infrastructure. IENE, Stockholm (2020)
22. IPBES: Global Assessment Report on Biodiversity and Ecosystem Services (2019). https://ipbes.net/global-assessment
23. Isailovic, M., Widerberg, O., Pattberg, P.: Fragmentation of Global Environmental Governance Architectures: a Literature Review (2013)
24. Joumard, R., Nicolas, J.-P.: Transport project assessment methodology within the framework of sustainable development. Ecol. Indic. **10**(2), 136–142 (2010). https://doi.org/10.1016/j.ecolind.2009.04.002
25. Ognjanoska, L.: Environmental Impact Assessment in the Context of EU Environmental Law and Policy (2021)
26. Rehbinder, E.: Environmental Impact Assessment and Environmental Quality Standards. (2011)
27. Rosell, C., et al.: IENE Biodiversity and Infrastructure: A Handbook for Action. IENE, Stockholm (2023) https://www.biodiversityinfrastructure.org/
28. Xu, H.: Regulatory fragmentation and corporate innovation. J. Empir. Financ. (2025). https://doi.org/10.1016/j.jempfin.2025.101614

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Hydrodynamics and Multi-physics Simulations Towards Systematic Development of Digital Twin in Shipping

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Abstract. Shipping efficiency is a critical factor in reducing fuel consumption and emissions in maritime transport. Enhancing propulsion efficiency in maritime transport not only reduces operating costs for shipping companies but also contributes to global sustainability efforts by minimizing the sector's carbon footprint. To address these challenges, the industry has been exploring various strategies, including advancements in ship design, adoption of novel technologies for energy saving, alternative fuels, digitalization, and improved logistics management. Regulatory frameworks, such as the IMO emissions targets, further drive the push toward greener and more efficient shipping practices. In TwinShip project, the Engine Propeller Combinatory Diagram (EPCD) is developed based on existing domain knowledge through model-based systems engineering and simulations, i.e. Hydrodynamics and Multi-physics simulation, as the initial step towards Digital Twin models for vessels with existing fuel and technologies. Various pilot vessels, including RoRo and cargo (tanker and bulk carrier) ships, are studied addressing any deviations through refined hydrodynamic calculations to minimize uncertainties. The development of analytical models and prediction of power performance for the above ships is presented and the method for calibration is described, supporting their extension to incorporate Energy Saving Devices for enhanced power performance.

Keywords: Ship propulsion power · digital twin · propulsion enhancement · energy saving technology · multi-physics simulation

1 Introduction

Digital Twin (DT) technology holds the potential to significantly transform the shipping industry, offering a way to effectively utilize vast amounts of vessel IoT & industrial data, categorized as extreme data, for valuable ship design, construction, operational & maintenance, retrofitting, and other business insights. This technology could lead to

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significant advancements in environmental and commercial efficiency in shipping by considering the whole life cycle of vessels. Strategic implementation of DT technology is crucial for pushing the green and digital evolutions of the maritime sector, enabling a smooth transition to net-zero-emission ship operations by 2050, in accordance with the IMO pathway for decarbonization; see, e.g., [1–3].

The shipping industry is limited to the traditional modeling approaches in ship design phase, where various hydrodynamic-based models are utilized [4]. These models will adequately perform during the ship design phase due to additional model scale tests conducted on the towing tank and ocean basin type environments, and experimental data that are collected and fed back into simulation models. However, the same models may often fall short in accurately predicting the holistic behavior of vessels during operations. This is mainly due to the fact that such models may have adequate capabilities to incorporate ship performance datasets from the operational phase and the challenges associated with the data quality issues, i.e. data veracity. These data quality issues are often related to onboard data handling complexities, such as possible sensor or data acquisition system (DAQ) failures, as well as unexpected ship system degradation conditions; see [5].

To address these challenges, the industry has been exploring various strategies, including advancements in ship design, adoption of novel technologies for energy saving, alternative fuels, digitalization, and improved logistics management. Moreover, regulatory frameworks, such as the IMO emissions targets, further drive the push toward greener and more efficient shipping practices.

In the framework of TwinShip Horizon Europe project (https://twin-ship.eu/), a set of technological elements has been proposed. An important component concerns the development of DT methodology supported by an open-source digital platform that is facilitated by several pilot study vessels with their ship performance data sets. The same digital platform will serve as the hosting foundation for DT development as well as its simulated environment so that a proper Decision Support System (DSS) can bring a significant step toward accelerating the maritime industry's digital evolution. The proposed DT technology can pave the way for a greener, more efficient future by setting early greenhouse gas (GHG) emission benchmarks for the world merchant fleet to reduce fuel consumption and emissions; see [5].

In TwinShip project, the Engine Propeller Combinatory Diagram (EPCD) is developed based on existing domain knowledge through data-calibrated physical model-based systems and simulations, where hydrodynamics and multi-physics simulations are utlized, as the initial step towards Digital Twin model development for vessels with existing fuel and technologies. Various pilot vessels, including RoRo and cargo (tanker and bulk carrier) ships, are studied, addressing any deviations through refined hydrodynamic calculations to minimize uncertainties. The development of analytical models and the prediction of power performance for the above ships is presented and the method for calibration is described, supporting their extension to incorporate Energy Saving Devices for enhanced power performance.

2 TwinShip Model for the EPCD

A model for the prediction of the propulsive behavior of the ship and propeller in waves based on the application of the surge equation with excitation from wind and waves and the propeller thrust, is used for a fast time scale prediction of the responses, as follows:

$$(1-t)N_pT_p + T_{WASP} - (R + R_{AW}) + F_1 = (m + a_{11})\ddot{\xi}_1 + b_{11}\dot{\xi}_1 \tag{1}$$

where $\dot{\xi}_1$ is the surge oscillatory velocity, N_p is the number of propellers, T_p denotes each propeller's thrust and $(1-t)$ is the thrust deduction; see [6]. Additional thrust components, as for example thrust from wind assisting devices, are denoted by T_{WASP}. Also, the ship resistance (possibly including effects from Air Lubrication Systems) at given ship speed is denoted by R, and the mean added wave resistance by R_{AW}, which is dependent on ship responses in waves [7–9], and more significantly from ship heave and pitch oscillations, and is usually estimated by means of standard seakeeping analysis. In the right-hand side of the above Eq. 1, m is the ship mass, a_{11}, b_{11} are the added mass and hydrodynamic damping coefficients in surge motion, and F_1 the wave excitation force, respectively. The above model is consistent with excitation by regular waves, however, it can be applied approximately to cases of irregular waves by considering the surge added mass and wave excitation force calculated at the peak frequency of the wave spectrum and estimating the surge hydrodynamic damping by means of the slope of the ship resistance curve at the given speed:

$$b_{11} = \frac{dR_T(V_s)}{dV_s} = \frac{d(R + R_{AW})}{dV_s} \tag{2}$$

In the case of small ship surge oscillations $\left|\frac{\dot{\xi}_1}{V_s}\right| \ll 1$, and small wave surge excitation $\left|\frac{F_1}{R}\right| \ll 1$ a simplification of the above dynamical model can be obtained, which permits the use of the steady open-water characteristics of the propeller(s), in conjunction with appropriate tuneable coefficients estimated by unsteady propeller hydrodynamic analysis for the inclusion of the wave effects, as described in more detail in the next subsection. We consider the following time-varying coefficient

$$\frac{K_T}{J^2} = \frac{(R + R_{AW} - T_{WASP})/N_p}{\rho(1-t)(1-w)^2(U + \alpha u_w)^2 D^2} = C(t) \tag{3}$$

where K_T is the propeller thrust coefficient and $T_p = \rho n^2 D^4 K_T\,(J; C(t))$ is the thrust, $J = U/(nD)$ is the propeller advance ratio, where $U = (1-w)V_s$ is the axial flow on the propeller and $1-w$ denotes the mean volumetric effective wake on the propeller disc (defined as the mean value of the axial propeller inflow), $n = \omega/2\pi$ denotes the propeller revolutions per second (ω is the propeller angular velocity), and D is the propeller diameter, respectively. Moreover, in the above Eq. 3, u_w denotes the wave velocity on the propeller disc and α is a tuning coefficient that enables the incorporation of the effects of the propeller(s) oscillatory motion at the stern of the ship, which will be presented with more detail below. The temporary operation point of the propeller is obtained from the propeller steady characteristics, from which propeller thrust, torque and the rotational

speed are obtained: $T_p(t), Q_p(t)$ and $n(t) = \frac{U}{JD}$, and finally the engine shaft horsepower is estimated from the propeller data as: $SHP = (Q_p\omega)/(\eta_R\eta_S)$, where η_R is the relative rotative efficiency and η_S the shafting system efficiency. An important factor concerning ship operation in realistic sea-states, strongly connected to ship dynamics, is associated with added resistance in waves. In the case of unidirectional waves, the responses of the system operating at various sea conditions labelled by a sea-state index ranging from 1 to 5 are considered, corresponding to values of the significant wave height and modal period as listed in Table 1. For calculations, the Bretschneider wave spectrum is used:

$$S(\omega) = (5/16)\left(\omega_p^4/\omega^5\right)H_S^2\exp\left(-1.25\left(\omega_p/\omega\right)^4\right) \tag{4}$$

where the modal (peak) period for various sea-states, with the severity characterised by the significant wave height, is provided in Table 1. The corresponding frequency of encounter is given by:

$$\omega_e = \left|\omega - \left(\omega^2/g\right)V_S\cos\beta\right| \tag{5}$$

in terms of the absolute wave frequency ω, the ship's speed V_s and mean wave direction β. The spectral density in terms of encounter frequency is

$$S(\omega_e) = S(\omega)(1 - 2(\omega V_S/g)\cos\beta)^{-1} \tag{6}$$

where the Bretschneider model in Eq. (4) is used for $S(\omega) = S(\omega; H_s, T_p)$.

Table 1. Significant wave height and modal period for various sea states

Sea state	1	2	3	4	5
H_S(m)	0.3	0.9	1.9	3.3	5
T_p(sec)	6.3	7.5	8.8	9.7	12.4

Using standard methods, the spectra of various quantities (i.e., wave velocity etc) can be calculated, and short-term time series simulations, with reference to a particular sea state (H_s, T_p, β) are obtained by considering the processes to be stationary characterized by the narrow band spectrum of the response(s). For example, the frequency spectrum of the horizontal wave velocity on the propeller disc is given by: $S_U(\omega_e) = \int_\theta |RAO_U(\omega_e, \theta)|^2 S(\omega_e, \theta; H_S, T_p, \beta)d\theta$ *and* $RAO_U = \omega(\omega_e)\ exp\ (-d\omega^2(\omega_e)/g)$,where d is the propeller submergence depth. Th e stochastic simulation of propeller vertical motion due to stern responses is similarly treated. For simplicity, the wave spectrum is modelled as a unidirectional one: $=S(\omega; H_s, T_p)\delta(\theta - \beta)$, representing long-crested seas. Subsequently, the random-phase model (see, e.g., [10]) is applied to obtain a short-term time series of horizontal wave velocity on the propeller plane, as follows: $u_w(t) = \sum_{n=1}^{N} U_n\cos\left(\omega_{e,n}t + \varepsilon_n\right)$, where ε_n are random variables uniformly distributed in [0,2π). The horizontal wave velocity is correspondingly simulated, and the set of discrete encounter frequencies are appropriately selected to cover the essential support of the spectra and to represent well the energy distribution around the peak frequency.

The above simulated time-series of wave velocities are used in the present model Eq. 1, which is integrated in time in order to obtain the responses of the engine-propeller and other ship systems, at a high-frequency scale, resolving in detail the variations due to the wave velocity at the ship frame of reference. Subsequently, average values are calculated in time intervals of the order of several minutes to tens of minutes in order to derive signals of the propeller and engine rpm and SHP time-series during the corresponding hourly-long segments of the voyage, where the wind and wave conditions are given, as recorded by the onboard measuring systems providing the performance data.

3 Application to a 50000 DWT Chemical Tanker

The main particulars of the studied chemical tanker are: $L_{\text{bp}} = 178.5$ m (overall length $L = 183.2$ m), $B = 32.25$ m, full load draft 12 m, service speed 12 kn. The ship's main engine is directly coupled to a 4-bladed propeller (unraked with 24.5 deg. skew at the tip) of diameter $D = 6.50$ m, pitch ratio $P/D = 0.792$, expanded area ratio 44.5% and hub ratio 0.18. The max speed reported from trials is about $V_O = 15$ kn, and the operational speed as obtained from data analysis is around V_S =11–12 kn.

Numerical predictions obtained by the developed analytical model of the propulsion performance of the studied chemical tanker are presented for various cases, and the prediction enhancement is illustrated as obtained by using the calibration factors obtained by regression analysis. Several segments of voyages corresponding to data points covering time intervals of the order of hours (100 data points) that are representative of specific travelling conditions are used. An example for the ship at full load condition is presented in Fig. 1. The wave and wind data in this voyage segment are presented in Fig. 1(a-c).

The propulsion data in these segments are shown using lines, and RPM and SHP are normalized by the engine SMCR values, and ship speed with respect to V_O, and are used to compare the model predictions and verification of the developed model. Waves are relatively stationary, verifying that the voyage segments correspond to continuous ship operation, while the apparent wind data present the expected variation, as measured from the ship devices.

The reported engine RPM and SHP (kW) for the considered voyage segments are plotted in Fig. 1(d, e). These data cover well the operation of the studied vessel in standard travelling conditions (excluding maneuvering tests, entering and departing from ports, etc).

For the full load condition, the prediction of the ship propulsion system performance concerning the normalized RPM and SHP as obtained from the developed analytical model and the same model after calibration for the corresponding voyage segment is presented in Fig. 1(d) and Fig. 1(e), respectively. Corresponding results for the ballast condition are presented in Fig. 2. We observe that the error in the predictions by the analytical (white box) model could become of the order of 8% for RPM and of 15% for SHP in several cases, however, after the calibration the present (grey box) model provides much more accurate predictions with deviations of the order less than 1% that is considered appropriate prediction for general applications of the 50000DWT chemical tanker propulsion performance. The analytically calibrated model is then used together with the calculated specific fuel consumption (gr/kWh) for various engine RPM, as obtained from the analysis of data.

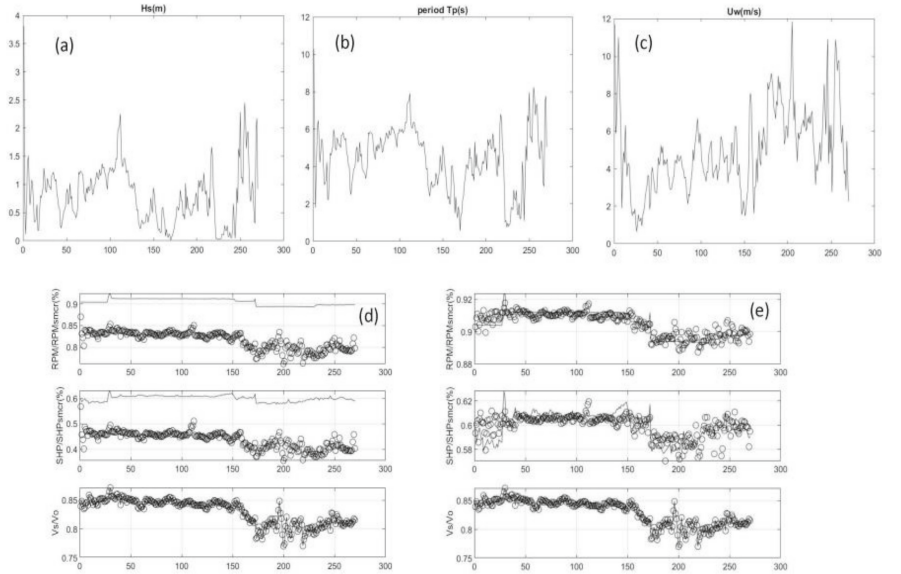


Fig. 1. Weather data in the case of a voyage segment of the chemical tanker at full load: (a) Hs(m), (b) Tp (s), (c) Uw (m/s). Prediction of the propulsion system performance concerning normalized RPM and SHP at given ship speed as obtained from (d) the developed analytical model and (e) the model after calibration for the same voyage segment and ship condition

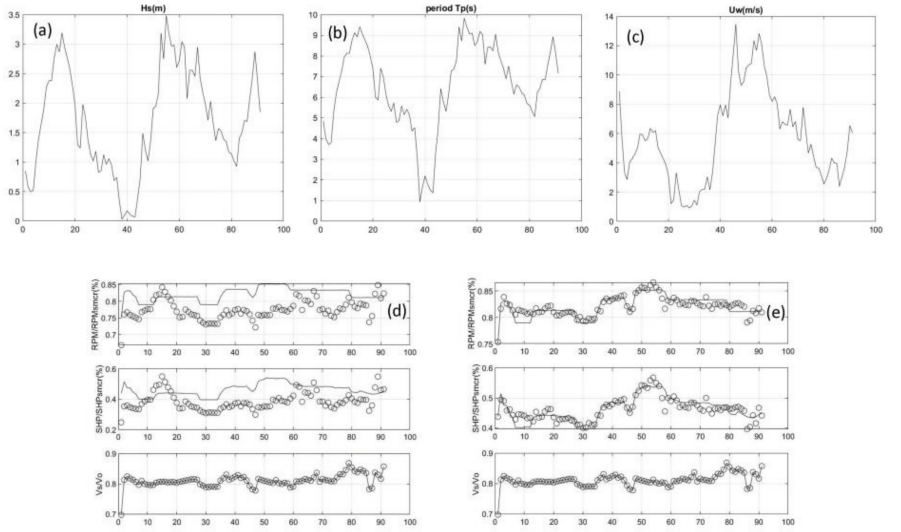


Fig. 2. Weather data in the case of a voyage segment of the chemical tanker at ballast condition: (a) Hs (m), (b) Tp (s), (c) Uw (m/s). Prediction of the propulsion system performance concerning normalized RPM and SHP at given ship speed as obtained from (d) the developed analytical model and (e) the calibrated model for the same voyage segment and ship condition

Results plotted in Fig. 3, for different full load and ballast conditions, in order to obtain predictions for fuel consumptions and applications concerning further trip optimization studies. It is observed that the SFOC ranges in 200-250 g/kWh and is found to be a little smaller in the full load conditions than in the ballast condition. Different accumulation of points at high RPM in the full load condition is due to environmental (wind and wave) effects. It is also noted here that from the sea trials of the chemical tanker the SFOC is reported to be 176–179 g/kWh, and the observed increase is justified by the age of the ship and the propulsion system.

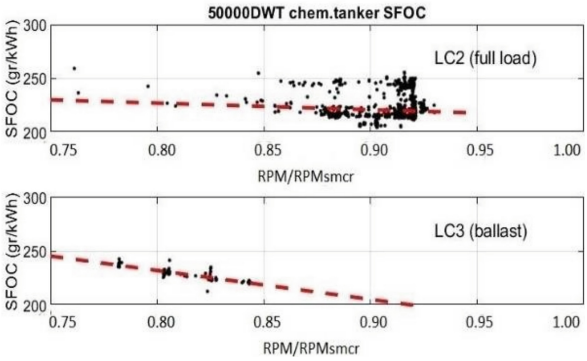


Fig. 3. Calculated specific fuel consumption of the Chemical Tanker in (gr/kWh) for various values of normalized engine RPM as obtained from the analysis of the data

4 Conclusions

In this work the models developed in the framework of TwinShip project for the prediction of power performance of ships based on the EPCD are presented, supporting their extension to incorporate Energy Saving Devices for enhanced propulsion performance. The models are exploited as an initial step towards the development of DT/DSS for three existing vessels and a conceptual futuristic vessel with the required green fuel and technologies to achieve the emission reduction targets of 30–40% by 2030, 80–90% by 2040 (compared to 2008 levels), and the final goal of net-zero emissions by 2045. As an example, selected results are presented and discussed in the case of a 50000DWT chemical tanker analyzed using existing domain knowledge and model-based systems simulations. Further investigation of the possible gains by other fuels, ESDs and renewable energy solutions that will be investigated in the framework of TwinShip project, and conclusions concerning the expected improvements compared to the retrofit investment cost will be presented in future work. It is expected that the proposed DT/DSS will support the shipping industry in achieving critical environmental milestones, which can also support sustainability and innovation in shipping.

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References

1. Mauro, F., Kana, A.A.: Digital twin for ship life-cycle: a critical systematic review. Ocean Eng. **269**, 113479 (2023)
2. Taghavi, M., Perera, L.P.: Digital twin development for ship fuel consumption predictions using multiple model adaptive estimation with eigensystem realization algorithm and observer/Kalman filter identification. Ocean Eng. **345**, 123743 (2026)
3. Taghavi, M., Perera, L.P.: Localized anomaly detection and recovery of marine engine data to support digital twin development in shipping. Ocean Eng. **351**, 124356 (2026)
4. Papanikolaou, A.D.: Holistic approach to ship design. J. Mar. Sci. Eng. **10**, 1717 (2022)
5. Perera, L.P., Belibassakis, K., Roman, D., Oster, M., Ruihua, L.: Digital twin framework to enable green ship operations towards zero emission vessels – TwinShip project overview. In: Spyrou, K., Themelis, N. (eds.) IMAM 2025 Lecture Notes in Computer Science, vol. 4, pp. 41–52. Springer, Cham (2025)
6. Belibassakis, K.: A vortex-element method for the calculation of waves and ship motions effects on propeller performance. In: Proceedings of the 34th Conference of the International Society of Offshore and Polar Engineers (ISOPE 2024), p. TPC-0238 (2024)
7. Arribas, P.F.: Some methods to obtain the added resistance of a ship advancing in waves. Ocean Eng. **34**, 946–955 (2007)
8. Lewandowski, E.: The Dynamics of Marine Craft. World Scientific, Maneuvering and Seakeeping (2004)
9. Loukakis, T.A., Sclavounos, P.: Some extensions of the classical approach to strip theory of ship motion, including the calculation of mean added forces and moments. J. Ship Res. **22**(1), 1–19 (1978)
10. Ochi, M.K.: Ocean Waves. Cambridge University Press, The Stochastic Approach (1998)

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Integrating Life Cycle Assessment into the Early-Stages of Solid-State Battery Design: The Impact of Material Sourcing

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Abstract. Solid-state batteries (SSBs) are promising alternatives for next-generation electric mobility, offering enhanced safety and potential for higher energy density compared to traditional lithium-ion batteries. However, it's important to address their environmental sustainability from the early design stages, particularly regarding raw material sourcing. Given the strategic importance of critical raw materials (CRMs) such as lithium, nickel, cobalt, and manganese, reducing Europe's dependency on primary sources is crucial. The integration of recycled CRMs offers a viable strategy to mitigate these concerns and foster a resilient battery value chain. This study proposes a methodological approach to integrate life cycle assessment (LCA) into the early-stage design of SSBs. A case study is conducted using lab-scale SSB data developed within a European research project. The analysis compares two scenarios: one using primary materials and another incorporating recycled materials. Although the battery cells are still under development and data remain preliminary, the findings indicate that the use of recycled inputs can reduce the environmental impacts of SSB production by up to 10%. The results highlight the influence of material sourcing on environmental performance and the influence of current battery legislation on environmental performance.

Keywords: Life Cycle Assessment · Solid-state · Critical Raw Materials · Recycled materials · Sustainable battery design

1 Introduction

The global transition towards sustainable mobility requires the development of advanced battery technologies to meet the growing demand for electrification. While lithium-ion batteries (LIBs) have led due to high performance and relatively mature production chains. However, concerns remain regarding energy density limitations. Solid-state batteries (SSBs) are promising for next-generation energy storage. Replacing flammable liquids with solids improves safety and energy density, ideal for electric vehicles and demanding uses. However, their sustainability is underexplored, with most developments at lab scale and limited industrial data. A key challenge for LIBs and SSBs is sourcing

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critical raw materials (CRMs) like lithium (Li), nickel (Ni), cobalt (Co), and manganese (Mn), essential for batteries but facing supply risks from geopolitical constraints, limited reserves, and high demand. Europe relies heavily on imports, raising supply security concerns. Recycling and integrating secondary materials are viable strategies to address challenges. Incorporating recycled CRMs reduces environmental impact from primary extraction and enhances the resilience and circularity of the battery value chain. Early integration of environmental assessment tools, such as Life Cycle Assessment (LCA) is essential to guide material choices, reveal trade-offs, and support sustainable design.

This paper explores the environmental impact of material sourcing in SSBs via LCA in a preliminary LCA case study of two scenarios using primary and recycled materials. While data are preliminary, the study aims to highlight the importance of embedding LCA into early-stage battery design to support environmentally responsible innovation.

2 Literature Review – SSB Environmental Impacts

2.1 Material Sourcing in the Li-Ion Battery Value Chain

SSBs play a crucial role in the decarbonisation efforts by the European Commission (EC) by enabling higher efficiency rates and safety when compared to current LIBs [1]. However, the rise of CRMs in SSB design challenges environmental, economic, and social aspects. CRMs like Li, Ni, Co, and Mn face growing supply risks due to geopolitical constraints, limited mining, refining and growing demand [2] Projections indicate that to achieve the Paris Climate goals, demand by 2040 will increase fortyfold for Li, nineteenfold for Ni, and twenty-one-fold for Co, driven by EVs and energy storage (ESS) [3]. As the supply of battery-critical materials are outside the EU, reliance on external sources creates supply chain vulnerabilities for the EU economy and its strategic goals. The EU introduced the Critical Raw Materials Act to mitigate such vulnerabilities and dependencies by focusing on strategic critical materials that are crucial to the digital and green technology transition [4]. Establishing minimum domestic extraction, processing, and recycling rates will require new infrastructure and circular supply chains in Europe. For primary LIB CRMs, energy used in extraction, processing, and manufacturing of cell components mainly drives environmental impacts. CRMs extraction and processing mainly impact GHG (Greenhouse gas) emissions from electricity use, resource depletion from mining, and toxicity from sulfidic tailings in copper and Ni extraction [5]. In current LIBs, materials (as Ni and Co) account for over 70% of the total cell costs [6]. CRMs such as Co and Ni are related to social impacts such as child labour, corruption and worker safety [7]. Recovering these materials at the end of life (EoL) is crucial to reducing demand and environmental, economic, and social burdens.

