On the right track: Cost-optimal choices to decarbonize the European railway network

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On the right track: Cost-optimal choices to decarbonize the European railway network

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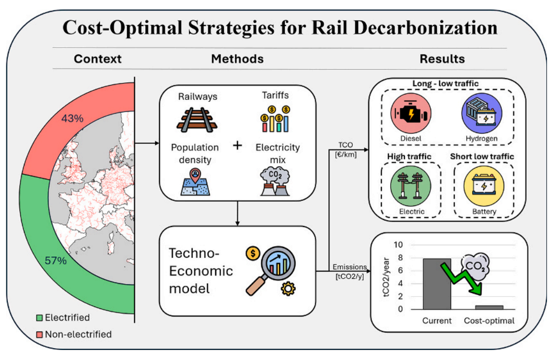
HIGHLIGHTS

- A geospatial framework identifies cost-optimal rail decarbonization strategies.
- Batteries suit short routes, hydrogen long ones, electrification dense lines.
- Single-technology strategies raise total costs by up to 30%.
- Cost-optimal portfolios reduce well-to-wheel carbon emissions by up to 90%.
- Hydrogen competitiveness strongly depends on future fuel cost reductions.

GRAPHICAL ABSTRACT



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ABSTRACT

As Europe accelerates toward climate neutrality, the phase-out of diesel trains creates an urgent need for cost-effective alternatives on non-electrified railway lines. With over 40% of the network still lacking electrification, regional services face a critical decarbonization challenge. This study introduces a geospatial techno-economic framework to identify cost-optimal strategies for regional passenger rail, integrating high-resolution network data, demand estimation, lifetime costs modeling, and emissions assessment. Three archetypes emerge: (i) short low-traffic lines favor battery; (ii) long low-traffic lines favor hydrogen, provided that hydrogen prices decline to approximately €5–6/kg; and (iii) dense high-traffic lines favor electrification. The results indicate that no single propulsion technology can simultaneously minimize costs across heterogeneous line conditions. In particular, a single-technology strategy leads to significant economic penalties, increasing Total Cost of Ownership by 10–30%. Furthermore, under the cost-optimal configuration, well-to-wheel carbon emissions can be reduced by up to 90% compared to a diesel-only baseline. Overall, the analysis demonstrates that only a diversified technology mix can ensure a successful and economically sustainable transition toward zero-carbon regional rail.

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Nomenclature

Abbreviations

BEMU	Battery Electric Multiple Unit
BMU	Battery Multiple Unit
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CI	Carbon Intensity
DMU	Diesel Multiple Unit
ECMS	Equivalent Consumption Minimization Strategy
EMU	Electric Multiple Unit
ESPG	Energy Storage and Power Generation
ETS	Emissions Trading Scheme
FC	Fuel Cell
HMU	Hydrogen Multiple Unit
HVO	Hydrotreated Vegetable Oil
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LTO	Lithium-titanate battery
MACC	Marginal Abatement Cost Curve
NZE	Net Zero Emissions (by 2050 Scenario)
OPEX	Operating Expenditures
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
VAT	Value Added Tax

Symbols

ATD	Annual traveled distance km/year
b	Rolling resistance coefficient N/(km/h)
BAT_{BEMU}	BEMU battery capacity kWh
c	Static resistance coefficient $N/(km/h)^2$
$CAPEX$	Capital expenditures €
CE	Total carbon emissions per year tCO_2/year
CI	Electricity carbon intensity $kgCO_2/kWh$
DCE	Direct carbon emissions per km $kgCO_2/km$
d_{ij}	Distance between two stations i and j km
e	Aerodynamic resistance term N
ECE	Equivalent carbon emissions per km $kgCO_2/km$
F_t	Tractive effort N
GWP	Global Warming Potential $kgCO_2/kg$ or $kgCO_2/l$
ICE	Indirect carbon emissions per km $kgCO_2/km$
K	Gravitational constant km^2/person
M	Train mass kg
N	Analysis horizon years
$OPEX$	Operating expenditures €/year
r	Discount rate –
t	Year index –
TCO	Total cost of ownership €/km
v	Train speed m/s
W_i	Population weight for stations –
α	Track slope rad or ‰
λ	Rotary allowance –
ω	Land use attraction coefficients –

1. Introduction

Considering that more than 40% of the European railway system is not electrified, urgent action is needed to align regional rail with Europe's climate neutrality goals [1]. Many countries and regions have already planned progressive policies to phase out diesel even earlier than the European long-term strategies [2]. Notable examples include France, where SNCF aims to eliminate diesel by 2035 [3]; Germany [4] and the UK [5], which target climate neutrality by 2040; and the Netherlands, Austria, Italy, Spain and other countries, which are piloting battery and hydrogen trains for passenger service. In this rapidly evolving landscape, choosing hasty decisions could lead to suboptimal solutions that would experience disproportionately high costs with limited benefits [6]. Given these constraints, a robust decision-support framework to identify cost-effective decarbonization pathways for the continental railway network becomes essential to support policy and

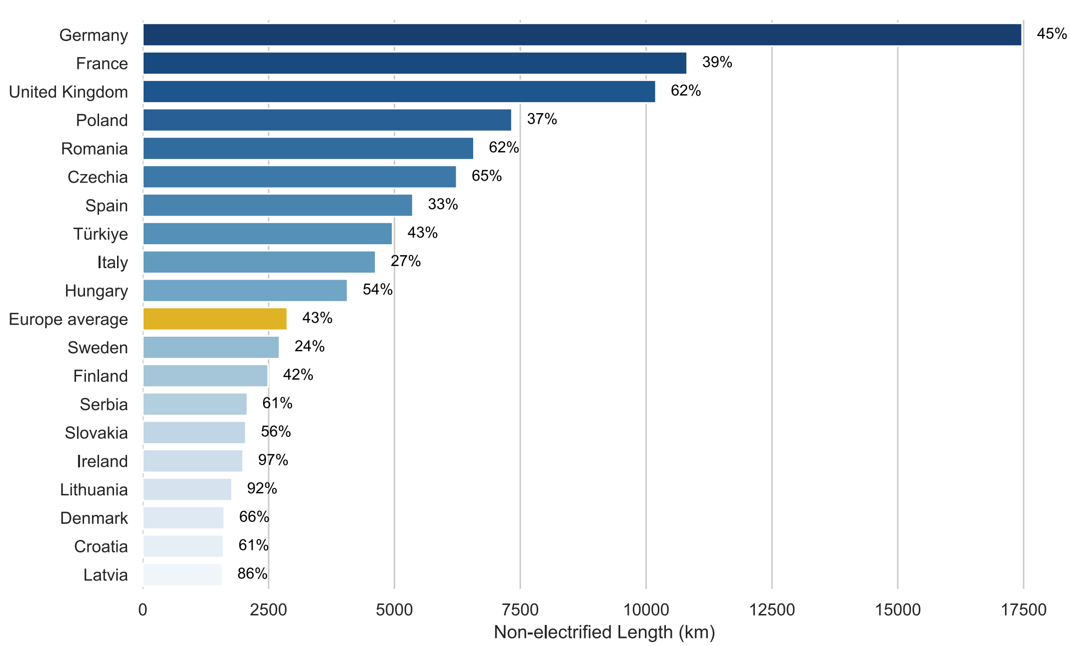

Fig. 1. Share and total length (km) of non-electrified railway lines in selected European countries with more than 2000 km of unelectrified track. Percentages indicate the share of non-electrified lines within each national network [9].

investment decisions. Although electrification dominates rail infrastructure in Europe, diesel traction remains the least efficient and accounts for 54% of the sector's final energy consumption [7]. The percentage of electrified lines even decreases if the worldwide picture is analyzed: only 31.7% of the lines have an overhead connection [8]. These numbers – reported in Fig. 1 for the European countries with more km of non-electrified lines – suggest an enormous potential for the decarbonization of rail transport through more efficient, sustainable and cost-effective propulsion systems.

Modernizing existing infrastructure and constructing new rail lines offer an opportunity to further reduce emissions and improve the transport network, driven by the growing demand for moving goods and passengers in a more sustainable way. To stay on track with the Net Zero Emissions (NZE) by 2050 Scenario, CO_2 emissions from the railway sector must decline by more than 5% annually to 2030, while the railway sector's energy demand is projected to increase by around 30% in the IEA Base Scenario and up to 70% in the IEA High Rail Scenario by 2050, compared with 2017 [10]. The urgent need to expand the role of railways in decarbonizing long-distance terrestrial travel may, however, conflict with technical and infrastructural constraints along individual lines. Indeed, electrification is not always feasible or economically optimal, particularly for remote or isolated regions.

Some of the most promising Energy Storage and Power Generation (ESPG) options to replace diesel traction are:

- Electric Multiple Unit (EMU): The most efficient and widespread option. However, constructing the overhead catenary infrastructure can be prohibitively expensive relative to the line's traffic volume.
- Battery Electric Multiple Unit (BEMU): Characterized by low costs and efficient operation, but the weight and volume of battery systems – and consequently their cost – increase rapidly with the distance they are required to cover. Commercially, declared ranges typically fall between 80 and 150 km, as shown in Table 1. The maximum covered range with a single charge is 224 km under optimal conditions [11], with a train with a nameplate autonomy of 150 km.
- Hydrogen Multiple Unit (HMU): Fuel cell hybrid trains can fill the gap left by other propulsion systems. Due to their comparable range, flexibility, and performance characteristics, HMUs can serve as viable alternatives to Diesel Multiple Units (DMUs) in many cases. The longest trip with a single refueling was completed in 2024, covering 2803 km over 46 h of continuous operation [12], with a commercial nameplate autonomy exceeding 1000 km. Table 2 summarizes upcoming HMU fleets and the most promising ongoing projects.

In a decarbonization scenario constrained by technical and economic limitations, the literature reveals a lack of studies focused on assessing the techno-economic potential of different propulsion options at the regional or national scale, taking into account the strengths and weaknesses of existing technologies that could contribute to railway decarbonization. Indeed, while several studies have modeled and predicted the energy consumption of different ESPG systems (e.g., *Kapetanović* et al. [48]) and examined lifetime optimization (e.g., *Parola* et al. [49]), only a limited number have developed criteria to identify the most cost-effective alternatives, and even fewer have done so at a regional or national level.

An important contribution is provided by *Jiang* et al. [50], who conducted a techno-economic analysis comparing BEMU, HMU and EMU. Their study highlights key parameters for cross-technology comparison, such as traffic volumes, hydrogen cost, and daily covered distances. However, their model extrapolates results from a single case study without offering a broader perspective on the national rail system. Additionally, it omits the DMU, which serves as a fundamental benchmark for the current non-electrified network, both economically and environmentally. In another study, *Hernandez* et al. [51] performed a Life Cycle Assessment (LCA) and techno-economic evaluation of fuel cell, battery, and biofuels locomotives, analyzing the transition costs associated with these alternatives in the United States. Nevertheless, their work focuses exclusively on freight traffic, neglecting passenger operations. Similarly, *Bakker* et al. [52] developed a strategic model for cost-effective rail freight decarbonization, accounting for fuel technology adoption, fleet inertia, and future uncertainties. Yet, this study also remains limited to freight transport and does not extend the analysis to passenger rail.

The present study addresses these gaps by developing a scalable, geospatial techno-economic framework to identify cost-optimal decarbonization strategies for non-electrified regional rail in Europe. By integrating validated datasets with high-resolution geospatial analysis, the proposed approach enables a robust assessment of alternative traction technologies – such as battery, electric, hydrogen, and diesel – through a generalized line-by-line approach. The methodology combines automated railway network extraction, capital and operational cost evaluation, and gravity-based demand estimation, producing consistent and comparable metrics across diverse geographic contexts. This approach is designed to support decision-makers in aligning decarbonization goals with territorial constraints, providing a replicable and data-driven tool to guide national and regional rail decarbonization planning.

2. Overview of propulsion technologies

This section introduces the propulsion technologies considered in the analysis. Each system is briefly described to outline its main components, operation principles, and role within the techno-economic

Table 1
BEMU recent and future commercial applications.