2.2 Environmental Impacts of Solid-State Technology

Literature shows SSB technology varies in materials and design, affecting its environmental impact assessment. This is mainly due to low TRL of production and multiple chemistries for solid-state electrolytes (SSE) [8–10]. Some studies have conducted LCAs of SSB cells in laboratory conditions [10–13] where results vary according to

system boundaries, functional unit or the selected materials for the SSE and anode. More recently, one study [14] conducted a sustainability assessment of several battery technologies, considering cradle-to-gate impacts to assess environmental performance. Compared to LIBs, SSBs with the same cathode typically have less environmental impact due to lower mass per capacity, except for climate change risks linked to higher manufacturing energy and Li-metal anodes, as noted in another recent study [15].

These studies focus on manufacturing and compare LIB design options with mass production and optimized designs, but little focus is given to material sources or recycling materials, crucial for future EU LIBs under the new Battery Regulation. Few studies evaluate new battery technologies with recycled content, and the impact of sourcing strategies in SSB literature is underexplored.

2.3 Recycling Processes for CRM Recovery in Solid-State Technology

Recycling and secondary material integration can enhance supply chain security and sustainability. However, studies haven't explored their use in SSB production.

Recycling approaches for CRM recovery from SSBs are still under development, as SSB technology has not yet been fully deployed in the market. One paper proposed an approach to identify target materials for SSB recycling, highlighting strong economic and environmental benefits of recovering CRM within SSB cells [16]. Despite advances in SSB cell recycling, a key gap exists in comparing environmental impacts of cells made with primary versus recycled materials. This comparison is vital to determine if secondary materials can lower impacts while maintaining performance.

3 Methodology

The assessment of the environmental impacts associated with material sourcing in SSBs was conducted following LCA methodology [17]. The study evaluates environmental impacts of sourcing materials for an NMC811-based battery cell, with system boundaries from raw material extraction to laboratory-scale manufacturing of one solid-state monocell (functional unit). Battery developers provided inventory data on material types, quantities, origins, and transport. The assessment was modelled using Ecoinvent database V3.9.1 and the software SimaPro V9.5.0.033 [18]. The impacts were quantified and characterised using the ReCiPe 2016 Endpoint (H) v1.08 impact method [19].

4 Case Study

To assess different sourcing strategies, two scenarios for producing the SSB monocell were modelled. Scenario 1 used only primary raw materials, representing the conventional supply chain. Scenario 2 incorporated secondary raw materials from battery recycling. These scenarios explored environmental benefits and trade-offs of circular material flows, providing insights into improvements through resource recovery strategies for SSB production. The functional unit was defined as producing one SSB monocell with a NMC811 cathode, a solid polymer electrolyte, and a Li-M anode. Both scenarios assumed identical electrochemical performance, requiring identical material quantities. Due to confidentiality, the inventory details can't be shared, as it's part of the Horizon Europe project SPINMATE.

Scenario 1 used datasets for primary production to model background data on extraction and processing. In Scenario 2, due to limited harmonised LCA data on recycled materials, it was assumed that environmental impact of recycled material was proportional to its unrecovered fraction recycling. Recycling efficiencies for different recycling routes were averaged from [21], as shown in Table 1. For example, Li was assumed to bear 2% of primary Li impacts, reflecting a 98% average recovery rate. Most LIB recycling processes do not prioritize Li recovery due to lower economic incentives compared to high-value metals, such as Co and Ni. This modelling approach assumes that most of the primary extraction burdens are avoided, while recognising that impacts related to chemicals, materials, or energy consumption in recycling processes are not explicitly included. Table 1 presents the recycling considerations applied in this study. The average recycling efficiencies for each CRM are reported based on recovery rates from conventional LIBs. SSB recycling is excluded because it's assumed that during SSB production, recycling mainly involves earlier LIB generations. Recycled content incorporation aligns with Battery Regulation (BR) targets for these materials [22].

Table 1. Recycling efficiencies and BR targets, assuming Mn shares the same target as Ni

CRM	Recycling efficiency	Recycled content	Impact allocation
Lithium	98%	12%	2%
Nickel	95%	15%	5%
Manganese	74%	15%	26%
Cobalt	95%	26%	5%

The electricity mixes for manufacturing aligned with each partner's location: Spanish for cathode and cell assembly, French for electrolyte, and Belgian for anode.

The system boundaries extend from raw material acquisition to cell manufacturing (cradle-to-gate). Cell assembly includes three key steps: (i) cutting of electrodes and components, (ii) stacking layers, and (iii) sealing the cell.

The recycling datasets for Li, Ni, Co, and Mn, primarily sourced from conventional Li-ion battery recycling, serve as proxies for SSB recycling. While this presents a limitation, it offers valuable insights into how recycling could mitigate the environmental impacts of next-generation battery technologies.

5 Results

A LCA was conducted to evaluate the environmental performance of different material sourcing strategies for SSB. The findings reveal the environmental impacts of using virgin raw materials compared to integrating recycled inputs, emphasizing the benefits of incorporating secondary resources into future battery value chains. Results are presented in ecopoints through normalisation and weighting, aggregating impacts across categories into a single score. This method identifies the most environmentally harmful processes and materials, highlighting the key stages contributing to overall environmental impact.

In Scenario 1 (Fig. 1), fine particulate matter formation and global warming potential are the main impact categories, representing 94% of the environmental burden. Fine particulate matter accounted for 76%, followed by global warming (18%). Across all categories, the cutting step emerged as the dominant contributor, representing 91% of the total aggregated impacts. This outcome mainly relates to cathode production, which depends on CRMs. Ni was the most influential, followed by Co and Li.

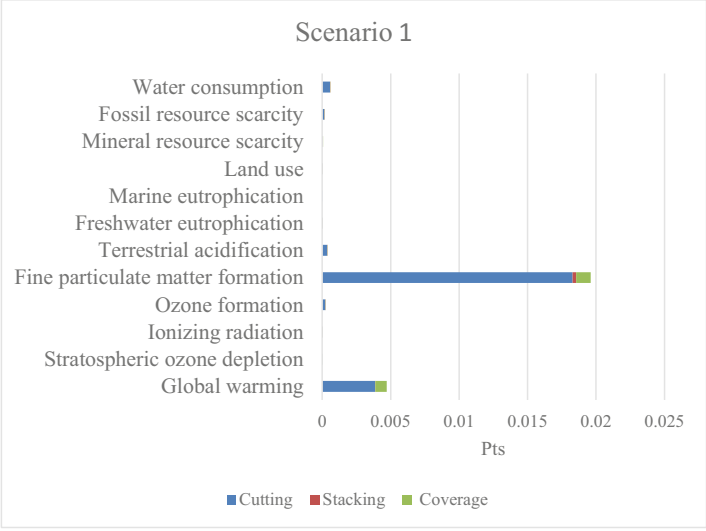


Fig. 1. Scenario 1: Cradle-to-gate LCA endpoint impacts of SSB manufacturing (one coin cell) with primary raw materials. Method: ReCiPe 2016 Endpoint (H)

In Scenario 2 (Fig. 2), fine particulate matter formation and global warming potential are the main impact categories, representing 94% of total environmental impacts: 75% and 19%, respectively. The cutting stage was the most impactful process, responsible for 90% of impacts, primarily due to cathode production (93%), which is the main hotspot because of its reliance on CRMs. Ni was the main contributor in the cathode, followed by Co and Li. These findings highlight Ni sourcing's role in environmental impact, even with recycled material inputs.

Figure 3 compares scenario 1 and scenario 2. Scenario 1 has more environmental impacts than scenario 2 (10% lower). The cutting step, especially due to cathode materials, remains the main contributor to total impacts. This shows that incorporating recycled CRMs reduces impacts, as recycled materials require less energy than extracting and refining virgin materials. Nonetheless, the targets for the recovery of CRMs under the EU BR should be higher to further reduce the impact of SSBs, and include other CRM materials, such as aluminium and copper.

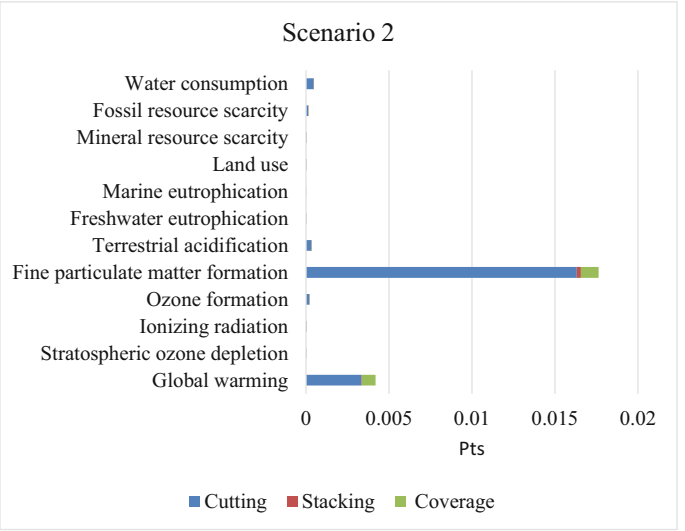


Fig. 2. Scenario 2: Cradle-to-gate LCA endpoint impacts of SSB manufacturing (one coin cell) with recycled cathode CRMs. Method: ReCiPe 2016 Endpoint (H)

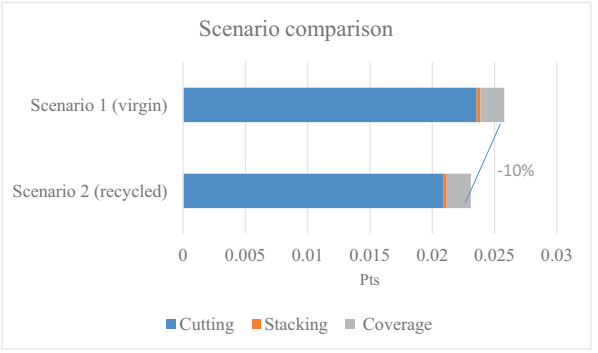


Fig. 3. LCA endpoint impact comparison between scenarios 1 and 2 for SSB manufacturing (one coin cell). Method: ReCiPe 2016 Endpoint (H)

6 Conclusions

This study assessed the environmental implications of material sourcing strategies in SSBs through a preliminary LCA, comparing a baseline scenario based solely on primary raw materials with an alternative scenario incorporating recycled content. Results indicate that using recycled CRMs can reduce overall impacts by up to 10%, with the cutting stage, with the Ni-rich cathode emerging as the main hotspot. Ni was the largest contributor, followed by Co and Li, underlining the critical role of material selection. While current Battery Regulation targets for recycled content show progress, broader, more ambitious targets for materials such as copper, aluminium, and SSE elements

would enhance environmental benefits and supply reliability. Recycling strategies should include all critical materials to maximise circularity. Although based on laboratory-scale data and battery recycling proxies, these findings provide valuable early-stage insights for SSB development. Another limitation is the simplification of environmental impacts from recycled CRMs, assuming they are proportional to unrecovered flows. While this maintains consistency, without harmonised datasets, actual recycling may be more energy - and material-intensive, increasing the environmental burdens. Future work should compare results with process-specific data to consider differences in recycling technology and its impacts on SSBs. Integrating LCA early in battery development and recycling is crucial for identifying hotspots and guiding sustainable, resource-efficient batteries.

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References

1. Schmaltz, T., et al.: solid-state battery roadmap 2035+ (2020)
2. Kampker, A., Heimes, H.H., Bernhart, W., Chan, I.: The value chain between economy and ecology (2025)
3. International Energy Agency: the role of critical world energy outlook special report minerals in clean energy (2021)
4. EU Office: Regulation (EU) 2024/1252 of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of CRM and amending (2024)
5. Hawkins, T.R., et al.: Comparative environmental LCA of conventional and electric vehicles. J. Ind. Ecol. **17**, 53–64 (2013). https://doi.org/10.1111/j.1530-9290.2012.00532.x
6. Volta Foundation: Battery Report 2024 (2025)
7. Rahimpour, S., El-Wali, M., Makarava, I., Tuomisto, H.L., Lundström, M., Kraslawski, A.: Selected social impact indicators influenced by materials for green energy technologies. Nat. Commun. **15** (2024). https://doi.org/10.1038/s41467-024-53652-0
8. Biçer, E., et al.: SSBs: chemistry, battery, and thermal management system, battery assembly, and applications-a. Crit. Rev. (2025). https://doi.org/10.3390/batteries11060212
9. Dolla, T.H., Ajayi, S.O., Sikeyi, L.L., Mathe, M.K., Palaniyandy, N.: Advances in solid-state batteries fabrication strategies for their manufacture. J. Energy Storage. **106**(1), 114737 (2025). https://doi.org/10.1016/j.est.2024.114737
10. Mandade, P., Weil, M., Baumann, M., Wei, Z.: Environmental LCA of emerging SSBs: a review. Chem. Eng. J. Adv. **13** (2023). https://doi.org/10.1016/j.ceja.2022.100439
11. Troy, S. et al.: LCA and resource analysis of ASSBs. Appl. Energy. **169**, 757–767 (2016). https://doi.org/10.1016/j.apenergy.2016.02.064
12. Schreiber, A. et al.: Oxide ceramic electrolytes for ASSBs - cost-cutting cell design and environmental impact. Green Chem. **25**, 399–414 (2022). https://doi.org/10.1039/d2gc03368b
13. Liu, Z., Li, X., Zhang, H., Huang, K., Yu, Y.: Are SSBs absolutely more environmentally friendly compared to traditional batteries-analyzing from the footprint family viewpoint. J. Clean. Prod. **447** (2024). https://doi.org/10.1016/j.jclepro.2024.141452

14. Popien, J.L., et al.: Comparative sustainability assessment of lithium-ion, lithium-sulfur, and ASS traction batteries. Int. J. Life Cycle Assess. **28**, 462–477 (2023). https://doi.org/10.1007/s11367-023-02134-4
15. Degen, F., Mitterfellner, M., Kampker, A.: Comparative LCA of Li-ion, Na-ion, and SBB cells for EV. J. Ind. Ecol. **29**, 113–128 (2025). https://doi.org/10.1111/jiec.13594
16. Kononova, N., Blömeke, S., Cerdas, F., Zellmer, S., Herrmann, C.: Identification of target materials for recycling of SSBs from environmental and economic perspective using information theory entropy. In: Procedia CIRP, pp. 185–190. Elsevier, Amsterdam (2023). https://doi.org/10.1016/j.procir.2023.02.032
17. ISO 14040:2006: Environmental management: life cycle assessment- principles and framework. Standard, International Organization for Standardization, Geneva. https://www.iso.org/standard/37456.html. Accessed 24 Feb 2026
18. PRé Sustainability: About SimaPro. Online database (2023)
19. Huijbregts, M.A.J. et al.: ReCiPe2016: a harmonised LCIA method at midpoint and endpoint level. Int. J. Life Cycle Assess. **22**, 138–147 (2017). https://doi.org/10.1007/s11367-016-1246-y
20. Iturrondobeitia, M., Vallejo, C., Berroci, M., Akizu-Gardoki, O., Minguez, R., Lizundia, E.: Environmental impact assessment of LiNi1/3Mn1/3Co1/3O2 hydrometallurgical cathode recycling from spent Li-ion batteries. ACS Sustain. Chem. Eng. **10**, 9798–9810 (2022). https://doi.org/10.1021/acssuschemeng.2c01496
21. European Parliament: Regulation (EU) 2023/1542 of the European Parliament concerning batteries and waste batteries (2023)

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Asset Management Strategy and Strategic Asset Management Plan for Motorways in Ireland

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Abstract. Transport Infrastructure Ireland (TII) applies an integrated, whole-life asset management approach to ensure the sustainable, safe, and cost-effective stewardship of Ireland's national road and light rail infrastructure. In response to increasing climate risks, asset deterioration, and funding pressures, TII has developed an Asset Management Policy grounded in a risk-based, data-driven framework that optimises performance, minimises lifecycle costs, and enhances network resilience. Central to this framework is the Strategic Asset Management Plan (SAMP) for Ireland's motorway network, which translates high-level goals into tactical and operational plans, guiding long-term planning and investment decisions. The strategy incorporates structured performance monitoring, evidence-based investment planning, and continuous stakeholder engagement to drive better decision-making. This paper examines the strategic model and demonstrates the benefits of structured long-term planning in supporting national transport objectives and European sustainability targets.

Keywords: Asset Management · Strategic Asset Management Plan · Motorway Maintenance and Renewal · Public-Private Partnership · Performance Indicators

1 Introduction

1.1 Asset Management Framework

Transport Infrastructure Ireland (TII) has established a structured hierarchy for asset management that provides a clear line of sight from policy to implementation. The Asset Management (AM) Policy sets out a commitment to managing national transport assets in a sustainable, risk-based, and data-driven manner, guided by principles of accountability, continual improvement, and evidence-based decision [1]. Building on this, the Asset Management Strategy [2] articulates how these principles translate into delivering safe, efficient, and sustainable infrastructure aligned with wider government priorities, including the National Development Plan 2021–2030[3], National Investment Framework for Transport Ireland (NIFTI) [4] and the Climate Action Plan (CAP) [5].

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The Asset Management Framework [6] operationalises this approach through eight strategic objectives: Safety, Reliability, Condition, Maximising Value, Customer, Environment, Sustainability, and Resilience. Together, they provide an overarching structure for managing performance in line with ISO 55000 principles. Within this framework, the Strategic Asset Management Plans (SAMP) review current practice, assess maturity, identify gaps, and outline improvement actions. Key performance indicators (KPIs) linked to the eight strategic objectives are identified, thereby enabling systematic monitoring of performance and demonstrating progress towards achieving strategic outcomes. The consistent implementation of KPIs establishes a robust performance system that demonstrates best practice while supporting long-term resilience and sustainability goals (Fig. 1).

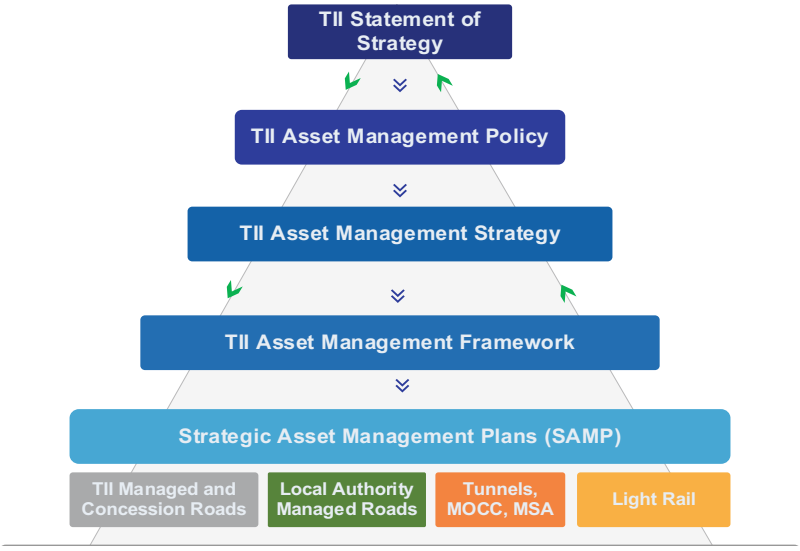


Fig. 1. TII's Asset Management Hierarchy-Line of Sight

1.2 Strategic Asset Management Plan for TII Managed and Concession Roads

TII directly manages approximately 1,350 km of motorway and dual carriageway routes, providing vital inter-urban links between major cities, ports, and airports. Designed to accommodate high traffic volumes, these assets are of recent construction and represent an estimated replacement value of over €20 billion, approximately 68% of the total national road network value. TII oversees governance and operations, with operational delivery structured through two principal contract mechanisms:

- **Motorway Maintenance and Renewals Contracts (MMaRC):** covering approximately 887 km of the network through geographically split, multi-annual regional contracts that bundle maintenance, winter service, renewals, and incident support.

- **Public–Private Partnerships (PPP):** covering 461 km across 13 schemes, under which concessionaires assume full operational and lifecycle responsibilities for periods of 25–45 years, with handback obligations at expiry.

The SAMP [7] establishes a structured approach to stewardship, reviewing the performance of existing practices, identifying gaps and improvement needs, and embedding systematic lifecycle planning. Climate adaptation and decarbonisation are treated as cross-cutting priorities, ensuring that efficient asset management not only sustains network condition but also enhances resilience and value for money in the long term.

The governance structure for TII's managed and concession road network is a three-tier hierarchy comprising TII, its appointed technical advisors, and the maintaining organisations (MMaRC contractors and PPP concessionaires). TII provides strategic direction in line with its Asset Management Policy and Framework, technical advisors deliver oversight and monitoring, and maintaining organisations manage day-to-day operations, maintenance, and renewals. TII's Network Management Division coordinates planning and delivery, supported by specialist engineering teams, overseeing both regional operations and functional asset management. TII's managed road network encompasses a wide range of motorway infrastructure assets. For management purposes, these assets are grouped into land and earthworks, pavements, structures, drainage and ducting, fencing and barriers, road lighting, traffic signs and road markings, intelligent transport systems, toll plazas and depots, winter service facilities, and staffing.

TII has developed strong asset management capability underpinned by established information systems and datasets to support evidence-based decision-making for the road network. Core systems include the Pavement Asset Management System (PAMS), based on the dTIMS platform, which stores pavement condition data and informs multi-annual rehabilitation programmes, and EIRSPAN, the bridge management system coordinating inspections, maintenance, and rehabilitation of structures. The Asset and Fault Management System (AFMS) is used to manage Intelligent Transport Systems (ITS) and other fixed infrastructures. At contract level, MMaRC and PPP operators maintain Routine Maintenance and Management Systems (RMMS) to manage asset inventories, defects, and Employer Instructed Works Orders (EIWOs). Geographic Information Systems (GIS), together with enterprise platforms such as ArcGIS Enterprise and FME Flow, support the development of a Common Asset Register (CAR) for integrated analysis and reporting. Collectively, these systems ensure consistent capture of inventory, condition, cost, and performance data across the network.

Protecting and renewing existing assets is fundamental to sustaining the long-term performance of motorway and dual carriageway network. In line with National Road 2040[8], the Climate Action Plan 2024 [9], and the National Investment Framework for Transport in Ireland [4], TII seeks to maintain the network in a steady-state condition while addressing pressures from ageing assets, increasing traffic volumes, and environmental risks. Core activities include pavement rehabilitation, bridge and tunnel maintenance, winter service, safety improvements, and the renewal of ancillary assets such as barriers, drainage, and lighting. Between 2020 and 2023, annual spending on the MMaRC networks rose from €45.6 million to €87.6 million, with pavement renewals accounting for the greatest increase. Complementing this, strategic infrastructure investment provides targeted funding for projects that extend capability and resilience beyond

steady-state maintenance. These investments encompass intelligent transport systems (ITS), climate adaptation measures, energy efficiency upgrades, and safety retrofits, with annual allocations typically ranging from €7 million to €17 million in recent years.

2 Key Performance Indicators

The workshops and focus group discussions undertaken as part of the SAMP process led to the identification of KPIs aligned with TII's eight asset management objectives. These indicators translate strategic objectives into measurable outcomes, covering both technical performance (e.g. asset condition and availability) and broader policy goals (e.g. sustainability, climate adaptation, and customer experience). While many KPIs are supported by existing data systems, others require further development, reflecting the continued maturation of asset management practice. Collectively, the KPI framework establishes a systematic basis for monitoring progress, guiding investment decisions, and demonstrating alignment between day-to-day operations and long-term strategic priorities (Fig. 2).



Fig. 2. TII's Asset Management Objectives

2.1 Asset Performance Measures

The KPIs provide a structured framework to consistently measure asset management performance across the motorway network, supporting performance assessment that

balances technical, financial, and environmental priorities in motorway management. Table 1 presents the core KPIs aligned with AM strategic objectives, ensuring consistent monitoring across managed and concession roads. Present metrics use existing data and are readily implementable.

Table 1. KPIs Aligned to Asset Management Objectives – Present and Future Metrics

Objectives	Potential Metrics and Implementation
Safety	Present: Contractor Lost Time Accident Frequency Rate, % of safety inspections and patrols carried out, Average defect repair time, Skid Resistance measurement Future: Sign Retroreflectivity
Reliability	Present: Static Lane Closures exceeding permitted times Incident response times, % of incidents responded to within target time Future: Average additional delay due to roadworks Observed and speed limit travel time difference, Freight travel time reliability % time that network is available for uncongested use
Condition	Present: Asset Condition - % in acceptable condition Pavement Surface Health, Pavement Structural Health Bridge Condition Rating, Street lighting operational % of time that roadside technology assets are available & functioning Future: VRS condition rating and defect reporting Lighting condition rating and defect reporting
Maximising Value	Present: Asset Sustainability Index – Maintenance, Asset Sustainability Index - Renewals Future: Change in Asset Value
Customer	Present: Accuracy of ITS Signage messaging % of relevant staff that have completed disability awareness training Future: Perceived quality of road maintenance, % of drivers satisfied with their journey, % nighttime works to minimise disruption to users on high volume routes
Environment	Present: Targeted reduction to grass cutting regime Compliance with maintenance of environmental noise barriers Compliance with litter collection activities Future: Strategic road network links > legal NOx limits Implement biodiversity accounting metric, No. or area of invasive alien plant species treatments required, No. of households within mitigated Noise Important Areas complying with noise requirements

The climate adaptation-focused objectives and measures, reflecting TII's proactive approach [10] to strengthening network resilience against the increasing frequency and severity of extreme events, are presented in Table 2.

Table 2. KPIs Aligned to Climate Adaptation Focused AM Objectives

Objectives	Potential Metrics and Implementation
Sustainability	**Present**: Scope 1 and Scope 2 CO2 emissions rel. to baseline % Maintenance fleet converted to EV Reduction in total energy consumed % of lighting that is LED % of water from collected rainfall CO2 emissions associated with the maintenance fleet **Future**: kWh energy generated through own renewable sources
Resilience	**Present**: Number of reported flooding incidents % winter service treatments within required timescale % carriageway length not susceptible to carriageway surface water problems **Future**: Lane Closure duration due to flooding Time to restore minimum required performance level after disruption % of investment addressing identified vulnerabilities

3 Continuing Improvement

Continuing improvement is a core principle of the SAMP [7], reflecting the need to strengthen governance, enhance data quality, and broaden the scope of practices across all asset classes. The following strategic actions are prioritised to enhance long-term asset management and resilience.