Vehicle's Name	Train company	Specifics			
		Routes	Fleet dimension	ESPG	Ref.
Coradia Continental	Alstom	Verkehrsverbund Mittelsachsen (2024–2025)	11	Range 120 km	Alstom [13,14]
Flirt AKKU (BEMU) – 1000 kW	Stadler	Schleswig-Holstein, Lower Saxony, Thuringia, Mecklenburg-Vorpommern (2023–2027), Sjælland (2028), Austria (2028)	311	Range 80 km, ∼500 kWh, 15 kV catenary operation	STADLER, Railvolution, Railmarket, Railwaygazette [15–20]
Hitachi Masaccio (BEMU) – 1170 kW	Hitachi	Italy (2022–2026)	135	Range up to 120 km, three possible configurations depending on hybridization	Hitachi [21,22]
Mireo B – from 1700 kW	Siemens	Baden-Württemberg (2025), (2025), Mitteldeutschland (2025), North Rhine-Westphalia (2026), Midtjyske Jernbaner (2025)	71	Range 80 km 2-part – 120 km 3-part, 15 kV and 25 kV catenary operation	Siemens [23–27]
Regiopanter – 1360 kW	Škoda – ABB	Moravian-Silesian Region (2025)	15	Range 80 km, 3 kV DC and 25 kV catenary AC catenary operation	ABB [28]

Table 2
HMU recent and future commercial applications and some remarkable projects.

Vehicle's Name	Train company	Specifics			
		Routes	Fleet dimension	ESPG	Ref.
Coradia Stream H – 1170 kW	Alstom	Brescia – Iseo – Edolo (IT, 2025–103 km); Apulia (IT, n.a.)	8 + 4 + 4	FC (400 kW) – G/ NMC (850 kWh)	Peyrani et al., ALSTOM [29–31]
FLIRT H2 – (950 and 1435 mm gauge) – 120 to 800 kW	Stadler	San Bernardino – Redlands University (CA, 2025–15 km); Merced – Sacramento (2027, ~160 km) Alghero – Alghero Aeroporto (IT, 2026–7 km); Cosenza – Catanzaro (IT, 2026–110 km)	21 + 33	FC (600 kW) – LTO (318–800 kWh)	Stadler, Hydrogen Tech. Expo, Bahn, Stadler, Rail Journal [32–34] [35–37]
Mireo Plus H – 1700 kW	Siemens	Heidekrautbahn (DE, 2024–60 km); Augsburg–Füssen (DE, 2024–105 km); Mühldorf – Tüßling – Burghausen (DE, 2026–32 km)	12	FC (400 kW) – LTO (1/3 of Mireo plus B)	SAFT, SIEMENS, BALLARD [23,38–41]
FV-E991 "HYBARI" – 195 kW	Hitachi, Toyota	Tsurumi Line and Nambu Line (JAP, 2022)	1 (prototype) – commercial in 2030	FC (240 kW) – Li-ion (240 kWh)	Ogawa, Toyota, East Japan Railway Company [42–44]
FCH2RAIL	CAF, DLR, Toyota, and others	Madrid – Mérida (ESP, 2024 test: ~804 km)	1 (prototype)	FC (480 kW) – LTO (238 kW) + pantograph	Toyota, FCH2RAIL, Holger [45–47]

framework. A detailed description of the modeling approach is provided in the Supplementary Material.

2.1. Hydrogen multiple unit (HMU)

The hydrogen multiple unit is powered by a Proton Exchange Membrane (PEM) fuel cell system, which generates electricity from compressed hydrogen stored on board. The powertrain includes auxiliary components to manage air, heat, water, and power conversion. A lithium-ion battery provides extra power during rapid accelerations, helps stabilize operation, and enables regenerative braking.

The system layout is shown in Fig. 2a. The energy management strategy – an Equivalent Consumption Minimization Strategy (ECMS) for the current work – coordinates the power flows between the fuel-cell system and the battery to minimize hydrogen consumption and maintain efficient operation. This combination offers the advantages of zero local emissions and higher efficiency compared to diesel traction. However, the high cost of green hydrogen remains a key drawback, requiring precise energy consumption and optimization algorithms [31].

2.2. Battery electric multiple unit (BEMU)

Battery electric multiple units combine on-board batteries with a pantograph, allowing operation on non-electrified sections (e.g., tunnels) and direct supply from the overhead line when available. This hybrid approach reduces the required battery size and enables partial energy recovery during braking (regenerative braking), though it depends on careful charging management and route-specific constraints. As a result, BEMUs are more sensitive to service delays or interruptions,

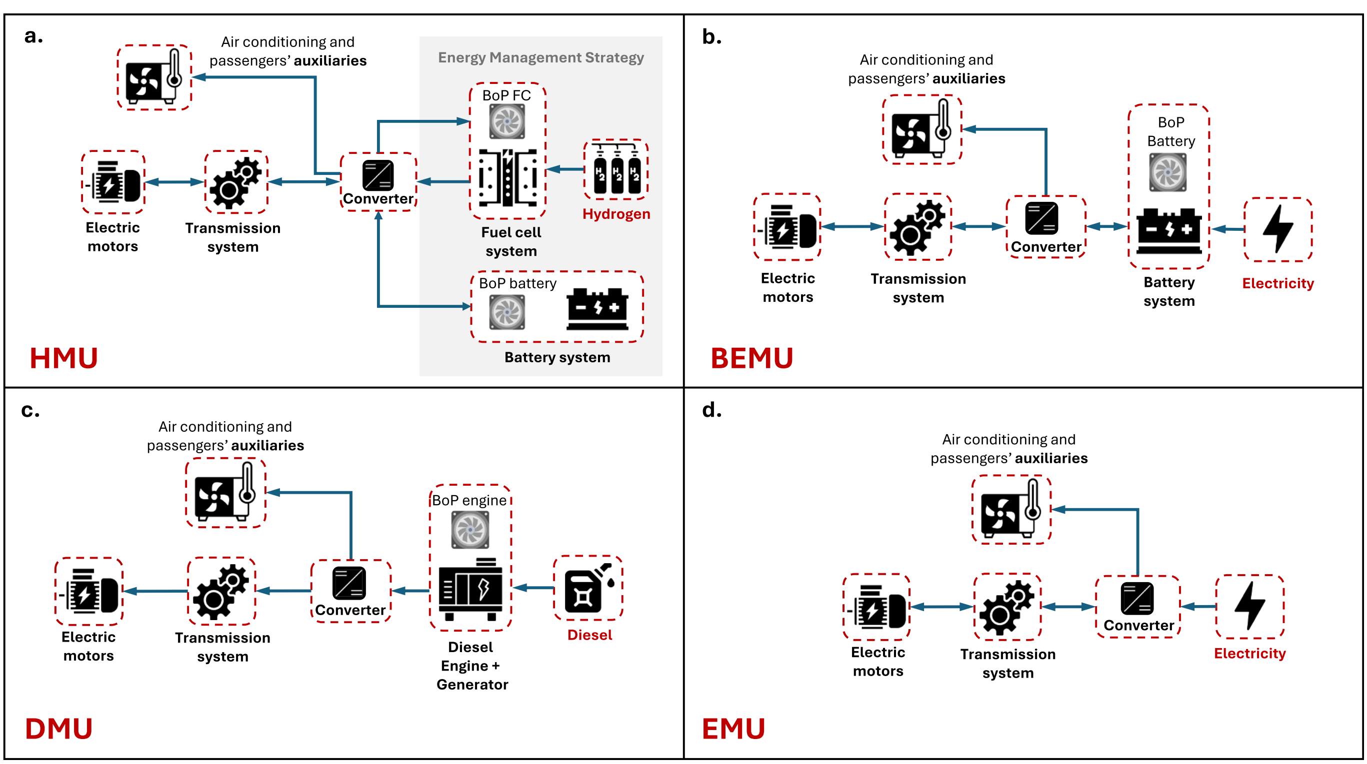

Fig. 2. Schematic layout of the propulsion systems under study: a. Hydrogen Multiple Unit (HMU); b. Battery Electric Multiple Unit (BEMU); c. Diesel Multiple Unit (DMU); d. Electric Multiple Unit (EMU).

which may disrupt charging schedules and affect operational reliability.

In this work, to simplify the analysis at the network level, the system is modeled as a Battery-only Multiple Unit (BMU), despite most commercial examples being BEMUs equipped with pantographs. This choice is justified because the range is the key operational constraint under investigation, and the model optimizes the battery capacity to achieve ranges consistent with current BEMU commercial portfolios (Table 1). This battery-only modeling approach ensures continental-scale feasibility but serves as a conservative economic baseline, as it does not account for the battery capacity and weight optimizations achievable through mid-journey contact wire charging. Thus, the findings remain representative of the broader BEMU fleet. Since the range directly influences the battery capacity – and consequently both capital and operational costs – it is optimized according to the required distance. The system layout is shown in Fig. 2b.

2.3. Diesel multiple unit (DMU)

The diesel multiple unit employs a conventional diesel engine coupled with a generator to supply traction power, as shown in Fig. 2c. Its main advantages are proven reliability, robust components, the low cost of diesel fuel, and an established refueling infrastructure. However, compared with alternative propulsion systems, it exhibits lower overall efficiency, higher greenhouse gas and pollutant emissions, and is subject to volatile and rising fuel prices [53]. Moreover, maintenance costs are expected to be higher than for HMUs, BEMUs, and EMUs due to the large number of moving parts [54].

2.4. Electric multiple unit (EMU)

The electric multiple unit draws power directly from the overhead lines via a pantograph. Its main strengths are high efficiency, technological maturity, and zero local emissions, while its total environmental footprint ultimately depends on the carbon intensity of the electricity supply. On the other hand, EMUs depend entirely on the availability of electrified infrastructure, requiring substantial upfront investments in grid and track equipment, and offering limited flexibility on non-electrified routes. The average specific infrastructure cost can exceed €3 million per km in hard-to-electrify routes [55]. The propulsion system is modeled as the final stage of the other ESPG layouts – that is, only the transmission system – since no on-board power generation occurs [54] (see Fig. 2d).

3. Method details

Fig. 3 illustrates the modeling framework. A library of pre-computed train simulations is generated by varying key operating parameters: line length (15–150 km), station frequency (0.1–0.4 stations/km), and orography (0–25‰). These synthetic results are mapped onto the physical network via multi-dimensional linear interpolation using actual line attributes extracted from OpenStreetMap (length, elevation profile, and station spacing). By matching real-world data to this high-density grid, the model minimizes interpolation errors, as the underlying vehicle dynamics remain locally linear within the sampled parameter space.

The electrification cost is then computed by considering natural obstacles (e.g., tunnels and bridges) and combined with country-specific economic parameters – such as energy prices (electricity for the EU [56] and UK [57] countries, diesel for the EU [58] and UK [59] countries), national interest rates [60], VAT [61], and diesel incentives [62] – to calculate Capital Expenditures (CAPEX, in €), which accounts for rolling stock sizing and electrification costs. These values, along with Operating Expenditures (OPEX, in €/year) covering energy, maintenance, and salaries, are then aggregated.

These techno-economic parameters are integrated with the traffic volume estimation, obtained through a gravity-based model that uses population density [63], land use [64], and station distances [63] to estimate passenger demand and train frequency. The outputs are then processed within the techno-economic tool to derive the main Key Performance Indicators (KPIs):

- Total Cost of Ownership (TCO, in €/km),
- well-to-wheel equivalent carbon emissions of different scenarios, and
- marginal emissions abatement costs (€/tCO_2).

This workflow ensures a consistent line-by-line comparison of alternative propulsion technologies across Europe. A brief explanation of the methodology involved is provided in the following section, while