- **Adopt extended forward planning horizons:** Implement 25+ year lifecycle planning for Ireland's motorway network, which remains largely in its early–midlife stage following the 2000s investment boom. Using lifecycle optimisation models, anticipate renewal peaks affecting most assets over the next 10–20 years. Proactively manage the transition from capital expansion to preservation to sustain asset value, safety, and steady-state performance within constrained funding.
- **Integrate Climate and Sustainability Objectives:** Align implementation of SAMP with the Climate Action Plan [9] and TII's Climate Action Roadmap [10] by reducing greenhouse gas emissions and energy use across the managed and concession road network. Assess vulnerability to extreme weather and flood risk, and prioritising circular economy measures such as material reuse, energy-efficient upgrades, and biodiversity enhancements.
- **Embed tiered risk management**: Strengthen the framework to identify, assess, and mitigate network performance risks using risk registers, geospatial analysis, and scenario modelling. Prioritise interventions based on probability, consequence, and whole-life cost of failure to enhance resilience, transparency, and resource allocation.
- **Develop asset-group specific forward strategies:** Implement targeted strategies for each asset group to ensure long-term resilience and functionality. Extend pavement life through innovative and recycled materials, manage structures using lifecycle-based and probabilistic interventions while incorporating PPP handback requirements, integrate geotechnical assets into formal risk and monitoring frameworks,

optimise ITS through lifecycle reassessment, strengthen climate resilience of drainage and hidden assets, and rationalise ancillary assets through performance-based replacement and maintenance optimisation.

- **Establish an integrated asset data environment**: Address data fragmentation by strengthening inventory, condition, and performance data, supported by tools such as the Road Weather Information System (RWIS) and the National Salt Management System (NSMS) for winter services, and MapRoad AMS, managed by the Road Management Office, which stores pavement renewal as-built data. Develop a Common Asset Register (CAR), supported by enterprise GIS and FME Flow, to provide a unified repository of network-wide asset data. Collectively, these systems ensure evidence-based decisions, systematic risk management, and performance monitoring and reporting [7].
- **Embed lifecycle optimisation across all asset classes:** Apply lifecycle planning to optimise long-term investment across the network, balancing performance, cost, and risk. Using inventory and condition data from systems such as PAMS and EIRSPAN, models deterioration and identify cost-effective interventions. Inform multi-annual rehabilitation, inspections, and major works for pavements and structures, and extend this approach to ITS, drainage, and ancillary assets as data quality improves. Combining deterioration modelling with optimisation tools enables prioritisation of interventions that sustain steady-state performance, maximise long-term value, and strengthen transparency and resilience.
- **Implement PPP Handback Preparation and Planning:** The staged handback of Ireland's 15 PPP road concessions (2033–2052) presents a significant challenge for TII's asset management framework, with the M4/M6 transfer setting an important precedent. Early preparation is essential to ensure assets are returned in agreed condition through consistent standards, robust monitoring, and clear contractual arrangements. Variability across concession agreements highlights the need for common condition benchmarks. Data quality must be strengthened to support compliance. Renewal and maintenance must align with contractual obligations to mitigate financial and legal risks.

4 Conclusion and Way Forward

The SAMP for TII's managed and concession roads establishes a comprehensive framework for protecting and enhancing a €20 billion national asset base. It defines governance arrangements for MMaRC and PPP contracts, operationalises eight strategic objectives through KPIs and embeds climate adaptation and sustainability as cross-cutting priorities. Developed through workshops and expert review, the SAMP provides an evidence-based foundation for aligning asset management with national strategies. Future asset management emphasises greater consistency across asset classes, extending programmes for pavements and bridges to tunnels, ITS, and barrier systems. Key priorities include strengthening governance under the AM Framework, embedding risk management in decision-making, and building organisational capacity by upskilling teams. Operational

improvements focus on integrating additional asset types into the dTIMS system, extending forward planning horizons, and asset inventory gaps. In parallel, TII is refining its asset management objectives to emphasise sustainability, environment, resilience, and customer outcomes alongside traditional priorities of safety, condition, and value, while enhancing visibility of investment needs across all major assets.

References

1. Transport Infrastructure Ireland: TII asset management policy. Online document (2026). https://www.tii.ie/media/wbenzcxd/asset-management-policy.pdf. Accessed 1 May 2026
2. Transport Infrastructure Ireland: TII asset management strategy. Online document (2023). https://www.tii.ie/media/klxd5mt0/am-strategy-dec2021-v13-08-09-2023.pdf. Accessed 23 Sept 2025
3. Government of Ireland: Project Ireland 2040: national development plan (2021–2030). Technical Report (2021). https://assets.gov.ie/static/documents/national-development-plan-2021-2030.pdf. Accessed 1 May 2026
4. Department of Transport: National investment framework for transport in Ireland. Online document (2021). https://www.gov.ie/en/department-of-transport/press-releases/new-national-investment-framework-for-transport-in-ireland/. Accessed 23 Sept 2025
5. Government of Ireland: Climate action plan. Online document (2025). https://www.gov.ie/en/department-of-climate-energy-and-the-environment/publications/climate-action-plan/#climate-action-plan-2025. Accessed 23 Sept 2025
6. Transport Infrastructure Ireland: TII asset management framework. Online document (2023). https://www.tii.ie/media/txenraht/am-framework-v42-08-09-2023.pdf. Accessed 23 Sept 2025
7. Transport Infrastructure Ireland: Strategic asset management plan TII managed and concession road. Online document (2024). https://www.tii.ie/media/2k4lgsjo/tii-managed-and-concession-roads-issue2-07-03-2024_landscape.pdf. Accessed 23 Sept 2025
8. Transport Infrastructure Ireland, AECOM: National roads 2040 final report. Joint Report (2023). https://www.tii.ie/media/kbab00uv/nr2040-final-strategy.pdf. Accessed 23 Sept 2025
9. Transport Infrastructure Ireland: Climate adaptation strategy Transport Infrastructure Ireland. Online document (2022). https://www.tii.ie/media/bpvf2gms/climate-adaptation-strategy-2022_v2.pdf. Accessed 23 Sept 2025
10. Transport Infrastructure Ireland: Climate action roadmap. Online document (2024). https://www.tii.ie/media/se2nmhve/170724-climate-action-roadmap-2024.pdf. Accessed 23 Sept 2025

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Preparing Innovation for a Resilient Railway Transport System: Risk Management of Innovation Components

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Abstract. Innovation inherently involves risks, whether in its successful implementation or acceptance by the market. Yet, when discussing transport innovation, we often overlook the specific products, components, and materials that make up these innovations and their potential vulnerabilities. This paper explores flagship innovation programmes of Europe's Rail Joint Undertaking and presents the Map of Rail Needs 2030, a forward-looking inventory of innovation products and components essential to transforming the European rail sector by 2030. The objective is to identify not only the key technological advancements but also the underlying components and raw materials necessary for their effective deployment. Using a hypothesis-driven methodology combining programme analysis and expert interviews, the study identifies key innovation components and evaluates their exposure to supply and implementation risks. Results highlight that several enabling technologies depend on materials identified as critical or strategic in the EU's Critical Raw Materials Act. A semi-quantitative risk scoring framework is proposed to classify component vulnerabilities and support proactive supply-chain risk management. The proposed framework contributes to bridging innovation policy and material risk management by providing a practical tool for anticipating resource constraints and strengthening the resilience of the European rail innovation ecosystem.

Keywords: risk management · supply chain resilience · innovation · rail · Europe's Rail joint undertaking

1 Introduction

Innovation is widely recognised as the driving force behind the transformation of Europe's railway system into a more sustainable, efficient, and competitive mode of transport. However, innovation inherently involves risks, both in terms of successful technical implementation and market acceptance. In the railway sector, where safety, reliability, and interoperability are crucial, these risks are particularly significant. While

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much of the debate focuses on system-level challenges, the specific products, components, and raw materials that underpin these innovations are often overlooked. This omission creates blind spots in risk assessment, leaving potential vulnerabilities in supply chains, material sourcing, and technology readiness insufficiently addressed.

The Europe's Rail Joint Undertaking (EU-Rail) has launched a set of flagship projects (FPs) [1] that aim to transform the European rail system by 2030. Within this framework, the LEADER 2030 project [2] has produced a forward-looking inventory, the Map of Rail Needs 2030, identifying innovations, key components, raw materials identified as critical or strategic in the EU's Critical Raw Materials Act (CRMA) [3] and that are likely to shape the sector in the coming decade. This paper builds on that mapping exercise to highlight risks at the component level, with the objective of supporting better risk management and resilience of the rail sector.

The scope of this study is limited to the innovations explicitly outlined in the strategic and operational documents of EU-Rail, with particular emphasis on their material and component dependencies. While software and digital services are acknowledged as critical enablers, the analysis concentrates on hardware and tangible inputs, as these pose the greatest challenges in terms of sourcing and long-term resilience.

2 Framework: Europe's Rail Joint Undertaking

The EU-Rail is the European Union's main public–private partnership for rail research and innovation. Its mission is to deliver a radically transformed, sustainable, and competitive railway system that supports the objectives of the European Green Deal and the Single European Railway Area (SERA). By combining technological development with systemic integration, EU-Rail seeks to accelerate the uptake of innovations such as ERTMS Level 3, Digital Automatic Couplers, hydrogen and battery trains, and intelligent asset management, thereby strengthening rail's role as the backbone of a decarbonised European mobility system.

For the purpose of this study, we have examined in detail all EU-Rail Flagship Areas (FA) and their dedicated FPs, which are organised around the following thematic domains listed below.

- FA1 (MOTIONAL – Mobility Management in a Multimodal Environment and Digital Enablers) aims to improve strategic and tactical planning of the rail network, enhance resilience in real-time operations, and integrate rail services within multimodal mobility. Its cornerstone innovation is ERTMS Level 3.
- FA2 (R2DATO – Rail to Digital Automated up to Autonomous Train Operations) develops the technologies required for digital and autonomous train operations, centred on advanced Automatic Train Control (ATC) and ERTMS/ETCS standards. Core innovations include ATP, ATS, ATO, and moving block operations enabled by ERTMS Level 3, supported by next-generation communications such as 5G, FRMCS, and V2X.
- FA3 (IAM4RAIL – Intelligent and Integrated Asset Management) focuses on optimising the lifecycle and performance of railway assets through a comprehensive Integrated Asset Management System (IAMS). FP3 aims to reduce lifecycle costs, improve reliability, and enable sustainable and efficient asset management.

- FA4 (RAIL4EARTH – Sustainable and Green Rail Systems) targets decarbonisation and energy efficiency, promoting green propulsion, circular economy solutions, and healthier, more attractive rail systems. Innovations include hydrogen propulsion, battery storage, smart grids, modular stations, and sustainable HVAC systems.
- FA5 (TRANS4M-R – Transforming Europe's Rail Freight) is dedicated to enhancing the competitiveness and sustainability of rail freight through digitalisation, automation, and green technologies. Its central innovation, the Digital Automatic Coupler (DAC).
- FA6 (FUTURE – Innovative Rail Services to Revitalize Capillary Lines and Regional Rail Services) addresses the revitalisation of regional and low-density lines through cost-efficient, modular, and zero-emission solutions.
- FA7 (PODS4RAIL – New Approaches for Guided Transport Modes) explores disruptive approaches for next-generation guided transport, focusing on flexible, energy-efficient, multimodal, and high-speed systems. Building on technologies from other flagship areas.

3 Methodology

The methodological framework adopted in this study is hypothesis-driven and structured to align with the EU-Rail Master Plan and Multi-Annual Work Programme while embedding a risk-management perspective. A sequential analysis was carried out across all seven FAs, extracting the technological intelligence relevant for enhancing each FP. For every innovation pathway, the associated products, components, and sub-components were mapped, with attention to both functional outputs (e.g., digital signalling, propulsion) and their material underpinnings (e.g., semiconductors, rare earth magnets, battery-grade lithium). The analysis systematically cross-checked these needs against documented past or ongoing disruptions, enabling the identification of potential vulnerabilities. In parallel, technologies likely to reach obsolescence by 2030 were flagged to support transition planning. The methodology also included the specification of implementation timelines and the prospective evaluation of criticalities (e.g., TRL maturity, sourcing risks, supply concentration). This provided robust evidence base for generating recommendations aimed particularly at suppliers and SMEs, emphasising strategies for supply chain diversification, material substitution, and resilience-building across the innovative ecosystem. This methodology ensured that the analysis was not only technology-driven but also attentive to vulnerabilities in supply chains and material dependencies.

Besides these two phases—sequential analysis and desk research—focus group interviews were conducted with industry experts and the leaders of FPs. The total sample consisted of 32 experts, including 4 coordinators of FPs, 4 coordinators of exploratory projects, and 24 experts representing major stakeholders in the rail industry. The interviews were conducted over a six-month period, from May – Novembre 2024. These interviews not only validated the desk research findings but also provided additional insights and real-world perspectives.

This framework enabled a forward-looking mapping of material needs and risks up to 2030. The results show that while some flagship technologies may achieve TRL9 by 2031, others (notably FP6 and FP7) may struggle to exceed TRL7. Stakeholder

consultations further stressed the importance of relying on Commercial-Off-The-Shelf (COTS) solutions to mitigate supply chain risks and ensure resilience, although also COTS can be subject to dependencies and disruptions, hence not always available.

4 Findings – Map of Rail Needs 2030

The Map of Rail Needs 2030 confirms that Europe's railway transformation relies on a concentrated set of innovative products and components. These span digital systems such as ERTMS Level 3 and Automatic Train Control (FP1, FP2), asset monitoring platforms like Integrated Asset Management System – IAMS - (FP3), green propulsion technologies (hydrogen fuel cells, batteries, smart grids in FP4), freight enablers such as the Digital Automatic Coupler (DAC) (FP5), and modular, zero-emission rolling stock (FP6). At the frontier, disruptive solutions such as pods, maglev, and vacuum-tube systems (FP7) extend this innovation pathway.

Table 1. Short Summary of Technology and Material Disruptions

FP	Technology Disruptions (Hardware)	Software Disruptions	Key Material Disruptions
FP1	GNSS, IMU, High-Frequency Antennas, Firewalls	Positioning, Analytics, Cybersecurity	GaAs, Cu, Au, Si
FP2	AI Systems, LIDAR, RADAR, Edge Computing	AI GoA4, Predictive Maintenance, Digital Twins	REEs, GaN, Reduced Steel
FP3	IoT Sensors, Centralized Hubs	AI Analytics, IoT Frameworks	Lightweight Alloys, Si, Pt
FP4	Regenerative Braking, Traction Systems, Batteries	Energy Management Systems	Li, Co, Rare Earth Magnets
FP5	Automated Systems, Modular Carriages, RFID	Freight Management, Predictive Logistics	Al, Cu, Reduced Iron
FP6	Modular Rail Systems, Compact Units	Optimization Algorithms, Scheduling Platforms	Ti, CFRP, Reduced Cast Iron
FP7	Modular Pods, Autonomous Navigation Systems	Self-Adaptive Navigation, Experience Platforms	Al-Li, Advanced Polymers

The mapping of these products to raw material needs shows that a narrow set of critical raw materials (CRMs) underpins most flagship projects. The short summary of technologies and material disruptions is presented in Table 1. The analysis applied a sequential approach by FP, ensuring that each innovation and its associated raw materials were considered separately. Desk research on the EU-Rail Master Plan and MAWP was complemented by focus group interviews with industry experts and FP leaders, validating findings and adding practical insights. The specific hypotheses for analysing criticalities were structured around three main steps:

1. Identify trends in raw material use (increased vs. stable).
2. Assess technology readiness (TRL levels from the EU-Rail MAWP, 2022).
3. Determine overall criticality by combining demand trends, TRLs, and the Critical Raw Materials Act (CRMA, 2024). The criticality of raw materials is linked to potential bottlenecks in their supply chains. In this analysis, criticality is assessed based on two elements: (i) the technological requirements for raw materials associated with the analysed innovations and (ii) the expected timeline for the deployment of these technologies, which determines the actual supply risk.

4.1 Hypotheses

- **H1: Technology readiness**. TRL levels from EU-Rail MAWP (2022) were used as the benchmark, assuming they represent the minimum readiness achieved by 2030. The likelihood of implementation was modelled through three qualifiers:

  - High likelihood → technology commercialised by 2030 (TRL 9 by 2027).
  - Moderate likelihood → technology reaching prototype stage by 2030 (TRL 7 foreseen by 2027 in EU-Rail MAWP).
  - Low likelihood → technology at best demonstrated by 2027 (TRL 6).

- **H2: Raw material criticality**. Criticality was aligned with the CRMA list (2024).
- **H3: Overall criticality.** Defined by combining material demand, TRL likelihood, and CRMA status, with four categories: Very High, High, Moderate, Low.

  - Very High criticality:

    - Raw material with increased usage and on the CRMA list.
    - Technology has a High likelihood of implementation by 2030.

  - High criticality:

    - Raw material with increased usage and on the CRMA list.
    - Technology has a Moderate to High likelihood by 2030.

  - Moderate criticality (three cases):

    - Increased usage + on CRMA list + Moderate to Low likelihood, or
    - Stable usage + on CRMA list + High likelihood, or
    - Stable usage + not on CRMA list + Moderate to High likelihood.

  - Low criticality (three cases):

    - Increased usage + on CRMA list + Low likelihood, e.g., FP2 V2X (TRL 8 by 2027, only for GoA2), or
    - Stable usage + not on CRMA list + Moderate to Low likelihood, or
    - Stable usage + on CRMA list + High likelihood.

These hypotheses enabled us to focus on the most impactful elements of each innovation, optimising the analysis for clarity and relevance. A synthesis of the findings is presented in Table 2, where frequency refers to the number of occurrences of a given material in the components associated with the analysed innovation.

Table 2. Synthesis of the results

Material	FRQ	Likelihood of Use	Criticality	Flagship Projects (FPs)
Silicon (Si)	526	High	Moderate (semiconductor dependency)	FP1 MOTIONAL, FP2 R2DATO, FP3 IAM4RAIL
Platinum Group Metals (PGMs)	414	Medium	High (fuel cells, hydrogen catalysts)	FP4 RAIL4EARTH
Aluminum (Al)	367	High	Moderate (lightweight structures, wiring)	FP6 FUTURE, FP4 RAIL4EARTH
Cobalt (Co)	322	High	High (batteries, energy storage)	FP4 RAIL4EARTH, FP5 TRANS4M-R, FP6 FUTURE, FP7 PODS4RAIL
Copper (Cu)	220	High	High (electrification, motors, wiring)	FP5 TRANS4M-R, FP4 RAIL4EARTH, FP6 FUTURE
Steel (St)	120	Very High	Low–Moderate (rails, rolling stock, DAC)	FP5 TRANS4M-R, FP6 FUTURE
Rare Earth Elements (Nd, Dy)	80	High	Very High (magnets, sensors)	FP1 MOTIONAL, FP2 R2DATO, FP3 IAM4RAIL
Nickel (Ni)	60	High	High (battery cathodes)	FP4 RAIL4EARTH
Lithium (Li)	55	High	Very High (battery storage)	FP4 RAIL4EARTH, FP6 FUTURE
Gallium (Ga)	35	Medium	High (semiconductors, GNSS chips)	FP1 MOTIONAL, FP2 R2DATO

The results show that semiconductors (silicon, gallium) are central to FP1–FP3 innovations; battery and hydrogen technologies (lithium, cobalt, nickel, PGMs) dominate FP4 and are fundamental for FP5-FP7; structural enablers (aluminium, copper, steel) are spread across FP4–FP6; and rare earth elements are indispensable for FP1–FP3.

5 Risk Analysis

The analysis of the EU-Rail Master Plan and Multi-Annual Work Programme reveals a set of core innovation products and components that underpin Europe's railway transformation to 2030. Across the seven Flagship Areas and their respective Flagship Projects, several recurring technologies emerge as essential. ERTMS Level 3 is central to both network management (FA1) and automation (FA2), requiring advanced signalling equipment, on-board units, and resilient communications infrastructure. Automatic Train Control (ATC) and related systems (ATO, ATP, ATS) depend on high-performance computing and sensor platforms. On the asset side, Integrated Asset Management Systems (IAMS) (FA3) are enabled by IoT sensors, predictive monitoring devices, and digital twins. Green technologies (FA4) introduce components such as hydrogen fuel cells, lithium-ion battery modules, and smart energy grids, while freight innovation (FA5) centres on the Digital Automatic Coupler (DAC), electronically controlled braking systems, and telematics devices. Regional revitalisation (FA6) calls for light zero-emission rolling stock and modular stations, and disruptive guided transport (FA7) incorporates pods, maglev, and vacuum-tube infrastructure. Together, these components represent the building blocks of Europe's rail innovation ecosystem.

Mapping these products to their raw material requirements highlights strong dependencies on a limited set of CRMs. Electronics and digital systems (ERTMS, ATC) rely heavily on silicon, gallium, and copper, while permanent magnets for automation and propulsion require rare earth elements (neodymium, dysprosium, terbium). Energy storage and green propulsion systems demand large volumes of lithium, cobalt, and nickel, alongside platinum group metals for hydrogen fuel cells. Lightweight structures, modular stations, and vehicle bodies are dependent on aluminium and advanced alloys. These dependencies are not evenly distributed: for instance, FA2 and FA5 are particularly exposed to rare earth elements, while FA4 relies on battery and hydrogen-related materials. The Map of Rail Needs 2030 thus underscores the concentration of innovation pathways around a small number of strategically sensitive resources.

The reliance on these critical materials introduces three major categories of risk. First, technological risks arise from uncertainties around the maturity and scalability of key innovations, such as the readiness of ERTMS Level 3 or the large-scale deployment of hydrogen trains. Second, sourcing risks reflect the vulnerabilities of global supply chains: materials such as lithium, cobalt, and rare earth elements are geographically concentrated, with few suppliers and high volatility in price and availability. Third, geopolitical risks stem from Europe's reliance on imports from politically sensitive regions (e.g., cobalt from the Democratic Republic of Congo, rare earths from China, nickel from Russia), which may threaten continuity of supply. Taken together, these risks pose a challenge to the resilience of Europe's rail innovation programme. Addressing them requires proactive risk management strategies, including diversification of supply, recycling and circular economy approaches, and coordinated European action to secure access to critical resources.

6 Discussion and Conclusion

The results underscore the importance of aligning technological innovation with risk management strategies. By focusing on components and raw materials, this approach reveals vulnerabilities that could undermine the resilience of the European rail sector if not addressed proactively.

- For policy, implications include the need for an EU-level strategy on critical materials, incentives for circular economy solutions (reuse, recycling, substitution), and stronger collaboration with industry to secure supply chains.
- For industry stakeholders (OEMs, Tier 1/2 suppliers, SMEs), the mapping highlights both risks and opportunities: the chance to anticipate bottlenecks, diversify sourcing, and invest in resilient designs that reduce reliance on scarce materials.

Innovation in the rail sector is essential but must be pursued with an awareness of the risks inherent in its components and materials. The Map of Rail Needs 2030 provides a tool to anticipate these risks and guide strategic decisions.

Embedding risk management at the component level will help ensure that the ambitious objectives of the EU-Rail are met, while supporting supply chain resilience, strategic autonomy, and the broader goals of decarbonisation and digitalisation.

Future work should refine risk indicators, strengthen cooperation across industrial ecosystems, and maintain continuous monitoring of vulnerabilities as innovations mature toward 2030.

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References

1. Europe's Rail: Europe's Rail key documents. Online document. https://rail-research.europa.eu/about-europes-rail/europes-rail-reference-documents/europes-rail-key-documents/. Accessed 25 Mar 2026
2. European Parliament, Council of the European Union: Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (2024)
3. European Rail Clusters Initiative: EU-Rail project, LEADER2030. Online document. https://www.eurailclusters.com/erci_project/leader-2030. Accessed 3 Apr 2026
4. Carrara, S., et al.: Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – a foresight study. Technical Report, Publications Office of the European Union, Luxembourg, JRC132889 (2023). https://doi.org/10.2760/386650

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Methodological Framework for Energy - and Resource-Efficient Public Transport: The E-MED Project

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Abstract. The E-MED project is a Euro-MED initiative that aims to improve the energy and resource efficiency of public transport systems in Mediterranean cities through the development and validation of a structured set of tools and methodologies. These are grouped into three categories: (i) planning tools supporting decisions on network and fleet configuration, charging strategies, and integration of renewable energy sources; (ii) operational tools focused on eco-driving and analytical methods for energy consumption optimisation; and (iii) procurement-guided tools addressing sustainable and circular practices, including lifecycle-based procurement, battery reuse, rainwater harvesting, and tyre maintenance. The tools are tested through pilot applications and feasibility studies in cities such as Thessaloniki, Maribor, Lisbon, Bergamo, and Barcelona. The paper presents the methodological framework and structure of the developed tools, along with their implementation across different urban contexts. Emphasis is placed on the planning tool developed by CERTH for public transport network redesign. This tool supports the adaptation of bus routes to new vehicle technologies, additional public transport modes (e.g. tram, metro), and soft mobility. It applies operations research techniques to assess network modifications using indicators such as coverage, travel time, and environmental metrics, to support energy-efficient planning scenarios.

Keywords: planning tool · decision support · public transport · network redesign · energy-efficient planning scenarios

1 Introduction

Mediterranean cities face a dual challenge of rapid urbanisation and high vulnerability to climate change. The Mediterranean basin has experienced a temperature increase of 1.5–4 °C over the twentieth century, and motorisation rates in the region exceed the EU average, contributing to elevated greenhouse-gas emissions [1]. Transport emissions represent roughly 23% of global energy-related CO_2 emissions, and buses alone can

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account for up to 34% of vehicle emissions. Electrifying public transport holds substantial potential to mitigate urban air pollution; studies show that a complete transition of bus fleets to electric power may require more than 200 GWh of additional electricity depending on city size [2]. Economic analyses further indicate that electric buses are not always cost-optimal under volatile electricity prices, highlighting the need for planning tools that balance environmental benefits, operational costs, and service quality [3]. The European Green Deal and the EU Sustainable and Smart Mobility Strategy call for modal shifts, digital optimisation, and zero-emission mobility to be integrated into urban planning [4].