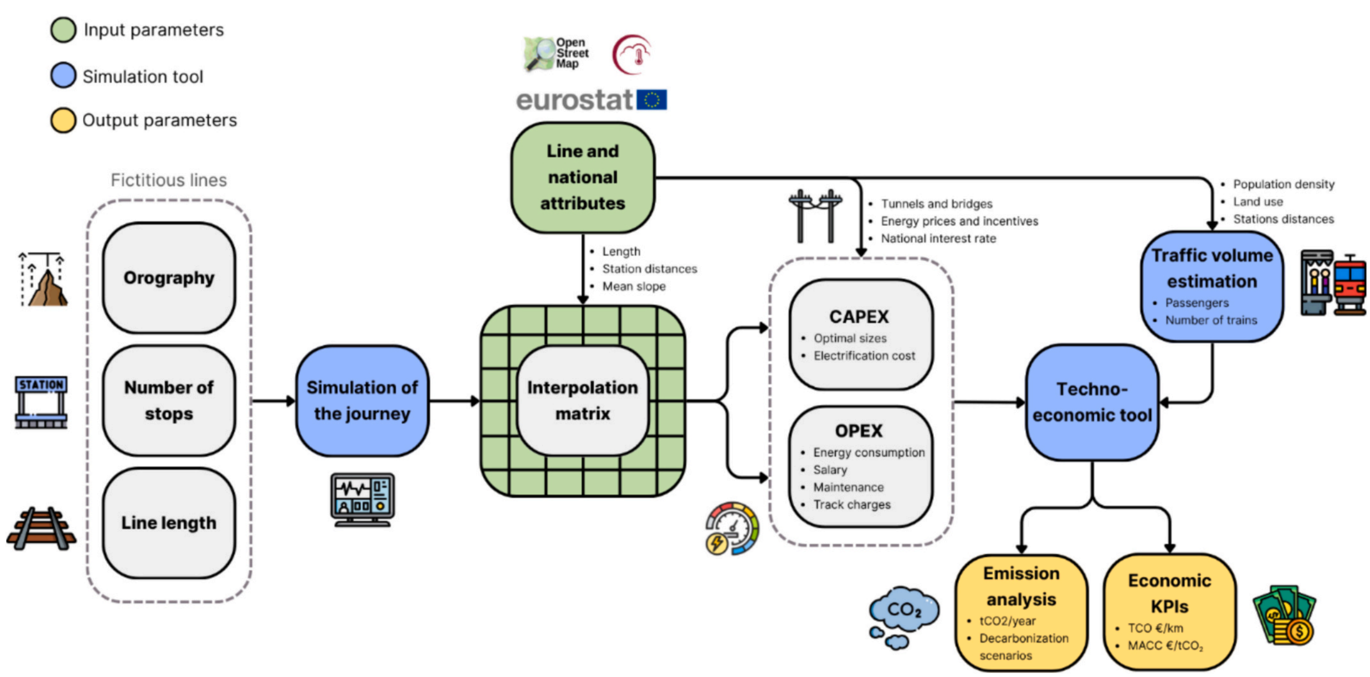

Fig. 3. Integrated techno-economic framework for the evaluation of decarbonization options in regional rail.

a full description can be found in the Supplementary Material.

3.1. Data interpolation

A wide range of railway routes with different characteristics (lengths, gradients, and number of stations) were simulated to capture the diversity of operational conditions. The resulting data were then used to construct a series of interpolation matrices. By inputting the parameters of a specific route into these matrices, the model estimates the corresponding train sizing requirements and associated energy consumption, effectively adapting the pre-simulated results to each line.

3.2. Train energy consumption estimation

The net energy demand of each propulsion system is estimated through a dynamic simulation of train operation along the route. Traction demand is computed from vehicle and track characteristics using Lomonossoff's formulation [65] (Eq. (1)), accounting for resistive forces, slope, and train mass. The mission profile is obtained by numerically solving the motion equations across acceleration, cruise, and braking phases, yielding time-resolved power requirements.

$$M\cdot(1+\lambda)\cdot\frac{d^2x}{dt^2} = F_t(v) - \left(c\cdot\left(\frac{dx}{dt}\right)^2 + b\cdot\left(\frac{dx}{dt}\right) + e\right) - M\cdot(1+\lambda)\cdot g\cdot\sin(\alpha) \tag{1}$$

The formulation accounts for tractive effort F_t (N), resistive forces and related parameters (static c, rolling b, aerodynamic e), slope α, and mass M (kg) with rotary allowance λ.

For HMUs, gross energy consumption is computed by applying an energy management strategy that allocates power between the battery and the fuel cell under charge-sustaining constraints, efficiency limits, and regenerative braking contributions (also applicable to BEMU). For diesel, battery, and electric units, consumption is derived directly from energy flows combined with system efficiency curves. Final energy use is normalized per kilometer, enabling a consistent comparison across propulsion technologies.

3.3. Total cost of ownership

To compare the different propulsion technologies, a techno-economic assessment is required, accounting for costs over the entire train lifetime. Economic viability is evaluated through the TCO indicator, which integrates CAPEX and OPEX. Expressed as a cost per kilometer (€/km), the TCO enables straightforward comparison across propulsion systems and configurations.

$$TCO = \frac{CAPEX + \sum_{t=1}^{N}\frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{N}\frac{ATD}{(1+r)^t}} \tag{2}$$

The analytical formulation is reported in Eq. (2), where r is the discount rate (equal to the long-term interest rate for each country) and N is the number of years considered in the analysis (25 years for trains [66] and 30 for the catenary). The variable t ranges from 1 to N and refers to the years, while ATD is the annual traveled distance (km/year). Country-specific values are also considered for electricity prices, VAT (%), diesel prices, and the related duty reductions in force, assumed as equal to those applied to freight transport.

Capital expenditures (*CAPEX*) include train purchases (both rolling stock and propulsion systems), replacements (e.g., fuel cells and batteries), and infrastructure (e.g., overhead lines for EMUs, charging stations for BEMUs). Operational expenditures (*OPEX*) include maintenance costs, substitutions, salaries, access fees, and fuel costs. The specific cost of overhead line installation is assumed to range between €1.5 M/km for easy installation and €10 M/km for difficult installation, as for tunnels and bridges [67].

3.4. Traffic volumes estimation

Traffic volume is a crucial parameter in this study, as it directly affects the competitiveness of alternative propulsion technologies. Low-traffic lines are more likely to adopt BEMU (for short distances) and HMU (for long distances), while high-traffic lines tend to favor EMU.

Passenger demand is estimated using a gravitational model, which quantifies the potential flow of passengers between pairs of stations on each railway line. Gravitational models are widely used in transport planning to estimate the potential traffic volume between two locations (T_{ij}, in passengers) based on their relative "masses" (W_i and W_j, representing the number of inhabitants for locations i and j, respectively) and the impedance between them (d_{ij}, in km). The impedance term is squared to reduce the contribution of more distant stations. Furthermore, the land-use type around each station is considered to account for the relative attractiveness of each area (ω_i and ω_j for locations i and j, respectively) [64]. A gravitational constant (K, in km^2/person/day) is then applied to convert the resulting value into the expected number of passengers per day. Passenger volume is subsequently converted into the required number of runs by assuming an average 50% capacity utilization, from which the annual traveled distance is derived. A minimum and maximum frequency of runs is also assumed to simulate realistic train operation: 1 run per hour in isolated regions and up to 8 runs per hour in densely populated areas.

$$T_{ij} = K\frac{\omega_i W_i\cdot\omega_j W_j}{d_{ij}^2} \tag{3}$$

3.5. Environmental analysis

For each propulsion technology, the model calculates the total carbon emissions (CE, tCO_2/year) as the sum of direct and indirect emissions, multiplied by the annual traveled distance (Eq. (4)). The system boundary for the environmental assessment is defined by a well-to-wheel (WTW) perspective, excluding embodied carbon associated with vehicle manufacturing and infrastructure construction.

$$CE = (DCE + ICE)\cdot ATD \tag{4}$$

Direct carbon emissions (DCE, tCO_2/km) are non-zero only for DMUs, since the other propulsion systems rely on carbon-free energy vectors. They are calculated as the product of the specific fuel consumption (in l/km) and the CO_2 emitted per liter of diesel combusted (2.69 $kgCO_2$/l).