Research on the Transit Network Design Problem (TNDP) provides valuable foundations for this transition. Early work concentrated on single-mode bus systems, and more recent reviews underline the hierarchical nature of network planning and call for integrated approaches that reflect multimodality [5]. Current studies stress the importance of combining buses with tram, metro, micromobility, and demand-responsive services, while noting that data-driven optimisation tools remain limited. Metaheuristic techniques such as evolutionary algorithms and simulated annealing have proven effective for multi-objective optimisation [6], but many existing frameworks treat new modes or technologies as external factors without fully exploiting real-time data or system complementarities [7].

Alongside structural redesign, operational strategies such as eco-driving have demonstrated significant efficiency gains. Eco-driving approaches combine predictive algorithms, adaptive speed control, and vehicle–infrastructure communication to lower energy uses. Reviews on connected and automated vehicles further highlight how real-time feedback and advanced control methods significantly decrease fuel use and improve safety [12]. Practical applications confirm these benefits: in one case, eco-driving training reduced fuel consumption by nearly 12% with corresponding CO_2 reductions [8]. Further experiments suggest that optimal speed-change patterns can reduce energy consumption by 10–20% while maintaining service quality [9], and multi-objective optimisation models for electric vehicle platoons based on deep reinforcement learning illustrate the potential of advanced control strategies [13]. Comparative assessments also reveal that energy efficiency in electric buses is significantly influenced by acceleration behaviour, route gradient, and regenerative braking [10].

Despite this growing body of work, there is a clear gap in integrated tools that bring together planning, operation, and procurement. Existing studies tend to address these dimensions in isolation and rarely account for the socio-spatial specificities of Mediterranean cities, such as dense historical centres, seasonal demand fluctuations, and limited public budgets [11]. The E-MED project responds to this gap by developing a structured suite of complementary tools aimed at improving energy and resource efficiency of public transport across Mediterranean cities. Funded by the Interreg Euro-MED programme, it brings together transport authorities, research institutions, and industry partners to test solutions in pilot cities including Thessaloniki, Maribor, Lisbon, Bergamo, and Barcelona.The project makes two key contributions: it proposes an integrated framework bridging planning, operational, and procurement dimensions that existing literature tends to address in isolation, and it presents a network redesign tool that jointly accounts for multimodal complementarity and zero-emission vehicle constraints within

a single optimisation framework. The following sections describe the E-MED toolkit, detail the methodology of the CERTH planning tool, discuss preliminary results, and outline future research directions.

2 Methodology

2.1 Overview of the E-MED Toolkit

The methodological framework of E-MED is structured around three categories of solutions (planning, operational, and procurement) each targeting a different dimension of the transition towards energy - and resource-efficient public transport. The design principle is complementarity: planning modules provide the analytical basis for restructuring networks and selecting technologies; operational modules ensure services are delivered efficiently; and procurement modules embed sustainability principles into investment and maintenance cycles.

Planning tools support strategic and tactical decisions on network and fleet configuration, charging infrastructure, and energy sources. Key components include:

- **PuT Design Optimization (OptiPuT):** A web-based optimization tool that allows operators to redesign bus networks for zero-emission fleets by employing a network optimization algorithm. The tool builds on the existing public transport network, making changes to enhance mode complementarity and electrification feasibility, balancing user, operator and environmental costs. It will be validated in Thessaloniki, Maribor and Lisbon.
- **Bus Fleet Planning:** Optimises electric bus fleet assignment per route: vehicle scheduling, charging strategy, and depot management. It will be validated in Thessaloniki, Maribor and Bergamo.
- **PuT Network and Scheduling Design:** Supports network-level scheduling decisions to ensure service reliability and efficient fleet deployment. It will be validated in Maribor, Thessaloniki and Lisbon
- **Bus Garage Charging Management:** Plans and optimises e-charging operations at depots, including scheduling of charging sessions and accounting for energy cost. Barcelona, Lisbon and Bergamo

Operational tools focus on energy-efficient operation, including eco-driving training programmes with personalised driver feedback, and AI-based analytics for predicting energy consumption and optimising speeds and schedules**.**

Procurement and resource-efficiency tools provide guidelines and feasibility studies for sustainable procurement, covering battery reuse, rainwater harvesting, tyre maintenance, and circular practices, aimed at extending vehicle lifecycles and reducing resource consumption.

2.2 Methodological Integration

The methodological framework does not treat these outputs as stand-alone deliverables. Instead, they are designed to interact: planning tools define scenarios of network and fleet

adaptation, operational tools test and refine these assumptions under real conditions, and procurement tools and feasibility studies provide mechanisms to lock in gains through sustainable investment strategies. For example, redesigning a bus network using zero-emission vehicles requires charging infrastructure that can be supported by renewable energy (studied through depot PV generation), efficient driving practices to minimise consumption, and procurement processes that ensure cost- effective adoption of batteries and vehicles.

Within this integrated approach, planning plays a pivotal role because it establishes the structure on which operational and procurement decisions depend. To illustrate the methodological depth of the E-MED framework, the following subsections present in detail the bus route-layout design tool developed by CERTH, which serves as a representative example of the overall approach.

2.3 Data and Inputs for the Planning Tool

The CERTH network redesign tool integrates multiple data streams to create a comprehensive representation of the transit system:

General Transit Feed Specification (GTFS) Feeds: These describe existing routes, stops, schedules and frequencies. They serve as the basis for generating initial solutions and evaluating service levels.

Origin–Destination Matrices: Derived from smartcard data, travel surveys or synthetic gravity models, these matrices represent trip demand between zones and are disaggregated by trip purpose and user category.

Analysis Zone Shapefiles: Zone geometries link OD demand to the bus network by associating each zone with the stops it contains, while zone-to-zone car travel times serve as the benchmark against which public transport performance is evaluated.

Vehicle Specifications: Passenger capacity and vehicle shape determine peak hour fleet requirements per route, while fuel type and battery capacity are used to assess electric range feasibility against each route's length and duty cycle.

2.4 Optimisation Framework

The tool employs a hierarchical optimisation framework inspired by state-of-the-art transit network design research. The process comprises of two phases:

1. **Scenario definition.** Planners specify modifications reflecting new modes (e.g., metro or tram lines), vehicle technologies (e.g., electric buses). A number of user parameters can be set, including the area of analysis and service parameters for the network (e.g., bus load factor).
2. **Optimisation algorithm.** A Monte Carlo optimisation algorithm iteratively modifies a candidate bus network initialised from the existing GTFS network. New routes are generated via shortest-path and deviation-based construction between terminal clusters derived from the existing GTFS, grounding the search space in operational reality. Each candidate solution encodes stop sequences for all bus routes; service

frequencies and fleet assignments are derived during evaluation based on simulated passenger loads and available fleet capacity. A multimodal graph is constructed for each candidate solution, integrating bus, metro, and walking edges with transfer penalties for mode change. To evaluate each solution, all OD pairs within the study area are simulated on the multimodal graph using shortest-path routing, recording average travel time, trip completion rate, and transfer frequency. Candidates are scored using a multi-objective fitness function balancing demand satisfaction, average travel time, fleet utilisation, and CO_2 emissions. Modifications are accepted or rejected based on a Monte Carlo criterion, with a controlled probability of accepting worse solutions to avoid local optima. The algorithm terminates after a predefined number of iterations, returning the highest-scoring solution.

The framework introduces two methodological contributions. First, fleet electrification is integrated within the network optimisation loop: electric vehicle range sufficiency is enforced as a hard constraint at every fitness evaluation, while CO_2 emissions from both electric and diesel operations are included in the fitness function, allowing joint optimisation of network topology, electrification deployment, and environmental impact. Second, the multimodal graph explicitly models bus–metro complementarity, incorporating transfer penalties between bus stops and metro stations. Metro edges are assigned lower weights reflecting higher speed and reliability, naturally shifting simulated passengers towards metro where available and incentivising bus network configurations that maximise feeder connectivity.

2.5 Implementation

The CERTH tool is implemented as a web-based application. Users can visualise the current and optimised bus network, highlighting retained, scrapped and newly introduced routes, and can inspect operational details per route including frequency, recommended vehicle type, electric suitability and road topology. The tool outputs alternative network designs along with passenger, fleet and environmental performance indicators, enabling planners to compare the original and optimised network and select the most appropriate design.

The overall process for a planner to generate an optimal solution is:

3. Data input: Upload GTFS data, OD matrix, zone shapefiles, and fleet specifications, metro line definitions can be provided to introduce new rail infrastructure into the optimisation scenario.
4. Optimisation: Configure parameters such as geographic bounds and bus load factor, and select an optimisation level from shallow (fleet allocation only) to deep (extensive network reconfiguration).
5. Comparison: Planners compare the original and optimised networks using a dashboard displaying route-level changes and aggregated metrics covering passenger service, fleet utilisation, and CO_2 emissions.
6. Export: The optimised network can be exported as GTFS data for direct use in transport planning workflows

3 Results

The E-MED project is currently in the development phase, and the results that can be discussed at this stage relate primarily to the expected outputs and their anticipated contribution to more sustainable urban transport systems. The tools being prepared are designed to address complementary dimensions of planning, operation, and procurement, and their combined application is expected to provide a coherent framework for energy and resource efficient mobility in Mediterranean cities.

The planning suite consists of three complementary tools addressing network design, vehicle technology, and operational reliability. The bus route-layout design tool developed by CERTH will be applied in Thessaloniki to test scenarios that compare the current bus system, a business-as-usual case including the new metro and electric buses, and optimised configurations generated by the model. The optimisation process, based on Monte Carlo algorithms, is expected to propose networks with stronger connections to metro stations, extended coverage of peripheral areas, and reduced overlap between bus and metro services, while maintaining acceptable travel times. Performance of the tool will be assessed through three categories of quantifiable indicators.

Network-level indicators include vehicle-kilometres, a time efficiency index expressed as the ratio of public transport to car travel time per OD pair, and demand coverage measured as the share of OD pairs successfully completed within the transfer limit. Passenger-level indicators decompose individual journeys into average time in bus, average time in metro, average waiting time, average walking time, and the distribution of transfers per trip, providing a disaggregated view of service quality across the network. Environmental indicators include daily energy consumption, daily diesel fuel consumption, tank-to-wheel CO_2 emissions for diesel buses, well-to-tank CO_2 emissions for electric buses, total CO_2 emissions, percentage of electrified routes, The two other planning tools complement this approach. The powertrain identification tool (IDIADA) will recommend propulsion technologies for different routes based on distance, gradient, and operating conditions. The reliable bus control tool (University of Maribor) will address technical constraints associated with electric fleets.

On the operational side, eco-driving support systems will provide guidance on speed and acceleration profiles, with analytical platforms for monitoring and forecasting energy consumption, expected to demonstrate measurable reductions in energy use. In the procurement stream, lifecycle-based approaches focus on total cost of ownership, battery reuse frameworks, predictive tyre maintenance, and rainwater harvesting. Pilots in cities such as Maribor will examine feasibility within existing procurement procedures, with the expected outcome being transferable guidelines that embed circularity into procurement decisions.

The overall result is therefore an integrated framework rather than a collection of stand-alone tools, with the CERTH bus route-layout tool providing the analytical foundation linking planning scenarios with the complementary contributions of the other tools.

4 Conclusion

The E-MED project offers a comprehensive framework for supporting the energy and resource transition of public transport systems in Mediterranean cities. The project develops complementary planning, operational and procurement tools, and validates them in diverse pilot contexts, addressing the interconnected challenges of network design, energy management and sustainable procurement. The public transport network redesign tool developed by CERTH stands out as a key component: it integrates standardized data inputs and hierarchical optimization to generate bus networks compatible with new modes and vehicle technologies. Though still in development, the tool's methodology, combining scenario definition, multimodal network simulation, and Monte Carlo optimization, illustrates a promising path toward data-driven, energy-efficient public transport planning. Future research will focus on full pilot deployment, integration with operational and procurement tools, and expansion of the framework to include additional modes and resilience considerations.

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References

1. Guida, C., Gargiulo, C., Papa, R., Carpentieri, G.: Vulnerability and exposure of Mediterranean coastal cities to climate change-related phenomena. In: Proceedings of the EWaS5 International Conference. MDPI, Basel, p. 79 (2022). https://doi.org/10.3390/environscipproc2022021079
2. Miraftabzadeh, S.M., Ranjgar, B., Niccolai, A., Longo, M.: Comparative analysis of sustainable electrification in Mediterranean public transportation. Sustainability. **16**, 2645 (2024). https://doi.org/10.3390/su16072645
3. Carteni', A.: A cost-benefit analysis based on the carbon footprint derived from plug-in hybrid electric buses for urban public transport services. Online document (2018)
4. European Commission: Sustainable and Smart Mobility Strategy – putting European transport on track for the future (2020)
5. Elbert, R., Müller, J.P., Rentschler, J.: Tactical network planning and design in multimodal transportation – a systematic literature review. Res. Transp. Bus. Manag. **35**, 100462 (2020). https://doi.org/10.1016/j.rtbm.2020.100462
6. Hu, J., Shi, X., Song, J., Xu, Y.: Optimal Design for Urban Mass Transit Network Based on Evolutionary Algorithms. Advances in Natural Computation, Lecture Notes in Computer Science., pp. 1089–1100. Springer (2005). https://doi.org/10.1007/11539117_148
7. Saber, M., Abdelhamid, A.A., Ibrahim, A.: Metaheuristic optimization review: algorithms and applications. J. Artif. Intell. Metaheuristics. **3**(1), 21–30 (2023). https://doi.org/10.54216/JAIM.030102
8. Basaric, V., et al.: Positive effects of eco-driving in public transport: a case study of the City Novi sad. Therm. Sci. **21**, 683–692 (2017). https://doi.org/10.2298/TSCI150219160B
9. Fang, Y., et al.: Speed change pattern optimization for improving the electricity consumption of an electric bus. World Electr. Veh. J. **15**, 16 (2024). https://doi.org/10.3390/wevj15010016
10. Sun, S., et al.: Powering up urban mobility: a comparative study of energy efficiency in electric and diesel buses across various lane configurations. Sustain. Cities Soc. **101**, 105086 (2024). https://doi.org/10.1016/j.scs.2023.105086

11. Soygür, A., Doratlı, N.: Rethinking local development in small-scale Mediterranean cities. Sustainability. **17**, 7899 (2025). https://doi.org/10.3390/su17177899
12. Li, J., Fotouhi, A., Liu, Y., Zhang, Y., Chen, Z.: Review on eco-driving control for connected and automated vehicles. Renew. Sust. Energ. Rev. **189**, 114025 (2024). https://doi.org/10.1016/j.rser.2023.114025
13. Zhang, Y., et al.: Multi-objective optimization of vehicle-following control for connected electric vehicles based on deep deterministic policy gradient. SAE Int. J. Elec. Veh. **13**, 79–91 (2023). https://doi.org/10.4271/14-13-01-0006

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Delays, Dependencies, and Development: Exploring Circular Aggregate Use Through the Lens of Lateness of Action in Swedish Construction

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Abstract. Circular economy (CE) principles offer promising pathways for reducing emissions and improving resource efficiency in construction, particularly through the reuse of aggregates. Despite technical feasibility, circular aggregate use remains limited in Sweden due to fragmented planning, regulatory barriers, and weak coordination among actors. This paper explores how delays in early-stage planning hinder downstream circular practices, using the Swedish Transport Administration (STA) and its megaproject Ostlänken as a case study. The research adopts a systems perspective and combines conceptual analysis with insights from a multi-stakeholder workshop involving STA and a County Administrative Board (CAB). Findings reveal that circular aggregate management is often deprioritized in early planning phases and delegated to later stages, where reuse opportunities are constrained by risk aversion, unclear guidelines, and information asymmetry. The mismatch in planning horizons between STA and municipalities further complicates coordination. While STA has developed overarching strategies, implementation varies across projects, and regional actors are rarely involved. The study highlights the need for synchronized planning, improved logistics, and coherent policy implementation. It concludes by recommending stronger regional coordination and clearer role definitions to support circular aggregate flows, especially in contexts where material abundance undermines reuse motivation.

Keywords: Circular economy · Urban planning · Interorganizational coordination

1 Introduction

Circular economy (CE) has gained significant traction in both industry and academia, offering promising pathways to reduce emissions and improve resource efficiency [1]. The construction sector, as one of the largest global consumers of raw materials and contributors to greenhouse gas emissions, is a critical arena for implementing CE principles.

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Among construction materials, aggregates (used in concrete, asphalt, and backfilling) are particularly relevant due to their high volume and potential for reuse. Despite technical feasibility, circular aggregate use remains limited in practice.

In Sweden as in most North European countries, aggregates can be sourced either from virgin quarries or recycled through sorting and upgrading of excavated materials [2]. While earlier estimates suggested that up to 40% of aggregates were recycled [3], recent figures indicate the share may be as low as 10% [4]. Aggregates are often viewed as a form of solid waste, making their management subject to environmental and waste legislation [5]. However, these regulations have traditionally focused on disposal rather than reuse, inadvertently creating barriers to secondary material markets [6].

A key challenge lies in the construction system's limited capacity to organize circular material flows. Prior research has identified numerous barriers, including fragmented planning, lack of logistics knowledge, and weak collaboration between actors [7]. Effective circularity requires a systems perspective that accounts for multi-actor and multi-level interdependencies. In Sweden, urban planning often lacks coordination with construction activities, particularly in early development phases. Municipalities play a central role through land agreements and procurement, yet planning gaps persist [8].

Policy implementation frequently conflicts with CE goals due to siloed planning structures and limited industry involvement. Information sharing is minimal, and trust between stakeholders is low, further hindering collaboration. Although technologies for recycling and upgrading aggregates exist, demand remains weak [9]. Increasing uptake requires improved understanding of how construction processes can be organized to support circularity.

The construction system is hierarchical, with developers, both public and private, setting project requirements early in the planning phase [10]. These requirements shape procurement and material choices downstream. Public developers face additional constraints, balancing regulatory responsibilities with fiscal accountability. This dual role can lead to risk aversion and reluctance to adopt innovative practices [11].

This paper adopts a systems perspective with the aim to highlight how delays in early-stage planning hinder downstream circular practices. It emphasizes the need for synchronized planning, improved logistics, and coherent policy implementation. Two key objectives guide the study: (1) understanding the developer's role and planning context, particularly the dual role of public developers as project owners and policy implementers, and (2) identifying time-sensitive activities that influence circular outcomes.

The rest of the paper is structured as follows. First, the research design is described, including a description of the data collection process. Thereafter, a conceptual background of aggregate supply chains and planning of logistics in construction is presented. This is followed by presentation of the results of the study. The paper is concluded with a concluding discussion.

2 Research Design and Data Collection

The aim of this paper is to highlight how delays in early-stage planning hinder downstream circular practices. To fulfil the aim, an inductive-deductive research approach is used [12], following the *discovery*, *description*, and *mapping* approaches highlighted by

Handfield and Melnyk [13]. Initially, the inductive discovery and description approach allow for understanding what is happening within a phenomenon [13]. In this case, the study focuses on early-stage planning and the uncertainties that arise in this planning process. Handfield and Melnyk [13] suggest that a mapping approach is useful when themes, patterns, and categories among key variables need to be developed whereas the relationship building identifies the underlying mechanisms of the problem.

To fulfil the aim, a workshop was conducted with the Swedish Transport Administration (STA) and one of the County Administrative boards (CAB) of Sweden. The STA is one of the largest developers in Sweden, responsible for all major infrastructure in the country. The workshop was focused on one of the current megaprojects in Sweden, the Ostlänken railway line that spans over five municipalities and three regions. Current estimates are that the project will exceed 100 MSEK in cost, not counting any additional excess costs.

The focus on the Ostlänken project is in part due to the scale of the project, both in terms of budget but primarily the geographic span of the project that means that the five municipalities and three regions all have responsibilities for land-use and overseeing. The workshop thus included experts and representatives from the STA as well as from the CAB, focusing on planning, overseeing, environmental expertise, and procurement. The three-hour workshop was held online to gather STA experts from different regions.

3 Conceptual Background

3.1 Aggregate Supply Chains

Aggregates are essential construction materials, used for backfilling and as key components in concrete and asphalt [9]. Their supply chains are shaped not only by market dynamics but also by environmental and waste management legislation, particularly in Sweden and other Nordic countries where aggregates are increasingly viewed as a form of solid waste [5]. Reuse on-site is generally preferred to meet sustainability goals [9].

In Sweden, aggregate governance spans national, regional, and local levels. National authorities, including Boverket, the Ministry of the Environment, and the Swedish Transport Administration, set legal frameworks and oversee infrastructure investments. Regionally, County Administrative Boards implement national regulations and lead environmental efforts, supported by Land and Environmental Courts. Locally, municipalities hold planning monopolies and act as environmental authorities, interpreting and applying the Environmental Act.

This multi-level governance structure reveals that circular aggregate flows are a cross-cutting issue, intersecting various policy domains and administrative silos [14, 15]. Municipalities also influence supply chains as landowners, clients, and developers [11]. Aggregates thus span both vertical governance, from national to local, and horizontal divisions within organizations. These institutional silos, each with distinct responsibilities and norms, complicate coordination and integration across the supply chain [16].

3.2 Planning and Logistics in Construction Supply Chains

Planning is a process of making sense of an uncertain future in a structured way [17]. In aggregate supply chains, two planning domains are relevant: urban planning and construction project planning. Urban planning operates hierarchically across three levels: strategic, detailed, and operational planning domains. Strategic planning sets long-term visions and spatial frameworks [18], which are translated into technical and visual specifics during detailed planning [19]. Operational planning occurs close to implementation, such as the start of construction.

Construction project planning includes four phases: (1) overall budgeting and scheduling, (2) design by architects and engineers, (3) procurement of contractors and suppliers, and (4) production on-site [20]. Traditionally, logistics has been treated as an operational issue, considered only during the production phase. However, material flow planning, including transport, warehousing, and handling, is closely tied to production planning which is typically managed by main contractors. However, suppliers generally conduct their own planning due to information asymmetry, i.e., a lack of shared or complete information across actors [21]. This asymmetry is common in construction, where temporary actor constellations and fragmented systems hinder coordination [22]. As Akerlof [23] illustrated in the used car market, information asymmetry can suppress demand, an insight equally relevant to recycled aggregates in construction. The chain of actors are typically acting in their own interests and with their level of knowledge, not necessarily considering that actors further down the chain may need the same information [24] leading to the construction industry adopting adversarial relationships and short-term contracts. These adversarial relationships and short-term contracts further increase uncertainty and reduce trust [24]. This leads to what Fredriksson, Eriksson, Janné and Lundberg [25] call *lateness of action*, where one actors hesitance to act on and make decisions under uncertainty leads to actors further down the line being forced to make their decisions later in the planning process. Lateness of action is not a malicious intent but builds on lack of knowledge in the earlier stages of planning. These late decisions, however, have an adverse effect on contractors and suppliers on the operative side of projects. Lateness of action differs from e.g., the waiting game or opportunism as the key component is uncertainty, and in the case of megaprojects, time.

4 Results

The Swedish Transport Administration (STA) is the country's largest developer and procurer of infrastructure projects, responsible for planning, constructing, and maintaining national road and rail infrastructure. As both a planning authority and developer, circular aggregate management is central to its operations. It is relevant during new construction, infrastructure expansion, and maintenance activities such as clearing ditches or replacing culverts.

Within STA, a national expert group works strategically with contaminated areas and circular aggregates. This group includes representatives from Planning, Maintenance, and Investment, as well as the project organization. However, regional parts of STA are rarely involved, despite overseeing early planning stages like action selection studies. These studies identify infrastructure needs and inform national and regional transport

plans, yet circular aggregates are generally not addressed, even though their volume and quality affect construction costs and feasibility.

STA's planning process involves corridor identification, route selection, and development of detailed plans. Mass balance considerations begin during route selection but are often deprioritized. Consultations with municipalities, county boards, and residents are part of the process, but differing legal interpretations across jurisdictions complicate coordination, especially when projects cross borders.

Although STA has overarching strategies, practical responsibility is often delegated down the actor chain. Project managers or consultants make decisions in later stages, limiting reuse opportunities. Consultants often avoid circular solutions due to risk concerns, and technical guidelines (e.g., the Swedish AMA) do not support reuse. As a result, circular aggregates are typically addressed by the main contractor during the production phase, complicating coordination and planning.

The Ostlänken project illustrates these challenges. It spans 11–12 separate rail plans across five municipalities and three regions, making coordination difficult. Each plan is reviewed individually, and run as separate projects, prolonging and complicating planning. STA attempts to plan for surplus material disposal, but contractors are often tasked with transport. Strategies are developed, but early-stage recipients are often unknown and unavailable. High transport costs and multiple handling steps make reuse economically challenging.

A key issue is the mismatch in planning horizons: STA works with a 7–8-year lead time, while municipalities plan 1–2 years ahead. This hinders alignment. Additionally, STA's internal review process does not always support project needs, such as proposed storage areas. Furthermore, circular aggregate management spans multiple parts of the organization and requires diverse competencies. A unified strategy and collaboration between project managers, consultants, municipalities, and regulators are essential. Quality assurance is critical to make reused materials viable. To improve outcomes, clearer guidelines, better coordination, and shared perspectives are needed. County boards and STA could jointly develop frameworks. In countries with material scarcity, reuse is more common; Sweden's challenge is to make reuse viable despite material abundance.

5 Concluding Discussion

The aim of this study was to highlight how delays in early-stage planning hinder downstream circular practices. Taking the example of the Swedish Transport Administration and their megaproject Ostlänken, we can see that different actors and even different levels of the same actor are involved in different stages. With many actors involved, the risk of information asymmetry increases [22], and even though the STA has good intentions with an overarching plan for aggregates and surplus materials, the long planning horizons of 7-8 years complicates matters further.

During the workshops, both the STA and CAB saw that they have responsibilities for ensuring circular aggregate handling. However, there were also suggestions from STA as to shifting some of the responsibility higher up in the hierarchy, i.e., the Swedish Environmental Protection Agency (SEPA): *"Perhaps it's SEPA's roll?"* However, shifting responsibility further up the chain was also seen as adding more to the complexity.

In relation to SEPA, the same STA participant said *"But their guidelines don't always work well, as there's still a lot of room for interpretation. I think it's better to work at the regional level."*. Another STA respondent added: *"There is considerable variation between STA's projects in how excavated materials are assessed and defined. It is part of STA's mandate that these materials should be handled as locally as possible."*

Even though the STA has the possibility and organizational power to address the circular aggregate issue, the above quotes show how difficult and complex the question is. This is due to the cross-cutting nature of the subject [14] and this is where clearer role definitions are needed. The STA is a vast and complex organization, but all their projects have one thing in common – the need for managing excavated materials and circulate aggregates. For an organization such as the STA, having clearly defined roles and guidelines could streamline processes across the internal organizational boundaries. This could include formalizing the aggregate management further, allowing the organization to integrate circular aggregate considerations earlier on in the planning process. This would also show main contractors that the STA takes responsibility for circulating materials in a resource efficient way. Early assessments could also lead to more cost-effective projects in the long run.

One of the greatest challenges of circular aggregate management in the context of Swedish megaprojects is *lateness of action* [25]. Looking at the timeline of STA's projects, they have a planning horizon of 7-8 years. It is understandable that the STA are averse in making decisions on circular aggregate management too early–who can tell what the market situation will be in 8 years? Thus, it is evident that the question of circular aggregate management is deemed too far away into the future to be considered on a more detailed level in the planning process. This decision, however, propagates through the actor chain and when engineering consultants are brought in at a later stage, they themselves are not ready to make decisions that promote circularity.

In the case of Ostlänken, it also consists of multiple railway plans and sub-projects, each with their own mandate to design the material management. This further increases the bounded silos within the overall megaproject. In fact, as each railway plan is deemed to be their own project, they all have their own budget restrictions. This has manifested itself as a phenomenon regarding internal transfer of aggregate materials in the overall megaproject; some of the subprojects will have excess aggregate materials that could be used in later stages of the megaproject, but the individual subprojects with excess materials do not want to be burdened with storing and/or transporting this excess material as these operations will incur costs that has to be covered by the individual subproject. Overall, storing and transporting the materials could benefit the whole megaproject and reduce resource depletion, but as individual budget constraints set the tone for the megaproject, it is up to each of the subprojects to solve the aggregate issue as best they can. Thus, we can see that lateness of action not only occurs in the overarching megaproject, but it also trickles down into the individual subprojects. Remember, lateness of action stems from uncertainty and lack of information [25]. If an organization such as STA raised the question of circular aggregate materials to a more strategic level, the subprojects would have clearer directives to follow.

This study took its departure from the Ostlänken megaproject. As such it is limited to the Swedish megaproject context. However, we believe that the findings and discussion

could be applicable in other contexts as well, as it promotes sharing information early in the planning process. As such, the study contributes to practice by highlighting how lateness of action in the early planning phases of a megaproject affects the operative phases negatively. However, the study also shines a light on the difficulty in including circular aggregate material management early on in a megaproject context as megaprojects in general have long planning horizons where whole societies can change throughout the planning process. Furthermore, the study contributes to theory by exemplifying lateness of action in a megaproject context, thus opening up for further exploration as to how to alleviate this phenomenon.

References

1. Zink, T., Geyer, R.: Circular Economy Rebound. J. Ind. Ecol. **21**, 593–602 (2017). https://doi.org/10.1111/jiec.12545
2. Magnusson, S., Johansson, M., Frosth, S., Lundberg, K.: Coordinating soil and rock material in urban construction – Scenario analysis of material flows and greenhouse gas emissions. J. Cleaner Prod. **241** (2019). https://doi.org/10.1016/j.jclepro.2019.118236
3. County Administrative Board of Stockholm: Krossat berg och återvunnet material ersätter grus. Report, County Administrative Board of Stockholm, Stockholm (2003)
4. Union Européenne des Producteurs de Granulats (UEPG): Home page. www.uepg.eu. Accessed 20 Aug 2026
5. Rylander, H., Lagerkvist, A.: From dumping to circular economy: There is no success like failure. Waste Manage. Res. **42**, 0734242X231221084 (2024). https://doi.org/10.1177/0734242X23122108
6. Aid, G., Lazarevic, D.: From waste management to natural capital management in the circular economy. In: Brandão, M., Lazarevic, D., Finnveden, G. (eds.) Handbook of the Circular Economy. Edward Elgar Publishing, Cheltenham, UK (2020)
7. Ababio, B.K., Lu, W.: Barriers and enablers of circular economy in construction: a multi-system perspective towards the development of a practical framework. Constr. Manage. Econ. **41**, 3–21 (2023). https://doi.org/10.1080/01446193.2022.2135750
8. Eriksson, L., Fredriksson, A.: A construction transport planning gap – An institutional logic perspective. Cities. **158** (2025). https://doi.org/10.1016/j.cities.2024.105698
9. Hale, S.E., et al.: The Reuse of Excavated Soils from Construction and Demolition Projects: Limitations and Possibilities. Sustainability. **13** (2021). https://doi.org/10.3390/su13116083
10. Janné, M., Fredriksson, A.: Construction logistics in urban development projects – learning from, or repeating, past mistakes of city logistics? Int. J. Logist. Manage. **33**, 49–68 (2022). https://doi.org/10.1108/ijlm-03-2020-0128
11. Eriksson, V., Hulthén, K., Sundquist, V., Fredriksson, A., Janné, M.: The role of public actors in construction logistics: effects on and of relational interfaces. Constr. Manage. Econ. **39**, 791–806 (2021). https://doi.org/10.1080/01446193.2021.1970785
12. Jebb, A.T., Parrigon, S., Woo, S.E.: Exploratory data analysis as a foundation of inductive research. Resour. Manage. Rev. **27**, 265–276 (2017). https://doi.org/10.1016/j.hrmr.2016.08.003
13. Handfield, R.B., Melnyk, S.A.: The scientific theory-building process: a primer using the case of TQM. J. Oper. Manage. **16**, 321–339 (1998). https://doi.org/10.1016/S0272-6963(98)00017-5
14. Boyle, R.: The management of cross-cutting issues. Technical Report, Committee for Public Management Research, Dublin (1999)

15. Molenveld, A.: Organizational adaptation to cross-cutting policy objectives. University of Antwerp (2016)
16. Rosales, R., Haarstad, H.: Governance challenges for urban logistics: Lessons from three Norwegian cities. Environ. Policy Governance. **33**, 221–231 (2023). https://doi.org/10.1002/eet.2015
17. Witzell, J.: Approaching transformative futures: discourse and practice in Swedish national transport policy and planning. KTH Royal Institute of Technology (2021)
18. Healey, P.: In search of the "strategic" in spatial strategy making. Plann. Theory Pract. **10**, 439–457 (2009). https://doi.org/10.1080/14649350903417191
19. Tonell, L., Nyström, J.: Planeringens grunder: En översikt. Studentlitteratur, Lund (2012)
20. Thunberg, M.: Developing a framework for supply chain planning in construction. Linköping University, Linköping (2016)
21. Clarkson, G., Jacobsen, T.E., Batcheller, A.L.: Information asymmetry and information sharing. Gov. Inf. Q. **24**, 827–839 (2007). https://doi.org/10.1016/j.giq.2007.08.001
22. Bäckstrand, J., Fredriksson, A.: The role of supplier information availability for construction supply chain performance. Prod. Plann. Control. **33**, 863–874 (2022). https://doi.org/10.1080/09537287.2020.1837933
23. Akerlof, G.A.: The market for "lemons": quality uncertainty and the market mechanism. In: Diamond, P., Rothschild, M. (eds.) Uncertainty in Economics. Academic Press, San Diego (1978)
24. Fernie, S., Tennant, S.: The non-adoption of supply chain management. Constr. Manage. Econ. **31**, 1038–1058 (2013). https://doi.org/10.1080/01446193.2013.830186
25. Fredriksson, A., Eriksson, L., Janné, M., Lundberg, K.: Breaking Barriers to Circularity: Understanding Multi-Actor Misalignment in Planning Practices. Circular Econ. Sustainability. **6** (2026). https://doi.org/10.1007/s43615-026-00775-9

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Implementing the 2ZERO Technology in Vehicle Parc Models: The Impact of Research and Innovation in Long-Term Outlooks for the EU

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Abstract. The European Commission has set ambitious CO_2 reduction targets for the transport sector as part of its broader carbon neutrality strategy for 2050 (Fit for 55). In response, the 2ZERO Partnership seeks to accelerate the transition toward zero tailpipe emission mobility focusing on affordable, user-centric technologies and services and supporting their widespread adoption. 2ZERO also supports progress in life-cycle analysis methods, the deployment of efficient charging infrastructure, and the mitigation of non-powertrain emissions and road transport-related noise within a circular economy context. LeMesurier is a Horizon Europe Coordination and Support Action that developed a framework for monitoring and evaluating the effectiveness of the 2ZERO Partnership in achieving its goals. It assesses progress against Key Performance Indicators (KPIs) outlined in the Strategic Research and Innovation Agenda (SRIA) of the Partnership. In this paper, long-term impacts (2025–2050) of introducing affordable, innovative zero-emission vehicle technologies (BEVs and FCEVs) are explored. A comprehensive modelling approach introduces three models: i) COPERT/SIBYL (tank-to-wheel); ii) PRIMES-TREMOVE, a techno-economic model (well-to-wheel); and iii) MOVEID, a resource optimization model (life-cycle assessment). The analysis quantifies 2ZERO innovation impacts on energy demand, CO_2 emissions and GHG intensity of vehicles, highlighting the importance of research and innovation in meeting decarbonization goals.

Keywords: Zero emission vehicles · Vehicle energy efficiency · GHG emissions

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1 Introduction

Achieving climate neutrality in Europe requires a fundamental shift in mobility. The 2ZERO Partnership, launched under the Horizon Europe Framework Programme, brings together public and private stakeholders to drive research and innovation in support of zero-emission mobility.

To track progress and ensure that public investments deliver real impact, a dedicated monitoring framework is essential. The LeMesurier project was called for to design and apply a practical system of methods to measure the Key Performance Indicators (KPIs) derived from the 2ZERO Partnership Objectives. The 2ZERO Partnership addresses aspects of sustainable road transport by promoting modular and recyclable vehicle designs, user-focused solutions, and seamless integration with renewable energy and digital infrastructures. A strong focus is also placed on circular economy principles, collaboration across sectors, and the full lifecycle of transport solutions, from design and use to reuse and recycling.

*Le*Mesurier, applies a two-step approach: the first step is to identify relevant indicators and suitable data sources; the second step is to identify relevant results of the projects funded within the Partnership. The focus is not just on measuring outputs but on understanding whether those outputs are aligned with the Partnership Objectives. This includes evaluating the clarity of each indicator, the ease of collecting data, and the relevance of the results for policy and programme planning.

Through this approach, LeMesurier contributes to a culture of learning, accountability and continuous improvement of the monitoring processes within the Partnership. In doing so, it strengthens the ability of the 2ZERO Partnership to adapt, scale impact and contribute to Europe's broader transition to sustainable mobility for people and goods.

2 Background

The 2ZERO SRIA defines a three-tiered structure of its Objectives - General (GO), Specific (SO), and Operational Objectives (OO), each accompanied by a set of KPIs to measure progress along technological, societal and environmental dimensions [1]. LeMesurier systematically maps and classifies these KPIs into two categories based on their nature and measurement complexity: the Direct and the Compound KPIs. Direct KPIs refer to measurable, single-count parameters, Compound KPIs are derived from the combination of multiple inputs and typically require modelling tools to estimate broader system-level impacts [2]. This paper focuses on Compound KPIs, how relevant data was collected and inputted to the modelling tools and the KPI projections derived.

The Compound KPIs are part of more than 40 2ZERO's KPIs, described in the Partnership's SRIA [3]. Their identifiers include a reference to the type of 2ZERO Objective (GO, SO, OO) and sequential numbering. KPIs considered as Compound KPIs at the outset of the project were:

GO.KPI.3: Reduction of CO2 emissions;
SO.KPI.1: Ability to determine realistically and reliably the energy intensity (tank-to-wheel);
SO.KPI.2: Reduction of GHG emissions from the mobility of people and goods;

SO.KPI.3: Reduction of development time and effort.

Another KPI was found to be essentially a Compound KPI when projections of future values are made, namely:

GO.KPI.4: Number of new vehicle registrations of zero tailpipe emission vehicles.

Finally, SO.KPI.3, whilst a necessary input into the projection of the other Compound KPIs, was determined by an approach more similar to a Direct KPI, so will not be consider further here.

For a more comprehensive overview of the KPI classification and measurement methodology, including specific data sources, definitions and baseline assumptions, the reader is referred to the publicly available LeMesurier Deliverables, D1.1 - *Methods, frameworks & baselines to assess the Direct KPIs* [4].

3 Objectives and Scope

In this paper, selected results from LeMesurier in supporting the 2ZERO Partnership's mission to accelerate the shift toward a greener, more sustainable road transport system in Europe, are presented. The focus is on how LeMesurier translates project-level outcomes into measurable indicators aligned with Partnership's Objectives. For Compound KPIs, this process involves the collection and analysis of quantitative data. The scope of the work spans most projects funded under 2ZERO between 2021 and 2024. These projects address a wide range of themes, from component, powertrain and vehicle technologies to infrastructure and behavioural aspects. Through engagement with project coordinators and project clusters, LeMesurier establishes a process that enables projects to understand how their progress aligns with Partnership's targets and how monitoring could be embedded within the projects from their outset. The framework is designed to be consistent, scalable and adaptable, ensuring long-term usability and institutional learning. Ultimately, the work aims to bridge the gap between individual project outcomes and the ambitions of the 2ZERO Partnership, providing actionable insights for policymakers and stakeholders, to inform future programming and decision-making.

4 Method

The method underpinning the work designed to establish a structured, transparent and scalable framework for assessing the progress of the 2ZERO Partnership in terms of the Compound KPIs. Determining the parameters such as the energy intensity of road transport or the GHG intensity of the road mobility of people and goods (expressed as tonCO2eq /p.km or t.km and toe/p.km and toe/t.km) required a broad model of the road transport system sensitive to the results of the 2ZERO Partnership projects. Hence, models which combine the effects of the multiple input data in order to derive these values needed to be used. Furthermore, given that these KPIs are determined from models which have multiple input data, it was also of value to have more than one source of such models, in order to determine the likely range of impact from the results of the 2ZERO project portfolio based on a variety of valid assumption, methods and measurements. As such, LeMesurier involved three such models, in order to compare, contrast and combine the results for the projection of the Compound KPI values.

The actual process of determining the Compound KPI values is shown in the Fig. 1 including five steps:

1. Those 2ZERO projects that could provide input to one or more of the Compound KPIs were determined. If needed, estimations of appropriate inputs from project were determined using digital twins. Furthermore, other sources of information, were reviewed to establish whether results from other activities validate or undermine the findings of the 2ZERO projects, their KPI measurements, such that reasonable input into the next step can be made.
2. The Compound KPI parameters, some of their interactions, effects and impacts were determined through the use of models as shown in Fig. 2 were used.
3. The models were used to produce data suitable for calculating the Compound KPIs (in steps 4. and 5.). Each of the models was used to determine baseline KPI relevant data (representing the European vehicle fleet behaviour in 2019–2020 - where 2020 values were affected by the CoVID-19 pandemic, 2019 pre-pandemic values were be used, as appropriate) [6, 7]; similarly, for intermediate KPI relevant data (for photo-years 2025, 2030 and 2035- during the LeMesurier project it was decided to extend the KPI value projections until 2050, such that the resultant impact of the running 2ZERO project could be more projected with improved resolution) without any additional technology developments and possible new product introductions as a consequence of the 2ZERO projects specifically; and, finally, a set of KPI data, as in the intermediate KPI relevant process, but now with the technology developments representative of the 2ZERO project result projections.
4. In the fourth step, the individual results, from the different models and different calculations, were 'translated' in the data set relevant for the estimation of the specific Compound KPIs.
5. In the fifth and final step, the actual KPI values, for the Compound KPIs, were calculated for the three cases (baseline, intermediate and measured).

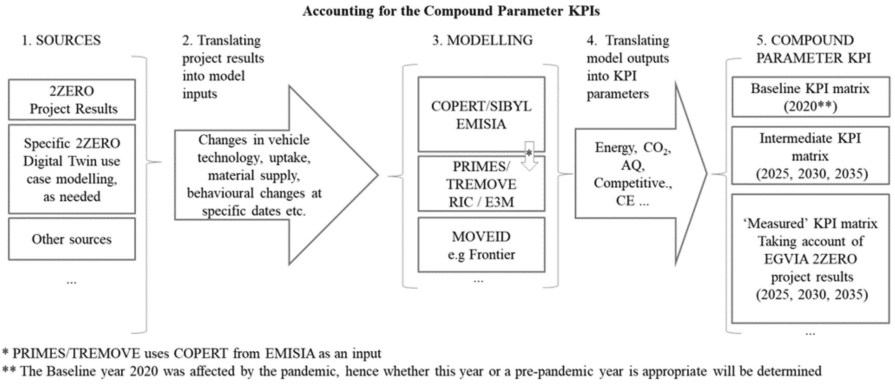


Fig. 1. The process used to account the Compound KPI values

4.1 The LeMesurier Vehicle Digital Twins

In Step 1 of the Compound KPI determination, see Fig. 1, a specific 2ZERO Digital Twin Use Case Modelling was proposed. Given the timing of the LeMesurier project, it was found that such Digital Twins were not yet available from the majority of the projects consulted. Therefore, a pre-planned fall-back solution was used, and LeMesurier partners developed their own Digital Twin models following a known procedure based on the expected results from the projects. Specifically, physics-based vehicle models were developed on a commercial multiscale platform; the aim being to derive energy consumption values for battery and fuel cell electric vehicles as a function of speed and other parameters. The results of these models were validated against project results where available. The results were used as input in the next steps for the Compound KPI determination. Full details of this process are reported in [8, 9] as well as D2.2 of the LeMesurier project [5].

4.2 The Models Used

LeMesurier used three different models during Step 3 to determine the Compound KPI values. In essence the three models represented different aspects of analysis for the European vehicle parc, from vehicle tank to wheels energy and emissions aspects (in COPERT/SIBYL), to mobility well-to-wheels energetic and economic aspects (PRIMES/TREMOVE), to life-cycle road mobility system greenhouse gas minimisation optimisation (MOVE-ID) [5]. Hence, use of these different models gave a range of perspectives on how the values of the Compound KPIs might be determined and projected. Further information on each of the models is available in the public domain, see [10–12].

5 Compound KPI Assessment Results

Presented in the following sub-sections, are the measurements developed by the three models regarding the three Compound KPIs this analysis targets in the scenario in which the effects of the expected 2ZERO Partnership innovations are adopted at scale. Due to the different scopes of analysis of the three models, the KPIs have been calculated departing from a each models' preexisting baseline. This means that results of the models might vary in absolute terms, however, the focus of the analysis is in assessing the improvement trend established for each KPI.

5.1 GO.KPI.3: Reduction of CO2 Emissions

Due to the different scope of CO2 emissions assessed, the three models present significantly different emission levels for year 2025. These are approximately 828 thousand kton of CO2eq for COPERT/SIBYL, while PRIMES estimates them to 679 thousand kton and for MOVEID to as much as 1305 thousand kton. The discrepancy stems from the different life-cycle scope used in the models. Although the results of the three models differ in absolute terms, the KPI development converges overtime as seen in Table 1.

Table 1. Reduction of CO2 emissions (GO.KPI.3) compared to 2025 as modelled with COPERT/SIBYL, PRIMES and MOVEID

	2025	2030	2035	2050
	(in thousand kton CO2eq)	(% reduction)		
COPERT/SIBYL	828	9	28	91
PRIMES	679	17	51	99
MOVEID	1305	41	86	97

In comparison to its baseline, COPERT/SIBYL projects CO2eq reductions of about 9% in 2030, escalating to about 28% in 2035 and as much as 91% by 2050. PRIMES, projects steeper reductions in CO2eq emissions reaching 17% in 2030, 51% by 2035 and as much as 99% in 2050. The resource optimisation performed by the MOVEID model leads to an even steeper drop in emissions with CO2eq reductions as high as about 41% in 2030, and already 86% by 2035 before levelling at about 97% in 2050 with the last bit representing difficult to abate emissions related to the full life-cycle scope. The three modelling perspectives indicate a very high level of CO2 emissions reduction is achievable.

5.2 SO.KPI.2: Reduction of GHG Emissions from the Mobility of People and Goods

Being consistent with the overall CO2eq emission projections, the models also anticipate a very steep reduction in the GHG intensity of all road-based transport segments. Comparisons presented here are focused on the GHG intensity trajectory for heavy duty vehicles (HDVs) as an illustrative example.

COPERT/SIBYL anticipates HDV CO2eq emissions to deflate from 120kt CO_2eq/Gp.km in 2025, to about 110 and 97 for 2030 and 2035 respectively. In 2050 this drops to about 26 kt CO_2eq/Gp.km.

A similar trend can be identified in the projections of PRIMES. GHG intensity values of HDVs go from 72 kt CO_2eq/Gp.km in 2025, to 62 and 38 in 2030 and 2035 respectively before reducing this even further to near 0 by 2050 driven by regulatory compliance.

In MOVE-ID, HDV GHG intensity is expected to fall from 163 kt CO_2eq/Gp.km in 2025, to 118 in 2030 and 28 in 2035 respectively. Finally, the GHG intensity reach 13 CO_2eq/Gp.km in 2050. All three models indicate a significant reduction in the GHG intensity of vehicles.

5.3 SO.KPI.1: Ability to Determine Realistically and Reliably the Energy Intensity

The energy intensity of vehicles is expected to follow a less steep reduction than the GHG intensity presented above. Hereby, the relevant energy intensity values for HDVs are presented as an example of the overall trend.

As seen in Fig. 2, all models project a progressively reducing energy intensity for freight transport overall.

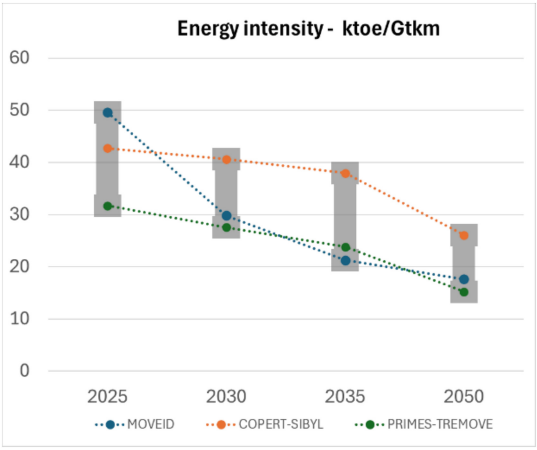


Fig. 2. Range of projected average freight energy intensity as calculated by the three models

COPERT/SIBYL projects a mild reduction in value from 38 ktoe/Gpkm in 2025, to 36 in 2030 and down to 35 in 2035 before finally dropping to about 26 in 2050. PRIMES projections start from a lower value of 29 ktoe/Gpkm in 2025. Here, energy intensity is also expected to decrease to 25 ktoe/Gpkm in 2030 and 22 in 2035 before resulting in 15 ktoe/Gpkm in 2050, a considerably lower value than that used in COPERT/SIBYL. Comparing to MOVEID results, 2025 sees HDV energy intensity in the area of 50 ktoe/Gpkm. This has further dropped to 28 ktoe/Gpkm in 2030 and 20 already by 2035. In the long run (2050), HDVs are projected to have an energy intensity of 18 ktoe/Gpkm.

Again, the specific results of the three models differ due to the different scope of the models with COPERT/SIBYL and PRIMES however following a very similar trend and MOVEID showing a steeper, earlier decline due to its optimisation focus pushing for an earlier decarbonisation of the road transport system.

6 Learnings and Conclusions

The compound KPIs provide an insightful evaluation of the 2ZERO Partnership's progress toward decarbonizing the road transport sector. Using three models—COPERT/SIBYL, PRIMES/TREMOVE, and MOVEID—this analysis offers projections on CO2 reduction, and improvements in energy efficiency from different perspectives.

Regarding the performance of the KPIs, the he main conclusions are:

All three models show a significant reduction of CO2 emissions (GO.KPI.3) over time. The reduction is small in 2025 and gradually increases in 2030, 2035, and 2050. The percentage reduction in 2050 compared to the base year 2019 or 2020 varies from 91% to 99.8% depending on the model.

Energy intensity (SO.KPI.1) for both passenger and freight activity presents a continuous improvement (i.e., decline) year by year. This is mainly attributed to the improved energy efficiency and to the gradual replacement of ICE vehicles with electric ones, which in general consume less energy per activity unit. The only exception to this general conclusion is that the energy intensity of MOVEID passenger activity slightly increases after 2035, as the e-fuels enter the market and require higher upstream energy provision but remains well below the 2020 levels.

GHG intensity (SO.KPI.2) for both passenger and freight activity present a continuous improvement (i.e., decline) year by year. This is mainly attributed to the gradual replacement of ICE vehicles with electric ones. All three models end up in values close to zero in 2050, with COPERT/SIBYL presenting slightly higher values than the other two models due to the slightly higher number of non-electric vehicles still circulating as mentioned above.