Indirect carbon emissions (ICE, tCO_2/km) represent emissions generated along the energy supply chain (i.e., vector extraction, processing, transport), rather than at the point of use. For electricity, they depend strongly on each country's energy production mix. Therefore, the average carbon intensity for each country is used, aligning the value with the respective current [68] or future [69] scenario being analyzed, while for diesel, a fixed value is applied [70].

Additionally, the model accounts for the impact of hydrogen and methane leakages occurring throughout their respective supply chains. These are converted into CO_2-equivalent emissions using their Global Warming Potential (GWP) factors [71].

4. Results

In this section, the techno-economic results are presented from both national and continental perspectives. Cost-optimal allocations of diesel, hydrogen, battery, and electrification across Europe are mapped; total costs are quantified in terms of TCO; avoided CO_2 emissions are assessed; and marginal abatement costs are estimated. In addition, a sensitivity analysis on the hydrogen price is performed to evaluate its influence on the cost-optimal configuration. The regional applicability of hydrogen supply is implicitly addressed through the hydrogen price sensitivity analysis, where higher fuel costs may reflect, among other factors, the lack of mature infrastructure in specific countries, thereby directly affecting the cost-optimal share of HMU solutions.

4.1. Decarbonization requires a mix of complementary propulsion options

The model was applied to the entire European railway network to identify the cost-optimal decarbonization strategy under two hydrogen price scenarios. The high hydrogen price case corresponds to current production costs from renewable energy sources (RES; €7.5/kg, from IEA [72]). The low hydrogen price case reflects both the projected 2030 cost of renewable hydrogen produced via electrolysis (€3.05/kg [72]) and the current cost of hydrogen from steam methane reforming with carbon capture and storage (SMR + CCU, €2.7/kg [72]). Given their close alignment, a reference value of €3.0/kg was adopted for the low hydrogen price case.

The results, shown in Fig. 4, reveal that the landscape of non-electrified European railways can be broadly categorized into three distinct groups:

- Short routes with medium to low traffic volumes,
- Long routes with medium to low traffic volumes, and
- Short-to-medium routes with high traffic volumes.

This classification captures the diversity of operational contexts and highlights how different technologies become optimal depending on each line's characteristics (length, traffic volume and electrification feasibility). In the figure, each route is represented as a bubble, whose size is proportional to the difficulty of electrification. This difficulty depends on geographical and infrastructural constraints along the line, which can significantly increase the cost of electrification works.

Each of these categories of lines exhibits a clear technological preference:

- Short-to-medium, low-traffic lines are dominated by BEMUs.
- Medium-to-long, low-traffic lines remain diesel-optimal (DMUs) under high hydrogen prices but shift to hydrogen (HMUs) when hydrogen becomes cheaper.
- High-traffic routes – even when difficult to electrify – favor electric multiple units (EMUs), as high-traffic density justifies the electrification investment.

An additional key finding is the significant shift from diesel to hydrogen under favorable hydrogen prices. As hydrogen prices decrease, a large share of routes currently operated by DMUs (represented as red bubbles in Fig. 4a) transitions to HMUs (shown as blue bubbles in Fig. 4b). This transition underscores the critical role of hydrogen multiple units in displacing diesel traction, especially on long and lightly trafficked lines where electrification is prohibitively expensive and batteries face autonomy constraints. BEMUs cease to be competitive on routes exceeding 60–70 km, corresponding to round-trip distances of approximately 120–140 km, which align well with ranges currently declared by the manufacturers (Table 1).

4.2. Each European country has its own cost-optimal decarbonization strategy

Because each country has distinct geographical, infrastructural, and economic conditions, the resulting technology mix varies significantly across Europe, producing diverse national profiles of diesel, hydrogen, battery and electrification-based solutions.

Fig. 4 illustrates this heterogeneity: each pie chart shows the share of cost-optimal propulsion technologies for non-electrified lines, with the chart size proportional to the total line length, and the background shading indicating the degree of electrification.

At a higher hydrogen price (€7.5/kg, Fig. 5a), DMUs retain an important share, especially in countries with extensive rural or mountainous networks, such as Spain, France, Portugal, Greece, and parts of Eastern Europe. In contrast, under the lower hydrogen price case (€3/kg, Fig. 5b), HMUs expand considerably, replacing diesel traction in nations with long and sparsely trafficked lines. EMUs remain competitive mainly in densely populated and industrialized regions, such as the UK, Germany, Belgium, and the Netherlands, where high traffic volumes justify investment in overhead lines. BEMUs play their strongest role in countries with shorter regional lines and low-to-medium traffic volumes, such as Denmark, Poland, Germany, parts of Scandinavia, and the Baltic states. This country-level differentiation demonstrates that decarbonization strategies cannot rely on a single technological pathway, but must instead balance national geography, traffic demand, and infrastructure readiness. Fig. 5c, Fig. 5d and Fig. 5e provide line-to-line visualizations for Germany, the UK, and Italy, respectively, under the low hydrogen price case.

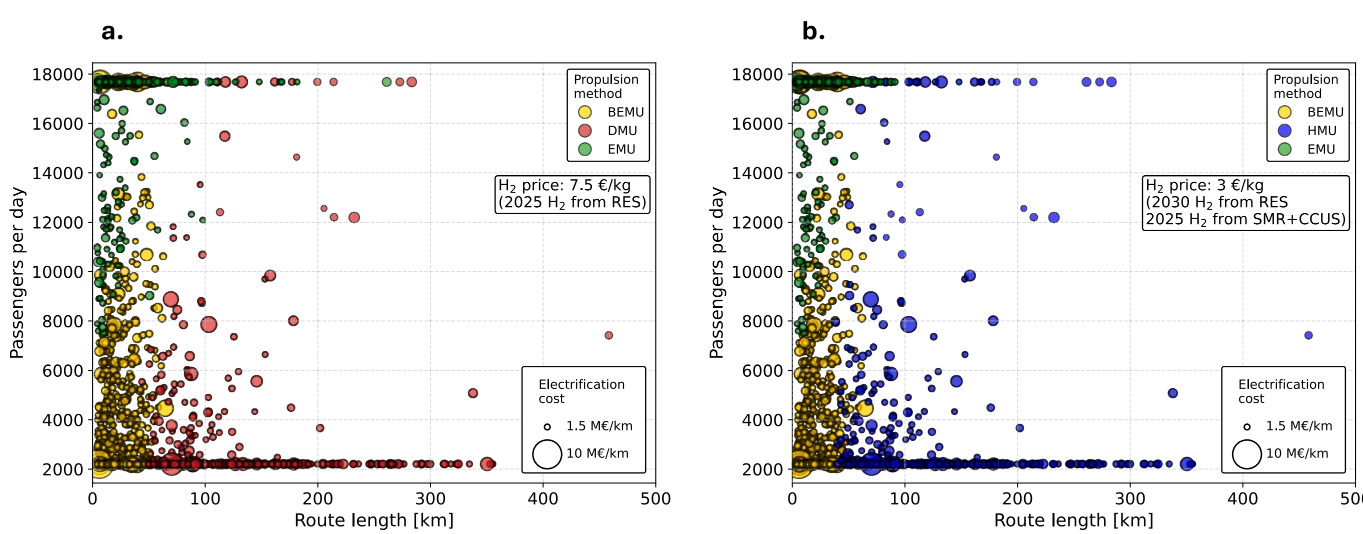

Fig. 4. Bubble plot of non-electrified European railway lines: a. €7.5/kg H_2 price (current price of electrolysis from RES); b. €3/kg H_2 price (current price of SMR + CCS and 2030 price of electrolysis from RES). The size of each bubble is proportional to the specific electrification cost of the line (M€/km).

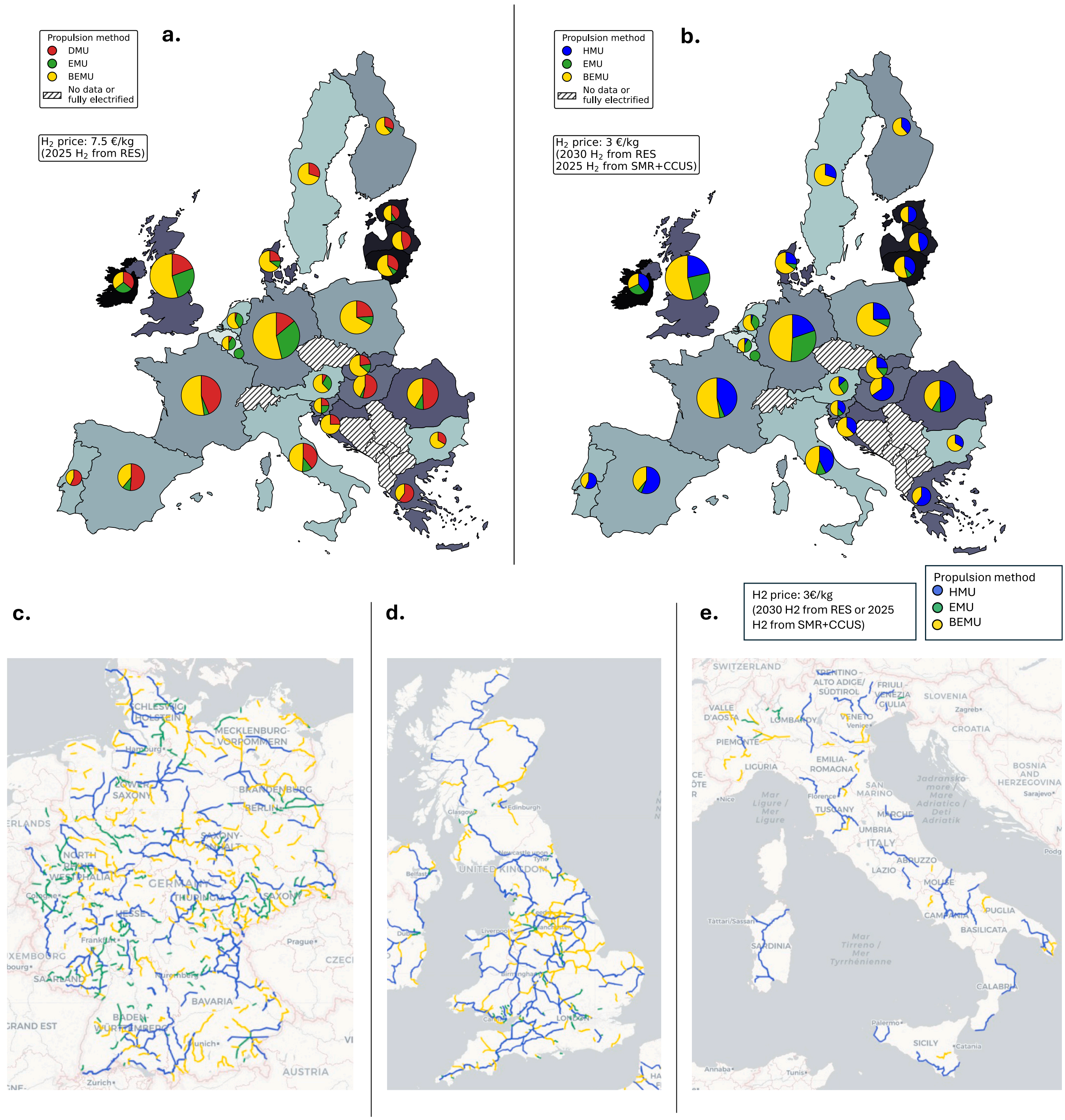

Fig. 5. Cost-optimal technology share under two hydrogen price cases: a. €7.5/kg H_2 price (current price of electrolysis from RES); b. €3/kg H_2 price (current price of SMR + CCS and 2030 price of electrolysis from RES). The size of each pie chart is proportional to the total length of the lines. Panels c, d and e show, respectively, the cost-optimal propulsion solutions for Germany, the UK and Italy, with a line-by-line visualization under the low hydrogen price case. Hatched regions are either fully electrified or represent areas where data are not available.

4.3. Hydrogen price plays a crucial role in cost-optimal decision-making

As previously demonstrated, the hydrogen price has a strong influence on the cost-optimal propulsion mix. To quantify this effect, a sensitivity analysis was conducted to assess how hydrogen price shapes adoption across non-electrified European railway lines.