References

1. 2ZERO Partnership: Towards zero emission road transport (2Zero) Partnership. https://www.2zeroemission.eu/ (2025)
2. LeMesurier: LeMesurier website. https://lemesurier-project.eu/ (2025)
3. 2ZERO SRIA.: https://www.2zeroemission.eu/what-we-do/strategic-research-and-innovation-agenda-sria/ (2025)
4. LeMesurier Consortium (D1.1): Methods, frameworks & baselines to assess the direct KPIs. LeMesurier Deliverable D1.1. https://lemesurier-project.eu/wp-content/uploads/2025/01/D1.1_Methods-frameworks-and-baselines-to-assess-the-direct-KPIs.pdf (2025)
5. Giannelos, G., et al.: Selected model inputs including translation of the 2ZERO project outputs. LeMesurier Deliverable D2.2. https://lemesurier-project.eu/wp-content/uploads/2025/12/Attachment_0-58.pdf (2025)
6. ACEA: The Automotive Industry Pocket Guide 2024/2025. European Automobile Manufacturers' Association. https://www.acea.auto/files/ACEA-Pocket-Guide-2024-2025.pdf (2024)
7. EAFO: Electric vehicle battery packs experience record price drop in 2024. European Alternative Fuels Observatory. https://alternative-fuels-observatory.ec.europa.eu/general-information/news/electric-vehicle-battery-packs-experience-record-price-drop-2024?utm_source=chatgpt.com (2024)
8. Lampropoulos, Z., et al.: Impact of 2ZERO technologies on energy consumption of electric vehicles: a simulation approach enabling integration into COPERT/SIBYL categories. Paper presented at the EARPA FORMforum, Brussels, October 2025 (2025)
9. Siamidis, P., et al.: Impact of the 2ZERO partnership project portfolio on the energy consumption of electric vehicles and EU27 GHG indicators to 2050 – the LeMesurier project. Paper presented at the Transport and Pollution Conference, Paris, November 2025 (2025)
10. EMISIA SA: COPERT and SIBYL baseline websites. https://copert.emisia.com/ https://copert.emisia.com/sibyl-baseline/ (2024)
11. E3 Modelling: PRIMES-TREMOVE website. https://e3modelling.com/modelling-tools/primes-tremove/ (2025)
12. Kramer, U., et al.: Transformation of European mobility to the GHG-neutral post-fossil age. FVV Fuels Study IVb, FVV H131 (2022)

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Digitalization and Circularity in Transport Infrastructure: A Pilot Study on the Croatian Motorways Network

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Abstract. The paper presents work carried out within the EU-funded CIRCUIT project, which supports the circular, smart, and resilient transformation of transport infrastructure through digital tools, novel KPIs, and sustainable engineering practices. A pilot study on the Croatian motorways network demonstrates the practical implementation of these innovations. The pilot focuses on digitalizing asset management by integrating a new Digital Platform with engineering tools and existing management systems. A selected motorway section, including bridges, tunnels, and road segments, is surveyed using UAVs to generate digital twin models for condition-based and risk-informed decision-making, replacing traditional inspection and maintenance approaches. Newly developed circularity KPIs, covering reusability, recyclability, embodied energy, and end-of-life value, are integrated into the platform to support circular asset management and Green Public Procurement (GPP). The pilot validates the CIRCUIT framework and demonstrates how interoperable digital tools can enable more sustainable, data-driven infrastructure management aligned with evolving EU regulations and digital transformation goals.

Keywords: Circularity KPIs · Digital Twin · Green Public Procurement · Infrastructure Digitalization · Motorway network

1 Introduction

Transport infrastructure is essential for economic development and connectivity, requiring reliable and sustainable management strategies. Recent EU initiatives emphasize digitalization and circularity as key drivers for transforming asset management practices [8–10]. This paper presents a pilot study on the Croatian Motorways network within the CIRCUIT project, demonstrating how digital tools and circularity indicators can improve decision-making and sustainability.

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Effective life-cycle planning depends on accurate data to support sustainable and cost-efficient decisions. Infrastructure managers must address multiple life-cycle stages while handling diverse assets, performance goals, and complex datasets. Although agencies collect extensive information, decision-making often remains judgment-based, limiting effective data use. Green Public Procurement (GPP) is a key instrument for achieving EU environmental and sustainability goals, yet its implementation remains limited, with most EU countries applying GPP in less than 5% of contracts [15]. To address this, the CIRCUIT project structures key performance indicators (KPIs) around social, economic, environmental, and circularity aspects to support transparent evaluation and integration into GPP processes [16].

2 CIRCUIT Framework

The CIRCUIT project aims to advance the circular, smart, and resilient transformation of transport infrastructure through the integration of digital tools, novel KPIs, and sustainable engineering practices. In the Croatian pilot, a selected motorway network is being surveyed using UAVs to capture high-resolution data of bridges, tunnels, geotechnical structures and road segments. These scans, combined with existing 2D CAD designs, are used to develop detailed BIM (Building Information Models), forming the foundation of a digital twin for each asset. The digital twin enables accurate, data-driven monitoring of infrastructure conditions, replacing traditional visual inspections and time-based maintenance strategies. During the maintenance and operation phase, the platform integrates KPIs addressing circularity, environmental performance, and other sustainability metrics. This allows decision-makers to evaluate infrastructure interventions based on multi-criteria analysis, balancing cost, environmental impact, and long-term durability [1]. The project also incorporates digital product passports to track materials and components, enhancing traceability and reuse potential. A circularity analytics tool (CAT) facilitates circular business models and resource optimization across the construction and maintenance phases, while an EPD tool enables comparison of environmental impact due to usage of different materials. All tools are integrated into a single open-source digital platform, ensuring interoperability and streamlined access for stakeholders. The Croatian pilot serves as a proof of concept, demonstrating how digitalization and circularity-focused KPIs can support sustainable, data-driven infrastructure management as illustrated in CIRCUIT framework (Fig. 1).

KPIs proposed in CIRCUIT framework are applied to different dimensions of construction product or work. The CIRCUIT project is developing and validating a suite of digital tools and solutions applied in the Croatian pilot to provide a proof of concept for the CIRCUIT approach, process flows shown in Fig. 1. The existing asset management system serves as the starting point, providing a database of structures for inspections and digitalization. Using this data, structures are documented through high-resolution 3D mesh and point cloud acquisition derived from terrestrial and UAV-based LiDAR (Light Detection and Ranging - Remote Sensing), which, when integrated with existing 2D CAD drawings, support the generation of BIM models within a scan-to-BIM workflow. During operation and maintenance phase, inspections and condition assessments inform decisions ranging from do nothing, monitor, repair, strengthen or replace at the

end-of-life of structures. All activities during the life cycle should be guided by GPP using novel KPIs, while end-of-life decisions are supported circularity analytics tool, which enables the evaluation of circularity and potential reusability of elements.

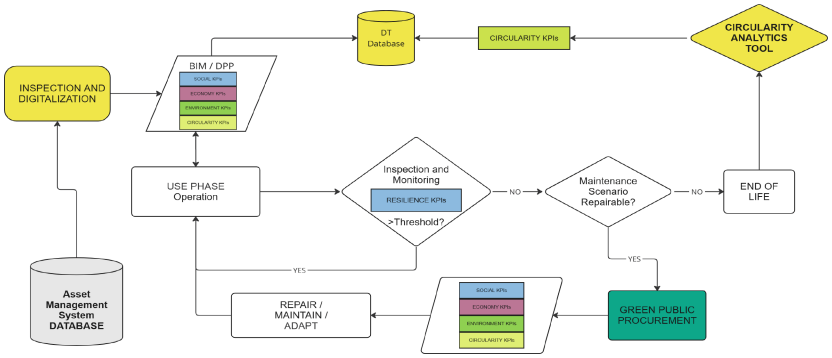


Fig. 1. Proposed CIRCUIT framework in life cycle decision flow process applied on transport network asset management system

3 Digitalization and Circularity for Motorway Infrastructure: Croatian Pilot Study

Traditional infrastructure maintenance relies on visual inspections and time-based strategies, which are often reactive and inefficient. Emerging technologies such as UAVs, digital twins, and artificial intelligence enable real-time monitoring and condition-based asset management. At the same time, circular economy principles promote reuse, recycling, and resource efficiency across infrastructure lifecycles. The CIRCUIT project combines these approaches with EU regulatory requirements by developing Key Performance Indicators (KPIs) for circular infrastructure management. Related EU projects, including CIRCuIT [19] and LIAISON [20], address circularity and sustainability in the built environment and transport infrastructure. Building on these efforts, CIRCUIT integrates circularity KPIs within a digital twin-enabled asset management framework to support data-driven decision-making.

The pilot study focuses on digitalization, recycling, and reuse, with emphasis on digitalization. It covers a section of the Croatian Motorways network, including roads, bridges, geotechnical structures, and tunnels. The project aims to replace traditional inspection and time-based maintenance practices with condition - and risk-based circular asset management in collaboration with Croatian Motorways.

3.1 Scan to BIM

The pilot integrates a newly developed Digital Platform with existing engineering and asset management tools, ensuring interoperability. UAVs equipped with high resolution

camera and LiDAR scanner are employed to conduct detailed inspections and gather high-resolution data. Scanning transport network structures provides detailed 3D point clouds and high resolution 3D mesh of the infrastructure. The scans capture both geometric dimensions and surface characteristics, enabling accurate mapping of all types of assets on a transport network. UAV inspection allows for efficient data collection without long traffic closures, minimizing disruption to road users. It also enables safe access to hard-to-reach or hazardous areas, reducing risk to inspection personnel. The collected data can be used to detect defects, deformations, and structural irregularities that may not be visible in traditional inspections. Combined with existing design information, the scans support the creation of precise BIM models for digital twin development and infrastructure management (Fig. 2).

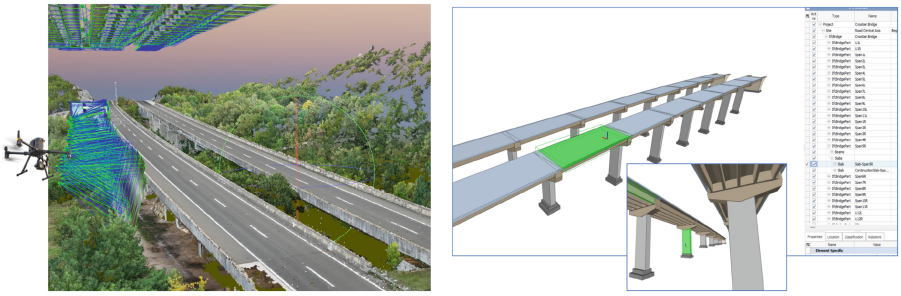


Fig. 2. Scanning with UAV and data rich BIM model of a bridge as a part of the selected pilot motorway section

3.2 Digital platform

The Trimble-Dodge Construction Network [18] highlights that digital workflows help identify the causes of delays and errors during pre-construction and construction. As project data grows in complexity with BIM and digital twins, a new level of interoperability is required. BuildingSMART has worked on this since 1994, introducing IFC (Industry Foundation Classes) to the industry [2]. Since then, updates such as integrating IoT into IFC have improved data exchange. However, data from newer systems is still not fully connected to existing interfaces. Structured vocabularies remain essential to ensure consistent terminology across the construction life cycle. Despite technological progress, only a few widely accessible AECO object type libraries and data dictionaries currently exist.

Within CIRCUIT, an open-source digital platform supports the adoption of circular principles across infrastructure design, construction, maintenance, and decommissioning. The digitalization process addresses existing barriers while ensuring interoperability through open-source standards like IFC. The platform functions as a data dictionary linked to existing resources such as bSDD. It provides standardized workflows to improve data quality and consistency. Users can search terms and visualize relationships in a tree-like graphical interface. Contexts allow scoping codes and hierarchies to

relevant local standards, reducing complexity. A graph database allows integration of CIRCUIT technologies with external datasets, including SRM and EPDs. Ultimately, material traceability from production through reuse will increase recycling and support secondary raw material uptake in the construction industry [13].

3.3 Circularity Assessment

The CIRCUIT project perceives a circular transport infrastructure as an industry that replaces the linear value chain model with a model that creates value by reducing, reusing, recycling and recovering construction materials and components throughout the whole life cycle. The project re-values the existing infrastructure stock as a resource of secondary raw materials and structural elements. Circularity in transport infrastructure focuses on maximizing the reuse and recyclability of materials, with reusability prioritized to preserve value, reduce emissions, and minimize resource demand. Alongside circularity, environmental KPIs based on LCA indicators—such as embodied energy, carbon footprint, and resource depletion—provide a transparent measure of sustainability performance across the asset lifecycle. Integrating these indicators into decision-making enables stakeholders to balance technical requirements with environmental and economic impacts. Within CIRCUIT, this combined approach supports data-driven strategies for sustainable asset management, from design and operation to repair and end-of-life. KPI for circularity is calculated based on two level assessment:

(i) Element level: Reusability which is determined based on following: Prefabrication, Damage level, Disassembly potential
(ii) Material level: Recyclability which is determined based on following: Market value, Resource depletion, Energy consumption, Carbon emission

3.4 Environmental Impact Assessment

The environmental impact assessment of different design and maintenance scenarios is crucial for the achievement of sustainability goals. Therefore, the Environmental Product Declaration (EPD) tool was developed to integrate data about environmental impacts defined in EPD into the CIRCUIT digital platform, allowing users to evaluate and compare the environmental impacts of different construction products and materials within built assets. EPDs provide a standard way of declaring the impacts of manufacturing and using products through Life Cycle Assessment (LCA). Construction products are assessed using a single set of Product Category Rules (PCR) ensuring consistent reporting for similar product, defined in the European Standard, EN 15804 [7].

The tool connects through an API to the ECO Portal, which acts as a central hub for digital EPD data. Through this connection, the tool accesses multiple established databases, including Environdec, EPD Italy, EPD Norway Digi, ECO Platform Small Data Providers Node, IBU.data, EPD International Data Hub, MRPI, EPD Ireland, ITB Poland, and the BRE Global EPD online tool [6, 13]. By consolidating these sources, the tool ensures that stakeholders can easily obtain reliable and standardized information on material performance. The main objective is to provide designers, engineers, and asset managers with data to assess and ultimately reduce the carbon footprint of materials used in construction and infrastructure management. The tool also supports visualization

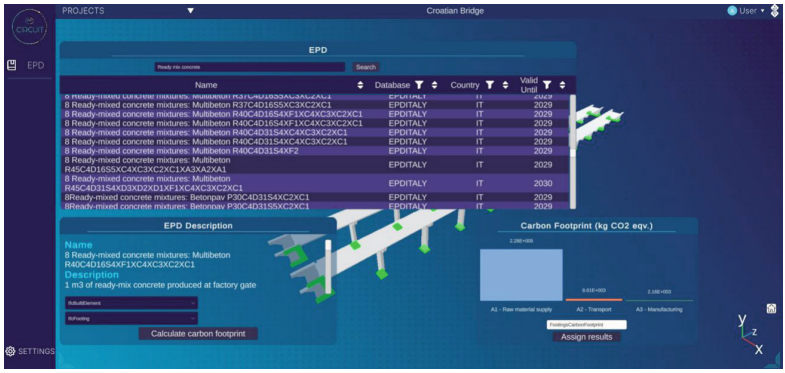


Fig. 3. Comparison of EPDs alternatives on a pilot section bridge example

of the results directly within BIM models on the digital platform, enabling intuitive comparison of alternatives, see Fig. 3, enabling informed decision-making that balances technical requirements with environmental sustainability.

3.5 Circularity Analytics Tool

The analysed transport network is viewed as a system in which assets act as donors or recipients of reusable elements, products, or recyclable materials depending on their life-cycle stage. Assets approaching end-of-life can provide materials for repairable assets, while wastes from other industries may also be incorporated into the system. Circularity performance indicators (PIs) were developed to quantify and assess material and element circulation based on an extensive literature review [3–5, 11, 12, 19, 20].

Within the project, a Circularity Analytics Tool (CAT) [17] was developed to evaluate the circularity of transport infrastructure assets and end-of-life scenarios. By calculating a circularity index, the tool supports engineers, asset managers, and decision-makers in assessing reuse, recycling, and resource optimization throughout the asset lifecycle. The tool focuses on two key indicators—reusability and recyclability—with priority given to reuse due to its lower energy demand and reduced emissions compared to recycling. Based on predefined algorithms and BIM model data, the tool automatically calculates recyclability, reusability and circularity values, see the example in Table 1, supporting sustainable and resource-efficient infrastructure management.

Table 1. Example of an Output from CAT tool with calculated Recyclability, Reusability and Circularity PI per structural element

Element_label	PL	DP	Tr	MT	DL	Reuse PI	Recycle PI	Circ PI
Girder-Span3R	0,00	0,10	0,70	Concrete	1,00	0,00	0,29	0,29
Beam-Span3R	1,00	0,68	0,10	Concrete	1,00	0,62	0,29	0,49
POT-U1R	0,00	0,29	1,00	Elastomer	1,00	0,00	0,08	0,08
AsphaltPavement:1294226	0,00	0,10	0,10	Asphalt	1,00	0,00	0,49	0,49
Guard rail	1,00	1,00	0,10	Concrete	1,00	0,71	0,29	0,59
Slab-Span4R	0,00	0,29	0,10	Concrete	0,60	0,00	0,29	0,29
Walls-U1L	0,00	0,10	0,10	Concrete	0,10	0,00	0,29	0,29
Walls-U1R	0,00	0,10	0,10	Concrete	0,60	0,00	0,29	0,29

PL – Prefabrication Level, DP – Disassembly Potential, Tr – Transportability, MT – Material Type, DL – Damage Level

4 Implementation into Asset Management Decision Making

The Croatian Motorway company manages, builds, and maintains more than 1300 km of motorways in Croatia. Since 2008, it has used a Cross Asset Management System [14] based on visual inspections, predefined damage catalogues, and algorithms for condition assessment. Inspectors classify observed damage using standardized categories, while the system generates condition indicators to support maintenance planning. Main inspections are conducted every two years and provide the primary source of maintenance data.

The CIRCUIT project demonstrates how digitalization and circularity can improve life-cycle management of transport infrastructure. UAV inspections and scan-to-BIM workflows generate accurate as-built data that support better design, material efficiency, and maintenance planning. Circularity KPIs and Life Cycle Assessment (LCA) indicators help evaluate reuse potential, recyclability, and embodied carbon, while the EPD tool enables comparison of material alternatives directly within BIM models. These methods support evidence-based design decisions and improve sustainability and cost efficiency.

The integration of UAV inspections, digital twins, circularity assessment, and EPD data also strengthens Green Public Procurement (GPP) by providing measurable sustainability criteria. Digital tools, LCA indicators, and circularity scoring enable procurement processes to include clear requirements for carbon footprint, resource efficiency, and reuse potential, shifting evaluation beyond price toward verified environmental performance.

5 Conclusions

The Croatian Motorways pilot study demonstrates the potential of digitalization and circularity in transport infrastructure management. By replacing conventional inspections with UAV-enabled digital twins and integrating circularity KPIs into asset management, the pilot supports smarter and more sustainable maintenance practices. Digitalisation of existing assets improved integration into the digital platform, enhancing data quality and decision-making. The inclusion of circularity KPIs enables broader sustainability assessment beyond traditional metrics, supporting Green Public Procurement and optimized life-cycle management of motorway infrastructure. The study confirms the applicability of the CIRCUIT framework in a real-world context and demonstrates the benefits of combining digital tools with circularity assessment for transport networks. The outcomes align with evolving EU regulations and provide a scalable model for other transport networks adopting digital and circular approaches.

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References

1. Allah Bukhsh, Z., Stipanovic, I., Klanker, G., O'Connor, A., Doree, A.G.: Network level bridges maintenance planning using multi-attribute utility theory. Struct. Infrastruct. Eng. **15**(7), 872–885 (2019). https://doi.org/10.1080/15732479.2017.1414858
2. buildingSMART: Industry Foundation Classes (IFC) standards platform. https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/ (2022)
3. BRE Global Ltd: CEEQUAL Version 6 Technical Manual: International Projects. Scheme Document SD6053, Issue 0.1. https://files.bregroup.com/CEEQUAL/SD6053-CEEQUAL-V6-International-Projects-Technical-Manual-0.1.pdf (2020)
4. CIRCuIT Consortium: Circular construction in regenerative cities: insights from the CIRCuIT project final report. EU Horizon 2020 Project Report (2023)
5. Dodd, N., Donatello, S., Cordella, M.: Introduction to the Level(s) Common Framework User Manual. Publications Office of the European Union, Luxembourg (2020)
6. ECO Platform: Environmental Product Declaration (EPD) Database portal. https://www.eco-platform.org/epd-data.html (2025)
7. European Committee for Standardization: EN 15804:2012+A2:2019: Sustainability of construction works – Environmental product declarations. CEN, Brussels (2019)
8. European Commission: Repair and prepare for the next generation. COM/2020/456, Brussels (2020)
9. European Commission: Sustainable and smart mobility strategy. COM/2020/789, Brussels (2020)
10. European Commission: Financing the green transition. Communication framework news release. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_17 (2020)
11. Ferrari, S., Zoghi, M., Blázquez, T., Dall'O, G.: New level(s) framework: assessing the affinity between the main international green building rating systems and the European scheme. Renew. Sust. Energ. Rev. **155**, 111924 (2022). https://doi.org/10.1016/j.rser.2021.111924

12. SI Institute for Sustainable Infrastructure: Envision Sustainable Infrastructure Framework Guidance Manual, Version 3. Institute for Sustainable Infrastructure, Washington (2018)
13. Khan, R., Posada, H., Tomar, R., Stipanovic, I., Martin-Portugues Montoliu, C.: Digital platform. CIRCUIT Deliverable D2.1 (2025)
14. Kuvačić, B., Jurić, S.: Asset management system at Croatian motorways. Ceste i Mostovi. **54**(6), 26–30 (2008) (in Croatian)
15. Lottero, L. et al.: D4.1 Manual for a successful deployment of GPP in CIRCUIT pilots (2024)
16. Stipanovic, I., et al.: Holistic circularity framework. CIRCUIT Deliverable D1.1 (2024)
17. Stipanovic, I., et al.: Circularity Analytics Tool. CIRCUIT Deliverable D1.3 (2024)
18. Trimble, Dodge Construction Network: Connected construction: the owner's perspective. SmartMarket Brief Research Report (2022)
19. Cartwright, B., Lowres, F., Turner, E., Hobbs, G., et al.: Recommendations on circularity indicators for WP8. CIRCuIT Project, Horizon 2020 Deliverable D3.3 (2021)
20. LIAISON Project Consortium: Deliverables and dynamic multi-infrastructure governance framework resources. https://liaison-transport.eu/liaison-resources/deliverables/ (2026)

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Environmental and Socioeconomic Impacts of Disrupted Rail Freight from Asia and Europe: A Scenario Analysis

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Abstract. With modern, globalized value chains, disruptions to transportation systems may have large, far-reaching economic and environmental effects. In this work, we investigate a hypothetical scenario with a widespread disruption to intercontinental rail freight transport between Asia and Europe. In addition to the disruption, we examine mitigation scenarios where alternative transport routes are adopted. The environmental and socioeconomic effects of the disruption and mitigation scenarios indicate negative effects both in Asia and in Europe, with the greatest impacts occurring in Asia.

Keywords: Resilience · Logistics · Disruptions · Environmental impact · Socioeconomic impact

1 Introduction

In light of increasing geopolitical instability and climate disruptions growing in both severity and frequency, resilience in modern supply chains is becoming a high priority. Modern value chains, being more complex and globalized than ever before, are more highly dependent on intercontinental freight and in turn more vulnerable to large-scale disruptions [1]. Disruptions to freight routes in one area of the world may therefore have ripple effects in others, as feedstocks and raw materials needed for economic activity in one region are sourced from other areas.

Economic systems have over the recent years become more susceptible to large shocks as a result of the world's increased interconnectedness and complexity of production networks over the past few decades [2, 3]. Research indicates that these shocks not only spread throughout the network but also have the potential to change its structure, which could have a major impact on the economy [2]. Recent conflicts like the Russia-Ukraine war have introduced significant shocks in the global transport sector, including the rail transport corridors between China and Europe [1].

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The Belt and Road Initiative (BRI) aims to improve transportation infrastructure between China and Europe, with the China Railway Express (CR Express) being a significant element [4, 5]. The CR Express route from China to Europe takes 12–16 days, representing around one-third of the time spent at sea, allowing traders to save a significant amount of time [4]. However, after the Ukraine-Russia conflict arose, initially, there was evidence of a decline in the cargo transported through the northern corridor through Russia and Belarus, which required the rerouting of shipments via sea transport, or using the central and southern corridor railroads [6]. However, since sanctions had no direct impact on route operators or transit rights, rail transport between China and Europe via Russia and Belarus increased again over time, evidencing resilience from the railway Silk Road to the shocks derived from the war, with increased cargo registrations at the end of 2022, in comparison to 2021 [6].

In contrast, literature highlights that there are still high risks and vulnerability of land-based supply chains between Asia and Europe, as it is also important to consider possible disruptions in countries adjacent to the Black Sea [7]. In fact, the Black Sea is the meeting point of corridors with considerable risks of potential conflicts, as cargo must first pass through Kazakhstan, the Caspian Sea, or Iran before continuing to Azerbaijan or Armenia and then Georgia or Turkey, or land through Turkey to Southeast Europe [7]. It is thus debatable to what degree the Black Sea is a safe shipping route [7] and a scenario with the complete closure of the rail and road transport routes from Asia to Europe is not entirely unrealistic; such a scenario necessitates the rerouting of cargo via other transport modes. In the present analysis, we use an Input-Output model to understand the socioeconomic and environmental impacts of hypothetical scenarios of disruption of land-based freight transport between the countries of Asia and Europe.

2 Methods

In this analysis, we use environmentally extended input-output to investigate the socioeconomic and environmental impacts of three disruption scenarios where rail freight services between Asia and Europe are disrupted, resulting in economic, employment and environmental impacts in both regions. These hypothetical scenarios illustrate the long-reaching environmental and economic impacts of large-scale disruptions that block major trade routes over longer time periods and between continents, such as that which was experienced under the Covid-19 pandemic.

Underlying the analysis is the EXIOBASE dataset from 2022, used in a macroeconomic input-output (IO) framework. EXIOBASE is an openly available multi-regional input-output table containing economic data for 49 countries and regions. The tables cover domestic production, imports, domestic transactions between economic sectors, value added, final demand, and international trade flows. EXIOBASE also has several environmental and social indicators, including greenhouse gas emissions and employment. In this study, the regions in EXIOBASE were aggregated into three regions: Asia (including China), Europe, and the rest of the world. The IO framework used is described in Miller and Blair [8] and exploits the inter-sectoral dependencies described in EXIOBASE to show the effects caused by shocks in the economy.

This analysis examines the environmental and economic impacts linked to each unit of monetary output. These impacts are represented by a multiplier matrix, M_i,

which reflects how both direct and indirect contributions to indicator *i* change across all originating and demand sectors. The multiplier therefore enables an assessment of how a 1-M€ shift in the final demand of a given sector influences the indicator *i* being investigated. Shifts in the final demand of transport sectors are the focus of this analysis. These sectors include rail, other land transport, pipelines, sea and coastal shipping, inland water transport, and air transport services across Asia and Europe.

Table 1 describes the scenarios analyzed. These scenarios assume that, under a global disruption, transportation services using standard modes can either be substituted with alternative modes or cancelled. Each mitigation scenario considers various degrees of re-routing rail cargo from Asia to Europe via maritime or air freight. For every re-routing scenario, two efficiency subcases are evaluated to capture potential inefficiencies that may result from the shift. This assumption acts as a simplified, overarching way to represent issues such as redirecting routes to ports instead of rail depots, increased warehousing needs, extended travel distances, or multimodal transport combinations.

Table 1. Description of hypothetical large-scale sub-cases in impact assessment

		Re-routing of rail transport in Asia	Assumed efficiency, sea transport
Sea	i	100% re-route via sea transport	Unchanged
	ii		Disrupted – 20% higher transport costs
Mixed	i	75% re-route via sea transport, 10% re-route using airfreight, remaining 15% is cancelled after the disruption	Unchanged
	ii		Disrupted– 20% higher transport costs
Cancel	i	25% re-route via sea transport, 5% re-route using airfreight, remaining 70% is cancelled after the disruption	Unchanged
	ii		Disrupted – 20% higher transport costs

The multipliers are also adjusted to reflect the variation in per-unit transport costs across different modes. In other words, the cost of moving an equivalent cargo load differs depending on whether it travels by rail, ship, or air. To address these cost differences when shipments are re-routed via alternative modes, freight rates for a standard shipping container between Asia and Europe were applied [3]. The resulting cost adjustment - factors that were used to modify the multipliers for re-routed cargo, relative to the original rail transport, are shown in Table 2. For example, redirecting a shipment valued at M€ from rail to sea freight would reduce the cost to 0.5 M€.

Using Eq. (1) and these cost-adjusted multiplier matrices, the change in impact indicators was calculated for each of the scenario described in Table 2. The outcome is a set of indicators that quantify how shifting 1 M€ of rail transport services in Asia (the baseline scenario) to other modes effects the broader economy in both Europe and Asia.

Given the global nature of greenhouse gas emissions, the environmental assessment considers emissions occurring in Asia as well as in the rest of the world (Europe and other aggregated regions). The economic assessment, however, highlights impacts on

Table 2. Relative freight rates

Freight mode	Cost of transport, relative to rail	Source
Rail (disrupted mode)	1	[9]
Sea	0.5	[9]
Air	4	[10]

the local Asian economy and on the European economy.

$$\Delta impact_{Asia} = M_{sea} s_{sea} a_{sea} (1 + \eta) + M_{air} s_{air} a_{air} - M_{rail} \quad (1)$$

where

M_t is the unadjusted multiplier matrix for transport mode *t*,
s_t is the re-routed share to mode *t*,
a_t is the cost-adjustment factor adapting rail costs to mode *t*, and
η is the assumed transport efficiency

3 Results

3.1 Environmental Impact

The effect of shifting 1 M€ worth of rail transport in Asia to other modes on greenhouse gas emissions is shown in Fig. 1 for all scenarios. All scenarios show an increase in emissions in the range of 100 to 830 t of CO_2-eq per 1 M€ displaced rail transport. These results indicate that even price-adjusted sea transport generates more emissions than rail transport per monetary unit.

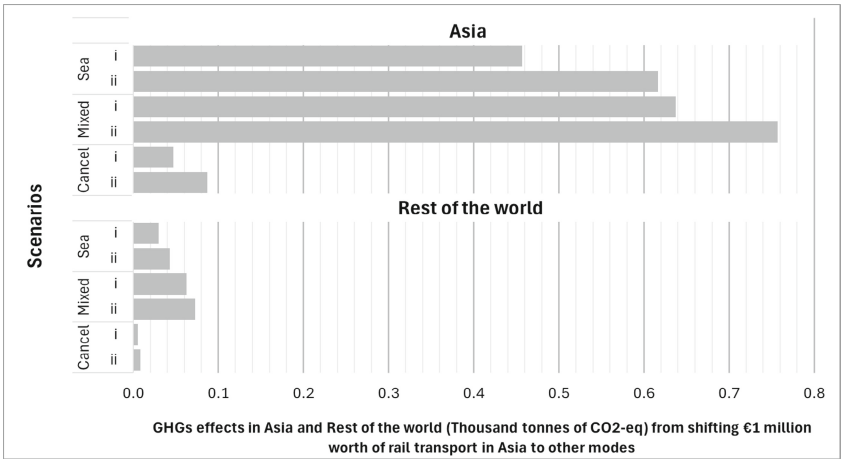


Fig. 1. Changes in GHGs after a decrease of 1 M€ in Asia rail transport

The Mixed scenarios had the greatest increase in emissions, most likely from partial re-routing with air transport. Of all of the disruption scenarios, the Cancel scenarios had the lowest GHGs. This is most likely due to the emissions avoided by cancelling shipments. Nevertheless, this scenario shows an overall increase in emissions due to the transport emissions from the re-routed goods in this scenario being greater than the transport emissions saved by cancelling the remaining shipments. Combined, since emissions increase across all scenarios, one can conclude that rail transport is an environmentally superior mode of freight transport.

Comparing the scenario effects on greenhouse gas emissions in Asia and the rest of the world, the effects are more pronounced in Asia. This is likely due to the combustion of fossil fuels used for transportation, which are allocated in Asia. When rail is re-routed to sea routes in the scenario analysis, higher GHGs are observed. This indicates that rail transport in Asia is generally an environmentally beneficial transport mode per monetary unit, likely due to a high rate of rail electrification. Consequently, we expect that disruptions to rail transport in Asia will generally result in higher GHG emissions.

3.2 Economic Impact

Employment. As with environmental impacts, employment effects of moving €1 million worth of rail transport in Asia to alternative modes are more pronounced in Asia than in Europe (Fig. 2). In the Mixed scenario, 9 to 13 jobs are created; all other scenarios show a likely decrease in employment, from 2 to 12 jobs per million €. The difference observed in the Mixed scenario may be associated with the relatively high share of re-routing through air transport in the scenario, which has relatively high employment intensity in jobs per million € in comparison to re-routing via rail or sea freight. Because cancelling shipments reduces activity in transportation sector, the Cancel scenarios lead to a decrease in jobs.

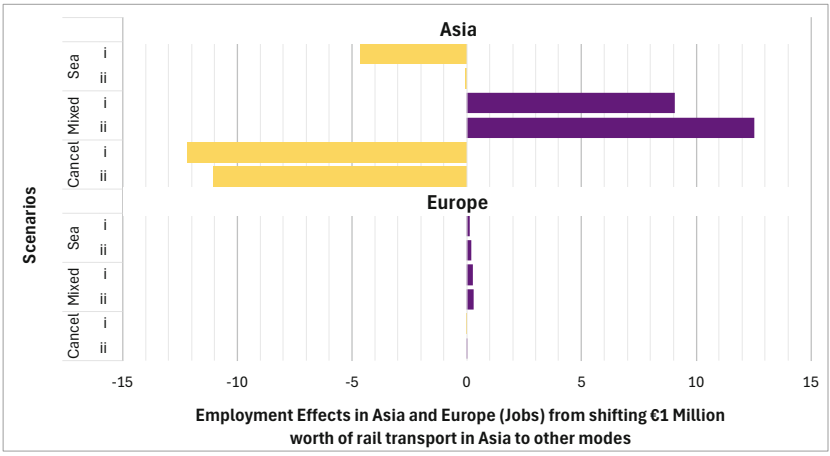


Fig. 2. Changes in employment from shifting 1 M€ of rail transport in Asia to other modes

Shifting transport in Asia results in relatively negligible employment effects in Europe. Across all scenarios, we observe a neutral to slight increase in employment in the European economy. This might be attributable to a lower rate of employment per €1 million in Europe than for the corresponding sector in Asia.

Value Added. All scenarios show a reduced value added in Asia, ranging from 230 k€ to 680 k€ per 1 M€ worth of rail transport in Asia shifted (Fig. 3). These results indicate that rail transport in Asia is a significant contributor to value added in Asia in comparison to sea and air transport. In the Cancel scenario, cancelling rail shipments rather than re-routing on other modes results in the most negative effects on value added of all the scenarios. This is the case in both Asia and Europe, as a lack of shipments presumably reduces activity in both economies. In the Sea and Mixed scenarios, however, the European economy experiences minor increases in value added; this may be due to the Asian air and sea transport sectors to which shipments are re-routed having greater value-added intensity in Europe than rail transport. Between the Sea and Mixed scenarios, however, the latter shows greater value-added effects in the European economy, likely due to air transport generally being associated with higher value-added goods.

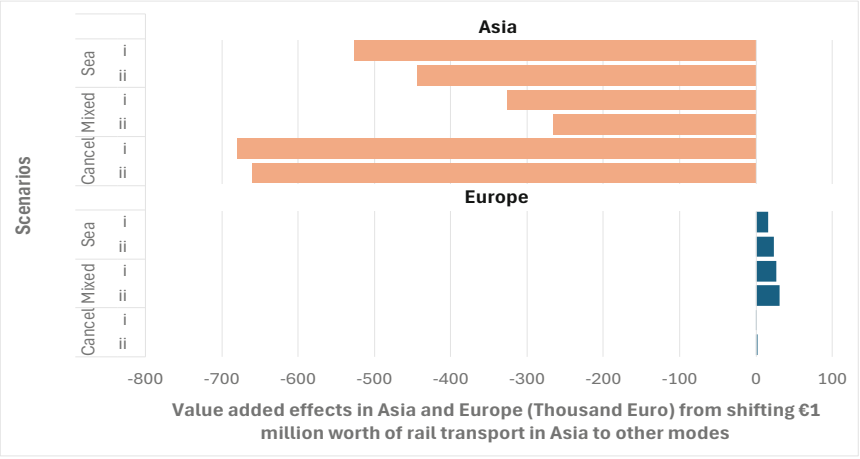


Fig. 3. Effects on value added from shifting 1 M€ of rail transport in Asia to other modes

4 Discussion and Conclusion

In this work, we model a large-scale disruption to the rail transport sector carrying goods from Asia to Europe. In the analysis, re-routing to other modes and shipment cancellations increases net greenhouse gas emissions in all regions. Economically, these same scenarios have primarily negative effects on value added and employment in Asia, and neutral to slightly positive effects in Europe. Although the study here is simplified, it nevertheless demonstrates dependencies between economic sectors and regions. The

findings show that higher costs, acting as a proxy for reduced efficiency, exacerbate negative environmental impacts in comparison to normal operations. In contrast, reduced efficiency has an amplifying effect on positive economic effects and buffered negative economic effects. Overall, the analysis shows that the greater the negative environmental impact a scenario has, the more positive (or less negative) the effects on economic indicators, and *vice versa.*

When the analysis adjusts transport sectors by price per unit, the results show that changes in the rail sector support higher levels of employment than changes in the sea transport sector when both direct and indirect effects are included. The air transport value chain, however, generates even more employment than rail for a given shipment. This illustrates the important employment benefits associated with rail transport and suggests that disruptions to rail freight are likely to produce net employment losses in Asia, with shipment cancellations resulting in the most extreme negative effects.

For value added, adjustments to the rail transport sector produce the largest impacts among all transport modes assessed. After normalising for price per volume in the scenario analysis, both Europe and Asia show higher positive value-added effects from rail compared with sea transport. This pattern implies that disruptions to the rail sector would likely lead to overall negative value-added outcomes.

4.1 Limitations and Future Work

An important point to interpreting these results is the limitation of that data, which represents a snapshot of the economic system; the analysis assumes all relationships between economic sectors remain static throughout the disruption. The economy therefore does not adjust to the disruption, for example by seeking alternative suppliers domestically or from non-disrupted regions.

Another limitation of the study lies in the nature of the underlying data. Due to the data being large-scale and aggregated, it limits our ability to identify precise drivers behind the observed patterns in the results. Despite this limitation, the results reveal a consistent inverse relationship between economic and environmental outcomes. Scenarios involving shipment cancellations tend to reduce environmental impacts more effectively than other options, yet also lead to greater losses in employment and value added compared with scenarios that impose higher environmental burdens, assuming all other factors remain unchanged. These findings underscore the trade-offs policymakers must consider, particularly the need to balance the continuity of transport services during disruptions with the associated environmental consequences, the financial costs of maintaining or adapting infrastructure. The findings also highlight that rail freight transport is a fairly environmental and economically optimised mode, and re-routing from this mode may lead to negative environmental and economic impacts.

Another limitation relates to temporal effects, with two manifestations. In the first, the effects of disruptions on the transport of sensitive and critical goods such as perishable items and medicines should be considered. During a major disruption, large quantities of such goods may potentially be needlessly destroyed if re-routing options are not found in time, or if emission-heavy rerouting options are ignored, representing both economic and environmental losses due to the embedded emissions in the production of these goods. Social harm may also be incurred by the inability to transport such goods to

the necessary areas. These effects are not captured in this study. The second temporal aspect is capturing the long-term effects from transport disruptions. Such effects can be difficult to predict and capture with the existing methods and available datasets. A domino effect arising from significant events with either (or both) far-reaching or long-lasting effects can have significant repercussions for value chains; prolonged blockages of raw material imports may hamper the operations of manufacturing industries, which in turn may cripple local economies until alternative sources are established. The dynamic aspect of these issues could be further investigated using simulation approaches, or given enough historical data, machine learning approaches to better understand these effects.

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References

1. Zhao, X., Duan, X., Chang, Y.-C.: The impact of war conflict on sustainable shipping: conference report. Sustainability. **15**(16), 12554 (2023). https://doi.org/10.3390/su151612554
2. Starnini, M., Boguñá, M., Serrano, M.Á.: The interconnected wealth of nations: shock propagation on global trade-investment multiplex networks. Sci. Rep. **9**(13079), 1–10 (2019). https://doi.org/10.1038/s41598-019-49173-2
3. Korovkin, V., Makarin, A.: Production networks and war. Preprint at arXiv:2011.14756 (2022). https://ideas.repec.org//p/arx/papers/2011.14756.html
4. Feng, F., Zhang, J., Liu, C.: Integrated pricing mechanism of China railway express whole-process logistics based on the Stackelberg game. Physica A. **609**, 128373 (2023). https://doi.org/10.1016/j.physa.2022.128373
5. Yu, Q., Xiao, Y., Wang, G., Cui, D.: Sustainable development of the China railway express under the belt and road initiative: focusing on infrastructure reliability and trade facilitation. Sustainability. **16**(18) (2024). https://doi.org/10.3390/su16188167
6. Antonowicz, M.: Impact of the armed conflict in Ukraine on rail freight between Asia and Europe. J. Civ. Eng. Transp. **6**(1), 25–38 (2024). https://doi.org/10.24136/tren.2024.002
7. Sielker, F., Dannenberg, P.: New economic geographies of war: risks and disruptions in Eurasian transport routes and supply chains through the military conflict in Ukraine. ZFW Adv. Econ. Geogr. **69**(1), 41–54 (2025). https://doi.org/10.1515/zfw-2024-0059
8. Miller, R.E., Blair, P.D.: Input-Output Analysis: Foundations and Extensions, 2nd edn. Cambridge University Press (2009). https://doi.org/10.1017/CBO9780511626982
9. Economic Commission for Europe Inland Transport Committee: Report on Phase III of the Euro-Asian Transport Links Project. Informal document No. 8, UNECE, Geneva (2018). https://unece.org/DAM/trans/doc/2018/itc/Informal_document_No_8_EATL_3rd-phase_report.pdf
10. Comprehensive guide to China freight rates per kg in 2025. FOB Ship Platform (2025). https://www.fobship.info/china-freight-rates-per-kg/

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Development of a Circular Economy Tool for National Roads and Light Rail Construction and Maintenance

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Abstract. Transport Infrastructure Ireland (TII) is responsible for construction and operation of the national roads, light rail (Luas) and Metrolink networks in Ireland. TII created the TII Circular Economy (CE) Tool, to implement the principles set out in its Circular Economy Policy and Strategy and to embed circularity along the lifecycle of national roads and public transport assets. In 2026, while in development, the Tool is for internal use only within TII. TIIs CE objectives are to reduce resource consumption; keep assets, components and materials at their highest value; maintain safety and technical function of services, assets and components; promote restorative and regenerative design and reduce emissions. Specialists for each asset within road construction and maintenance identified actions which can be taken along each stage of the asset lifecycle. Through the Tool, project managers and designers are prompted to review standards and specifications to identify opportunities to implement innovative circular measures. In 2024 user workshops were undertaken across the country on Tool implementation. The TII CE Tool is being expanded and developed for light rail assets from 2026, including the Luas Finglas Green Line extension in Dublin and the new 18 km Luas Cork line.

Keywords: Circular economy · roads · light rail

1 Introduction and Context

Transport Infrastructure Ireland (TII) is the Irish Government Agency with responsibility for delivery and operation of the national road network, light rail networks and Metrolink Dublin. In September 2023, TII published the TII Circular Economy Policy [1] and the TII Circular Economy Strategy [2] which set out what circular economy means to TII and the actions which would be taken to embed circularity into its activities and operations. The development and implementation of a Circular Economy Policy and Strategy by TII aligns with national circular economy policy including the Whole of Government Circular Economy Strategy 2022–2023 [3] (Government of Ireland, 2021), the National Waste Management Plan for a Circular Economy 2024–2030 [4]

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and the Climate Action Plan 2025 (CAP25) [5]. The Circular Economy Tool aligns with the National Investment Framework for Transport in Ireland (NIFTI) priorities [6], by introducing practical measures for the implementation of these priorities. The TII Circular Economy Tool is an innovative tool which is being created to support the successful delivery of the actions set out in TIIs CE Policy and Strategy. This paper sets out the approach taken to create the Tool, including the systems engineering and user focused approaches to its development.

2 Introduction and Context

2.1 General

The TII Circular Economy Tool is an Excel Tool which was initially developed for road earthworks, other road assets, PARR (Pavement Asset Repair and Renewal) maintenance schemes and light rail capital projects. The objective of the TII Circular Economy Tool is to provide guidance and signpost methods to embed circular economy in projects and programmes. A literature review of circular economy strategies was undertaken. The circular economy lifecycle themes and strategies included within the Tool are set out in Table 1 and are informed by selected documents and initiatives identified, as follows:

- The focus areas set out in the TII Circular Economy Policy and Strategy;
- The circular economy strategies set out in the Circular Buildings Toolkit (Refer to Table 1) [7];
- Regulation 27 By Products Irish legislation and guidance [8–12]; and
- Regulation 28 End of Waste Irish legislation and guidance [11–14].

Table 1. Themes used for the structure of the TII Circular Economy Tool (Adapted from [7])

Build Nothing	Build for Long Term Value	Build Efficiently	Build for the Right Materials
Keep existing assets in use	Layers of change design approach	Design optimization tools e.g. IAPDM* and Mass Haul	Increased reuse and recycled content
Increase intensity of use	Design for disassembly and reuse	Collaboration	Green procurement
	Systems engineering		

*The IAPDM is the Irish Analytical Pavement Design Method

The Circular Economy Tool was divided into asset groups which support the application of a systems approach to projects. Asset groups included within the Tool as Tabs are as follows: 0: General Questions; A1: Pavement and Earthworks; A2: PARR Schemes; B: Other Road Assets; C: Structures and Non Standard Structures; D: Drainage and

Utilities; E: Public Transport (PT): Rolling Stock; F: PT: Track, Earthworks, Trackside Infrastructure and G: PT: Depots and Earthworks. A series of questions was developed for each of the above which guide the user to develop more circular material management approaches for their assets. In order to promote lifecycle assessment, one of the key focus areas for circular economy in TII, an additional lifecycle phase was added to the Roads Capital Projects phases.

Traditionally the project phases for capital projects for assets end following construction. Phase 8 Operation and Maintenance was added within the Tool so that a lifecycle approach to circular economy and asset management is adopted. The Tool is depicted in Fig. 1, along with the drop down menus highlighted where the project phase and asset are selected within the Tool.

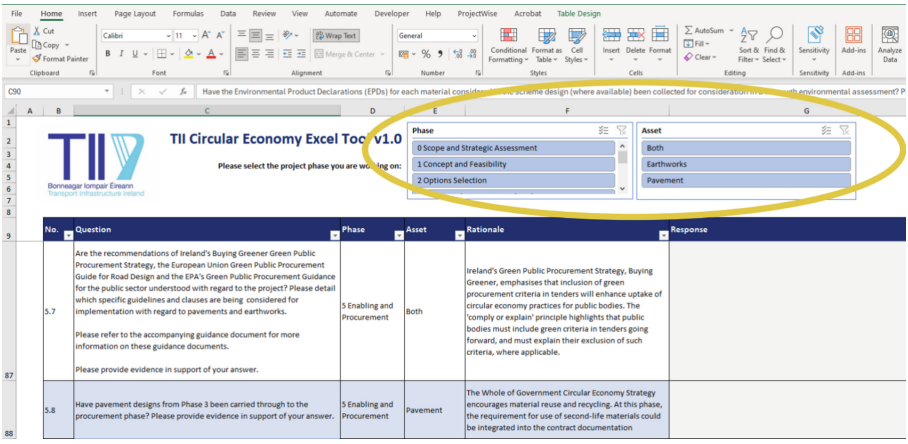


Fig. 1. Extract from the TII Circular Economy Tool

In the sections below the approach taken to selected aspects of the tool are described.

2.2 Systems Engineering

A system is a set of connected items or devices that operate together. For example, when considering the system of a road network, this consists of the pavements, ancillary infrastructure, bridges, drainage, utilities, and any receptors which are impacted by these assets or which impact these assets, along with the teams of specialists related to each of these assets. Systems engineering is a multidisciplinary approach to complex problems to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [15]. This systems thinking approach is vital for the systemic change required when introducing circular economy. A range of engineering design and technical specialists for each of the above assets were consulted in creation of the Tool to facilitate a "systems re-engineering" approach. The role of these specialists was to determine the CE strategies which were most applicable to each asset, and to review questions developed for each asset group for suitability and provide feedback.

2.3 PARR Schemes

Lifecycle assessment is a key element of pavement design in TII standards. To optimise pavement design, the IAPDM is used and referenced within the tool. IAPDM is a performance-based design method which provides the opportunity to reduce bituminous material requirements and to incorporate reused and recycled materials into designs, reducing the embodied carbon associated with road projects. On application, pilot projects using the Tool show materials and cost savings of approximately 10% for bituminous road pavement layers [16]. TII is also currently in the process of updating its standards and guidance to facilitate a more circular approach to projects and programmes. For example, CC-SPW-00800 Road Pavements – Unbound and Hydraulically Bound Mixtures has been updated to allow 100% reclaimed aggregate use in certain circumstances. Other similar standards updates are in preparation. A sample of key guidance questions relating to PARR within the Tool are as follows:

- Did you analyse your PARR programme for synergies between schemes, with the potential to generate CE opportunities? Did you record such opportunities in a tracker? (Programme specific tracker with opportunities likely to be relevant year after year)
- Did you contact your local material producers and contractors to gain an appreciation of what they can offer in terms of circular products and services?
- Did you quantify and characterise materials arising for potential reuse, recycling or disposal from this PARR scheme? (Note: valuable data likely to be available in PAMS (Pavement Asset Management System)
- Did you share the PARR and industry trackers with tenderers?
- Has construction data been recorded throughout the works in order to track and manage materials?
- Did you start recording lessons learned that will allow continual improvement of CE management on PARR schemes?

2.4 Earthworks Assets

A range of asset groups and circular economy measures to consider for each are included within the TII CE Tool. The circular economy strategies considered include ecosystem mapping, undertaking material flow analysis, and designing for disassembly and reuse, amongst others. In this section, the approach taken to implementing the strategy "build with the right materials" to the earthworks assets group is presented by way of an example. A resource which can support circular materials management is TII's Earthworks Analysis and Mass Haul Tool. This earthworks analysis tool can be most suitably integrated into Phase 2 Option Selection and Phase 3 Design and Environmental Evaluation of TII roads projects, to achieve objectives related to waste minimisation, optimal material re-use and a well-informed and sustainable design.

The tool works by assessing the allocation and haulage of material across a project with consideration of factors such as topography, proposed road alignment, earthworks volume, ground conditions, material sources and destinations, and haulage constraints. The TII CE Tool directs the User to adopt the Earthworks Analysis and Mass Haul Tool and other tools at the appropriate project phases. A flow diagram to support implementation of circular strategies to earthworks activities is depicted in Fig. 2. above. It sets out

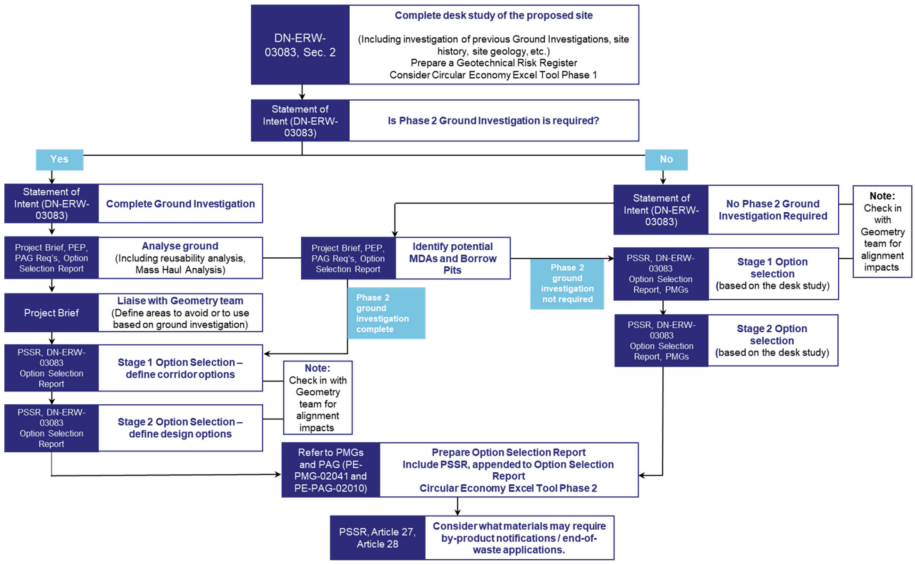


Fig. 2. Phases 2 and 3 Flow Diagram to Support Implementation of Circular Strategies to Earthworks Activities

links between key relevant project reports and the TII Circular Economy Tool. This can be used to support options selection and detailed design of earthworks. To maximise the benefits of reuse, new regulatory applications or notifications may be required to the Irish Environmental Protection Agency, such as through the Regulation 27 By Products and Regulation 28 End of Waste authorisation systems. Tool users are prompted to consider the need for such applications, including the mapping of material flows through projects and availability and need for materials on concurrent infrastructure projects to create a materials "ecosystem".

3 Results and Conclusions

3.1 User Focused Workshop – TII Roadshow

User focused workshops were held during the TII Standards Roadshows on 1st and 2nd of May 2024 trialing extracts from the TII Circular Economy Excel Tool which was in development at that time. The TII Standards Roadshow is an event which brings transport infrastructure Designers and Project Managers together to discuss updates and developments to TII standards. During the workshops verbal feedback was recorded and paper forms were provided so written feedback could be recorded and actioned. Key feedback themes emerged as recorded in Table *2* below, which were incorporated into development of the Circular Economy Tool.

The workshop findings included that there is a need for guidance in relation to application of circular economy on roads projects such as that provided by the TII CE Excel Tool and that updates to standards to support the Tool are likely to be required in the future.

Table 2. Synopsis of Workshop Participant Comments

Theme	Synopsis of Comments
Systems Approach	Where circularity is proposed for an asset this can impact planning, standards and contracts. A flow diagram identifying steps and collaboration needed was requested. Some assets such as safety barriers and lighting columns may require standards updates to capture circularity opportunities.
Inventory of Materials Arising	Materials arising from projects are not currently understood in all cases. A standard approach to an inventory of materials/ products available was suggested.
Materials Control	Advice on identification of valuable materials and their retention by local authorities or management by contractors was requested.
Regulation 27 and Regulation 28	Guidance on Regulation 27 and 28 implementation for roads projects was identified as potentially beneficial.

3.2 Next Steps

In 2026 the TII CE Tool is being expanded and the sections relating to light rail assets will be further developed. The tool will be applied to transport projects. TII is embarking on a series of light rail projects which include expansion of the existing network, and construction of new lines in Dublin and Cork. Implementation of the TII Circular Economy tool will take place on a trial basis on 2 light rail schemes as follows:

- The Luas Finglas project is a planned 3.9 km extension of the light rail Green Line from Broombridge to Charlestown in North Dublin. The project incorporates 70% grass track, a 350 vehicle park-and-ride facility and active travel facilities. The TII Circular Economy Tool will be implemented on Luas Finglas from Phase 5 Detailed Design and Procurement onwards.
- The Luas Cork project is a planned light rail project from Ballincollig to Mahon Point via Cork City Centre. It has an approximate length of 18 km with up to 25 Luas stops. The TII Circular Economy Tool will be implemented on Luas Cork from Phase 2 Concept Development and Options Selection onwards.

During 2006 each trial will include multi - disciplinary workshops with project leadership and design teams; tool completion by appropriate technical specialists; and delivery of actions identified in the tool by selected technical specialists

Each of the workshop participants, tool users and technical specialists involved in delivery of actions will be invited to complete a Microsoft Forms questionnaire on their experience of using the TII Circular Economy Tool and quality of the content. The tool will be applied to other TII light rail portfolio projects from 2027. Including the proposed Luas Lucan and Luas Poolbeg projects.

References

1. Transport Infrastructure Ireland: Circular economy policy (2023). https://www.tii.ie/media/u30p4awr/tii-circular-economy-policy-2023-2025.pdf. Accessed 31 Mar 2026
2. Transport Infrastructure Ireland: Circular economy strategy (2023). https://www.tii.ie/media/s3jotzfz/tii-circular-economy-strategy-2023-2025.pdf. Accessed 31 Mar 2026
3. Department of the Environment, Climate and Communications: Whole of government circular economy strategy 2022–2023: 'living more, using less' (2021). https://www.gov.ie/en/department-of-climate-energy-and-the-environment/publications/whole-of-government-circular-economy-strategy-2022-2023-living-more-using-less/. Accessed 31 Mar 2026
4. Department of the Environment, Climate and Communications: National waste management plan for a circular economy 2024–2030 (2024). https://www.mywaste.ie/sustainability/circular-living/national-waste-management-plan-for-a-circular-economy-2024-2030/. Accessed 31 Mar 2026
5. Department of the Environment, Climate and Communications: Climate action plan 2025 (2025). https://www.gov.ie/en/department-of-climate-energy-and-the-environment/publications/climate-action-plan-2025/. Accessed 31 Mar 2026
6. Department of Transport: National investment framework for transport in Ireland (NIFTI) (2021). https://www.gov.ie/en/department-of-transport/publications/national-investment-framework-for-transport-in-ireland-nifti/. Accessed 31 Mar 2026
7. Arup, Ellen MacArthur Foundation: Circular buildings toolkit (2022). https://ce-toolkit.dhub.arup.com/. Accessed 31 Mar 2026
8. Environmental Protection Agency: By-product – guidance note: a guide to by-products and submitting a by-product notification under Article 27 of the European Communities (Waste Directive) Regulations 2011 (S.I. No. 126 of 2011) (2020). https://www.epa.ie/publications/licensing%2D%2Dpermitting/waste/draft-by-product-guidance.php. Accessed 31 Mar 2026
9. Environmental Protection Agency: National by-product criteria reference number: BP-N001/2023 establishing detailed criteria on site-won asphalt (2023). https://www.epa.ie/publications/licensing%2D%2Dpermitting/waste/national-by-product-criteria-ref-no-bp-n0012023.php. Accessed 31 Mar 2026
10. Environmental Protection Agency: National by-product criteria reference number: BP-N002/2024 establishing detailed criteria on greenfield soil and stone (2024). https://www.epa.ie/publications/licensing%2D%2Dpermitting/waste/national-by-product-criteria-for-greenfield-soil%2D%2Dstone-bp-n0022024.php. Accessed 31 Mar 2026
11. Government of Ireland: European Communities (Waste Directive) Regulations 2011 (S.I. No. 126 of 2011) (2011). https://irishstatutebook.ie
12. Government of Ireland: European Union (Waste Directive) Regulations 2020 (S.I. No. 323/2020) (2020). https://irishstatutebook.ie
13. Environmental Protection Agency: National end-of-waste decision EoW-N001/2023 establishing criteria determining when recycled aggregate ceases to be waste (2023). https://www.epa.ie/publications/licensing%2D%2Dpermitting/waste/Final-Decision%2D%2D-National-End-of-Waste-Criteria-N001-2023.pdf. Accessed 31 Mar 2026
14. Government of Ireland: Waste Management Act 1996 (End-of-Waste) Regulations 2024 (S.I. No. 660 of 2024) (2024). https://www.irishstatutebook.ie/eli/2024/si/660/made/en/print
15. The International Council on Systems Engineering (INCOSE): Systems engineering (2023). https://www.incose.org/systems-engineering. Accessed 31 Mar 2026
16. Madden, E., Lynch, J., Evans, M., Perry, K., Halpenny, A., Gallagher, A.M.: Circular economy transition actions by a major transport agency – Transport Infrastructure Ireland. In: McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds.) Transport Transitions: Advancing Sustainable and Inclusive Mobility, pp. 1221–1232. Springer, Cham (2025). https://doi.org/10.1007/978-3-031-95284-5_122

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Sustainable Renewal and Maintenance Optimization of an Existing Railway Line Using AI and Digitalization Tools

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Abstract. With growing concerns over greenhouse gases (GHG) emissions and the environmental impact of transportation systems, there is a pressing need for sustainable solutions in infrastructure planning and maintenance. This study focuses on a repurposed railway line from freight to passenger service, assessing degradation and proposing maintenance strategies using artificial intelligence. Climate-related factors are incorporated into the analysis, and several maintenance/repair solutions are evaluated through Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis. These strategies are supported by numerical simulations and monitoring data. The approach integrates Global Warming Potential tracking, predictive maintenance, and optimized replacement strategies to address the challenges of urban mobility. A modular digital platform has been developed, combining real-time sensor data and Building Information Modelling (BIM), along with external tools for infrastructure management. Supported by the EU-funded NRPCES project (New Replacement Policy Considering Environmental Sustainability), the study aims to deliver a data-driven decision-support system that optimizes asset maintenance scheduling considering both environmental and economic aspects of sustainability. The outcomes of this study include the development of advanced tools for predictive maintenance and live emission monitoring. They are validated through application to a real-world railway infrastructure and environmental data.

Keywords: Predictive Maintenance · Railway asset management · Climate-resilient infrastructure

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1 Introduction

The transportation sector accounts for 23% of global GHG emissions [1], yet rail transport role is crucial for achieving the EU's decarbonisation goals under "Fit to 55" [2]. To contribute effectively, the sector must reduce GHG emissions across its entire life cycle [3]. Recent studies show that maintenance is a major source of railway-related GHG emissions, with track tamping accounting for 48.7% and track regulation 31.8% of GHG emissions from maintenance and renewal [4]. In parallel, the railway sector is undergoing a profound digital transformation. Digital twins are emerging as a pivotal enabler of future asset management strategies, offering dynamic, virtual replicas of physical assets synchronised through sensor integration historical records, and advanced analytics [5].

At the spatial level, Geographic Information Systems (GIS) provide the backbone for infrastructure modelling. Open-source platforms such as QGIS enable the acquisition, management, and visualisation of geospatial data in an open and reproducible manner [6]. BIM provides a structured environment for consistent asset representation and extends its scope beyond design to support performance, operation, and lifecycle management. In railway domain, the release of Industry Foundation Classes (IFC) 4.3 [7] by building SMART provides, for the first time, a standardised scheme for railways, ensuring that alignment, track elements, and facilities are consistently represented across platforms. Complementing this, the building Smart Data Dictionary (bSDD) [8] introduces a semantic layer that enables standard classification of railway assets, securing interoperability between different environments.

In this context, a study on a railway line is being carried out with the objective of assessing infrastructure degradation and developing maintenance strategies supported by artificial intelligence. An objective of this research is the development and implementation of a tool for real-time monitoring of GHG emissions during operations. This tool is expected to provide critical insights for advancing research and to inform strategies.

2 Description of the NRPCES Project

2.1 Project Description

The study aims to develop a data-driven decision-support system for a new railway replacement policy that balances economic and environmental performance. The tool optimizes the Economic Replacement Time (ERT) of tracks, whose validation will be undertaken through a case study. The determination of the optimal replacement point will be based on the integration of heterogeneous data—covering diverse categories, types, and sources — and quantified through a set of relevant KPIs. As per Fig. 1, the workflow begins with data collection and structuring—including geometric, track condition, LCA and meteorological data—structured via an API to ensure compatibility.

Once processed, the data enter the modelling and simulation phase, estimating track degradation and supporting a condition-based maintenance model. The project is organized into seven work packages, encompassing technical, scientific, management and dissemination activities.

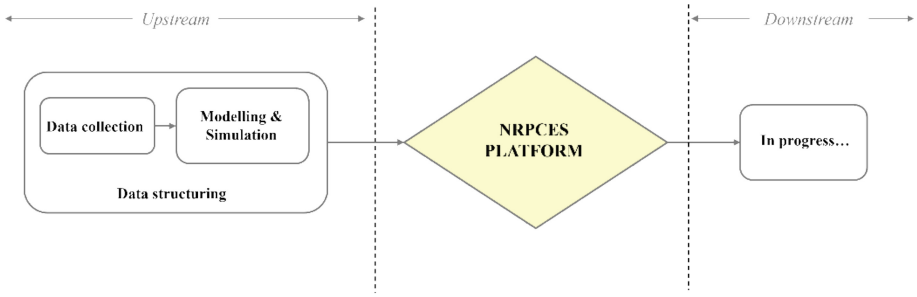


Fig. 1. Activities workflow

2.2 Description of the Case Study

This case study examines the Leixões Line, a 20.9 km railway corridor in the Porto Metropolitan Area linking Porto-Campanhã station to the Port of Leixões station. In recent years the infrastructure has been modernized and reinstated regular passenger operations. The studies line accommodates both freight and passenger services. On weekdays, 60 passenger trains operate, 30 in each direction, with a frequency of two trains per hour per direction during peak morning and evening periods. On weekends and public holidays, 34 trains are scheduled (17 per direction).

2.3 Data Collection and Structuring

The estimation of track geometry degradation is performed by a set of numerical and real monitoring data. These observations include track geometry layout, vehicle type and operating speed, wind direction, provided by infrastructure managers such as IP, mapping resources like Google Maps, rail irregularity measurements, and inspection reports. Data structuring is a key part of the NRPCES project. It transforms raw data into information that is clear, organized, and easy to interpret. Cleaning steps remove errors and inconsistencies to ensure the data is reliable. Basic statistics provide an overview, while mapping the data helps reveal patterns across locations. The final datasets can be saved in formats like CSV, shapefile, or GeoPackage, ensuring compatibility in the main platform. Finally, all structured data are stored in a PostgreSQL database with PostGIS, providing a strong and flexible system for analysis, research, and decision-making.

The advanced 3D model combined open geospatial data with official technical records. OpenStreetMap supplied railway alignment and assets, and OpenTopography DEMs provided accurate elevation, with both processed in QGIS through quality control and simplification for spatial coherence. The model was then strengthened with IP track-geometry reports (horizontal/vertical alignment, curvature, superelevation, speed restrictions) and continuous measurement-vehicle data (chainage, elevation, gradients, operating speeds). These inputs validated the alignment, ensured model consistency, and captured key infrastructure performance constraints.

In the current study, climate parameters such as temperature, humidity, precipitation, wind speed and direction, and solar radiation are considered, as they have a direct impact on track degradation. These factors influence rail behavior through thermal stress,

corrosion, ballast instability, drainage inefficiency, material deterioration, as well as the ERT.

Life Cycle Assessment evaluates the environmental sustainability of railway construction, operation and end-of-life in a Cradle-to-Grave scenario, in line with ISO 14040:2006 [9]. This case study focuses on the maintenance and replacement stages, specifically track tamping and grinding for maintenance, and ballast replacement. Environmental performance is assessed using a set of KPIs, primary: Global Warming Potential (GWP), and secondary: resource use, energy consumption, and waste management. Given the central role of the project in monitoring GHG emissions, GWP is calculated for all LCA stages and for the selected activities, while energy consumption is assessed in maintenance (B2) and replacement (B4) phases, and resource use only in ballast replacement (B4).

2.4 Modelling and Simulation

A 3D railway track model is developed in ANSYS® and coupled with SIMPACK® via FlexTrack to simulate the multi-layered track in multibody dynamics. The track includes rail, rail pad, sleeper, ballast, sub-ballast, and soil. Material properties [10] and meshes are assigned before performing modal reduction through Component Mode Synthesis (CMS). Interface nodes are defined as connection points with the vehicle, and the reduced model—containing condensed mass and stiffness matrices—is exported as a Flexible Body Input (.fbi) file. This enables accurate integration of the finite element track model.

The vehicle is simulated using a multibody dynamics model developed enabling the simulation of its three-dimensional motion and dynamic behavior for both freight and passenger trains [11]. The model describes the vehicle as a set of interconnected rigid bodies, where interactions are defined through joints, kinematic constraints, and force elements. To capture the interaction with the infrastructure, the vehicle model is coupled with the flexible track, which incorporates the elastic and damping properties of the track into the simulation. This integrated framework provides a consistent basis for analysing dynamic vehicle–track interaction under various operating conditions.

Predictive Condition-Based Maintenance Model. An AI-based predictive maintenance model is proposed with a focus on optimal tamping scheduling. A hybrid approach is proposed that integrates artificial intelligence track degradation prediction and optimization techniques. In this framework, machine learning methods such as Long Short-Term Memory (LSTM) networks and Random Forest (RF) algorithms are employed to forecast the degradation process, while mixed-integer programming determines the most efficient tamping schedule. The development of the model is structured into three phases. The first phase establishes the baseline predictive framework using real track geometry measurements and considering GHG emissions generated by tamping operations. The basic model is formulated as a mixed-integer optimization problem where the track is divided into discrete segments, and time is represented in predefined periods. A binary decision variable indicates whether tamping is performed on a given segment during a specific time period. Track degradation is described by the evolution of the standard deviation of the longitudinal level, while recovery after tamping is modeled as a function of the track condition at the time of intervention. Parameters

such as the degradation rate of each segment, the maximum permissible standard deviation depending on train speed, and the requirement that tamping operations begin and ends on straight alignments are all explicitly included. The model provides an initial estimation of GWP associated with tamping, linking maintenance planning to LCA. The second phase incorporates numerical simulation of vehicle–track interaction and AI-based forecasting. A dynamic vehicle-track interaction model simulates degradation of the longitudinal level as a response to repeated wheel-rail contact forces. This formulation captures how vehicle speed, axle load, and environmental conditions such as rainfall and temperature influence the deterioration rate. These simulation outputs are then processed using machine learning methods (LSTM and RF) for predicting degradation (intermediate model). These predictions form the basis for improved optimization of tamping schedules in subsequent steps. The final phase integrates the AI-based prediction and optimization scheduling approaches into a validated decision-support tool. The final model combines outputs from phases 1 and 2 with experimental data, ensuring both robustness and practical applicability. Once validated, it provides actionable insights for infrastructure managers, including LCA, LCC, and the optimal scheduling of tamping operations.

Automatic BIM Generation. The proposed framework integrates geospatial processing, alignment parametrisation and standard-based modelling (see Fig. 2). It is organised into four stages: i) data collection, ii) alignment analysis, iii) semi-automatic railway design, and iv) IFC 4.3 model enrichment.

Railway infrastructure digitalisation demands an accurate spatial foundation before any design or modelling process. The methodology acquires raw geospatial and topographic data through automated QGIS routines. This captures track centreline and infrastructure contextual assets (e.g., stations, level crossings, bridges, tunnels, and hydraulic features). The framework leverages established QGIS plugins (e.g., QuickOSM [12] for OpenStreetMap extraction, OpenTopography API for terrain/elevation, Profile Tool for elevation validation, Topology Checker for integrity checks, and DB Manager for multi-source data handling). Additionally, to reduce noise, dense polylines are simplified with the Ramer-Douglas-Peucker (RDP) algorithm [13]. The workflow supports user-defined corridor extraction and analysis by section, region, initial/final station or by chainage limits. This multi-process framework delivers a standardised geospatial dataset comprising horizontal and vertical alignments, profiles and DTM surface models, forming the backbone for IFC 4.3 generation.

In railway design, the Horizontal Alignment (HA) specifies the plan geometry of the track, comprising tangents (T), transition spirals (S), and circular arcs (C) segments.

When combined with vertical profiles and superelevation definition, the HA extends to a 3D alignment forming the geometric basis for track design and modelling. Initially captured as QGIS polylines, the HA is formalised into parametric descriptors, such as chainages, curvature, superelevation, permissible speed, and transition points (breakpoints). A curvature-chainage estimates points of intersection to segment tangents, transition spiral, and circular arcs. Following [14], the segmentation-fitting proceeds in three-stages: i) breakpoint identification using a dynamic heading-gradient threshold, ii) adaptive analytic reconstruction, and iii) optimal local parameter settings, minimising point-to-alignment deviation.

The methodology uses custom C#. NET commands in Autodesk Civil 3D to: i) load QGIS post-processed data, ii) create the baseline alignment, iii) perform alignment segmentation-fitting, iv) auto-generate profiles, assemblies/subassemblies, and the corridor, and v) export a standards-compliant IFC 4.3 railway geometric schema. The exported geometric model is semantically normalised through bSDD mappings, ensuring interoperability, scalability and providing a robust basis for subsequent enrichment into domain-specific digital twins.

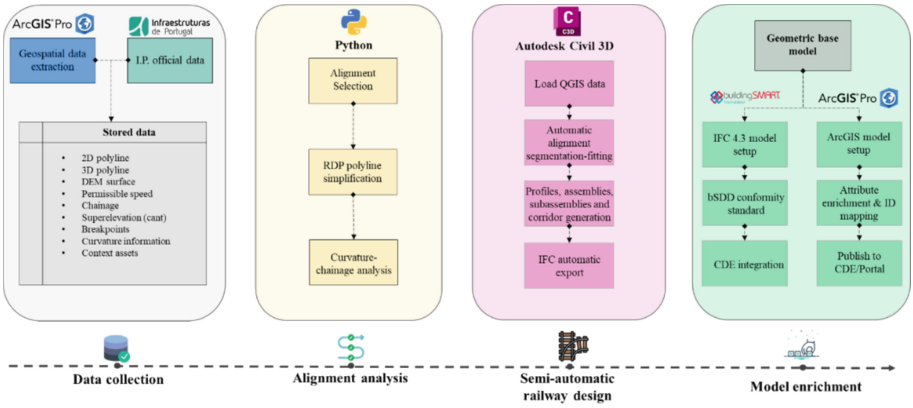


Fig. 2. Framework of the automatic infrastructure BIM generation

2.5 NRPCES Platform

The ArcGIS platform, designed by Esri, provides tools for data integration, analytics, and visualization while also supporting the development of web-based and desktop applications, enabling organizations to work with maps, 3D models, spatial analytics, and geodatabases. It integrates geospatial intelligence with LCA decision-making processes to estimate sustainable and cost-effective replacement times.

The ArcGIS platform's workflow involves gathering data from various sources in formats such as CSV, JSON, and Dictionary. This data is extracted through API HTTP request responses and processed using an ETL (Extract, Transform, Load) approach implemented with Python scripts. After that, the data is stored in a database or a local computer. A data structure API is implemented to run and test different data types, while unnecessary values are removed through an automated process. After importing data from the database and IFC protocol, the ArcGIS platform is enhanced with Reality Studio Tool by enriching the process with detailed 2D maps, 3D models, and map imagery. This integration ensures support for deeper analysis and simulations within ArcGIS.

The outputs of the system include clear visual insights through 2D and 3D mapping, data filtering, and trend analysis, with the option to export results for further use. It also provides real-time updates and integrates sensor and multi-source data streams

through the FIWARE Orion Context Broker, making processed information accessible via APIs. The commercial tool is adapted to project needs by integrating its 2D maps, 3D models, and imagery with IFC-based data, applying structuring and annotation to ensure consistency and alignment with project workflows. The technology stack for desktop application development consists of ArcGIS, Python, PostgreSQL, Jupyter Notebook, and a cloud platform.

3 Conclusions and Next Steps

This study has demonstrated the potential of integrating advanced digital technologies, predictive maintenance models, and sustainability assessment methods to improve the environmental and economic performance of railway infrastructure. By focusing on the repurposed Leixões Line, the work validated a comprehensive framework for railway infrastructure management that combines numerical simulation, real-time monitoring, and data structuring into a modular decision-support platform.

The outcomes highlight that predictive maintenance strategies can significantly reduce GWP and LCC when compared to conventional and schedule-based maintenance approaches. From a cost-benefit perspective, these reductions imply that the upfront investments required for monitoring technologies, data infrastructure and a qualified workforce with analytical capabilities can be offset by lower maintenance costs, optimization of maintenance interventions, prolonged railways infrastructure service life, and avoided environmental costs over the infrastructure life cycle.

The methodologies presented are replicable across other railway systems and scalable to larger railway networks. The next steps will include conducting a detailed functional analysis of features, followed optimisation of the engine and its integration with the API.

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References

1. Jaramillo, P., et al.: Transport. In: Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1049–1160. Cambridge University Press, Cambridge (2023). https://doi.org/10.1017/9781009157926.012
2. CER, EIM, UNIFE: EU strategy for long-term GHG reductions: the crucial role of rail. Position Paper, The European Rail Industry. https://www.cer.be/images/publications/positions/181129_CER-EIM-UNIFE_PositionPaper_EU-Strategy-for-long-term-greenhouse-gas-emissions-reductions.pdf (2018). Accessed 4 Feb 2026
3. Mahdavinasab, N., Beg, Z., Barabady, J., Juntti, U., Garmabaki, A.H.S.: The effect of climate condition on theCO_2 emissions of maintenance activities: a case study from railway. In: Abrahamsen, E.B., Aven, T., Bouder, F., Flage, R., Ylönen, M. (eds.) Proceedings of the

35th European Safety and Reliability Conference (ESREL2025) and the 33rd Society for Risk Analysis Europe Conference (SRA-E 2025) (2025). https://doi.org/10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P9621-cd
4. Krezo, S., Mirza, O., Kaewunruen, S., Sussman, J.M.: Evaluation of CO_2 emissions from railway resurfacing maintenance activities. Transp. Res. Part D: Transp. Environ. **65**, 458–465 (2018). https://doi.org/10.1016/j.trd.2018.09.019
5. Lim, K.Y.H., Zheng, P., Chen, C.-H.: A state-of-the-art survey of digital twin: techniques, engineering product lifecycle management and business innovation perspectives. J. Intell. Manuf. **31**(6), 1313–1337 (2020). https://doi.org/10.1007/s10845-019-01512-w
6. Graser, A., Sutton, T., Bernasocchi, M.: The QGIS project: spatial without compromise. Patterns. **6**(7), 101265 (2025). https://doi.org/10.1016/j.patter.2025.101265
7. buildingSMART: IFC4.3.x development – Cover (copyright section) (2024). https://github.com/buildingSMART/IFC4.3.x-development/blob/master/content/cover.md#copyrigh. Accessed 10 Feb 2026
8. buildingSMART International Limited: IFC 4.3.2 documentation (2024). https://ifc43-docs.standards.buildingsmart.org/. Accessed 10 Feb 2026
9. International Organization for Standardization: ISO 14040:2006 – Environmental management – life cycle assessment – principles and framework, 2nd edn. ISO, Geneva (2006)
10. Ribeiro, A.C.C.A.: Transições aterro-estrutura em linhas ferroviárias de alta velocidade: análise experimental e numérica. Dissertation, Universidade do Porto (2012). https://doi.org/10.34626/85c4-xy92
11. Guedes, A., Silva, R., Gonçalves, V., Montenegro, P.A., Meixedo, A., Fernandes, J.: Assessment of running safety of railway vehicles using acceleration data from an on-board system. In: Proceedings of the 1st International Conference on Transportation Systems (2025)
12. Trimaille, E.: QuickOSM – QGIS plugin to fetch OSM data (overpass API). QGIS Python Plugins Repository. https://plugins.qgis.org/plugins/QuickOSM/. Accessed 13 Feb 2026
13. Tripathy, S.: Ramer–Douglas–Peucker (RDP) algorithm in computer vision. https://medium.com/. Accessed 13 Feb 2026
14. Pu, H., Fu, H., Song, T., Schonfeld, P., Peng, X.: Recreating horizontal alignments of existing railways with a hybrid analytic and harmony search algorithm. Eng. Appl. Artif. Intell. **128**, 107354 (2024). https://doi.org/10.1016/j.engappai.2023.107354

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