Fig. 6 presents the resulting cost-optimal allocation of propulsion technologies across all non-electrified European lines as a function of the hydrogen price. At low hydrogen prices (€1–4/kg), HMUs occupy a larger share at the expense of BEMUs, while the EMU share remains relatively stable around 20%, reflecting its suitability for high-traffic routes where electrification is economically justified. As the hydrogen price increases, the HMU share progressively declines, and beyond approximately €4.5/kg, DMUs start to emerge. At today's renewable hydrogen production costs (~€7.5/kg), HMUs are no longer part of the cost-optimal technology mix. Overall, the results highlight a clear

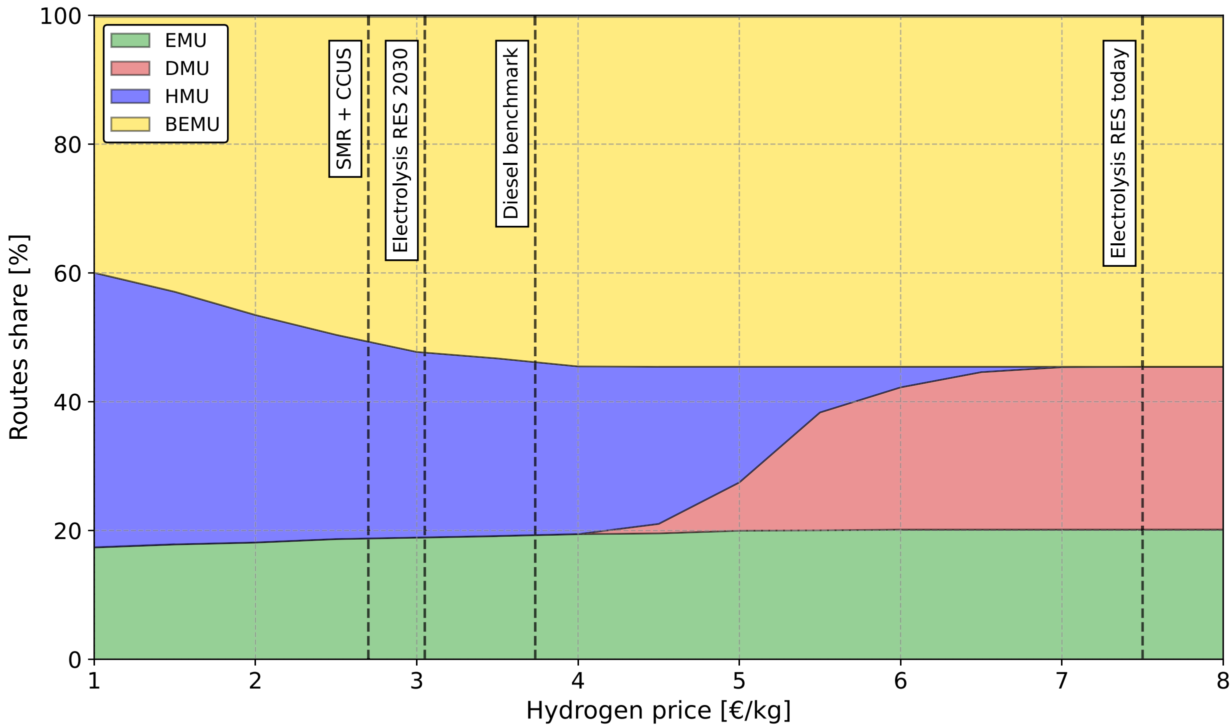

Fig. 6. Stacked-area chart showing the share of the different propulsion technologies as a function of hydrogen price of the European railway network. Vertical lines indicate benchmark values for hydrogen production costs.

transition threshold: below roughly €5–6/kg, hydrogen becomes competitive with diesel, while higher hydrogen prices limit its role and reinforce the adoption of BEMUs and DMUs. Furthermore, if hydrogen achieves energy cost parity with diesel (which corresponds to the vertical line of diesel benchmark in Fig. 6, i.e., ~€1.20/l), the HMU becomes economically dominant, fully displacing the DMU option in the cost-optimal network solution.

These outcomes underscore the importance of policies aimed at accelerating cost reductions in renewable hydrogen production. In particular, reducing hydrogen costs below the identified competitiveness threshold (~€5–6/kg) is crucial to unlock its large-scale deployment in regional rail. Transitional pathways may play a relevant role in this process. For instance, hydrogen produced via steam methane reforming (SMR) with carbon capture can already lower production costs compared to current renewable hydrogen, bridging the economic gap with diesel-based solutions until renewable hydrogen becomes widely available at scale.

Sensitivity analyses on key techno-economic parameters, reported in the Supplementary Material, further confirm the robustness of the framework, as the relative shares among propulsion technologies remain stable under plausible variations, reinforcing the validity of the main conclusions.

4.4. *What is the emission reduction potential of the cost-optimal configuration?*

The analysis of CO_2 emissions represents a crucial dimension of the decarbonization pathway. For alternative technologies such as HMUs, BEMUs, and EMUs, direct operational emissions are zero. However, their total carbon footprint also strongly depends on indirect upstream emissions occurring associated with energy supply. Electricity and hydrogen production can differ significantly in carbon intensity depending on the energy mix – for instance, hydrogen produced via electrolysis powered by renewables or grid electricity, or through SMR with or without carbon capture. Therefore, indirect emissions must be considered alongside direct ones to ensure a fair comparison across propulsion systems.

Fig. 7 presents the aggregated CO_2 emissions for the European non-electrified rail network under different scenarios. For each country, two values of electricity carbon intensity (*CI*, in gCO_2/kWh) are considered: a current value [56] and a forecasted future one [69], allowing the estimation of well-to-wheel impact under both present and future conditions.

The diesel-only baseline results in annual emissions close to 8 $MtCO_2/y$, consistent with current EU [73] and UK [74] yearly emissions of the railway sector. Moving to the cost-optimal scenario with today's renewable hydrogen price from electrolysis (€7.5/kg), total emissions decrease by almost 50% when applying current values for electricity carbon intensity, and by up to 58% when assuming future cleaner energy mixes. A further reduction is achieved for the cost-optimal scenario at a hydrogen price below €4/kg. In this case, the integration of HMUs fed by hydrogen from electrolysis results in a 51% reduction under the current energy mix, and up to a remarkable 90% reduction under the future expected carbon intensity values under a fully renewable energy system.

Beyond renewable electrolysis, hydrogen from SMR coupled with CCS emerges as a transitional pathway. Here, the model indicates that emissions can be reduced by approximately 80% under current carbon intensities, and by almost 90% when future carbon intensity values are considered, mainly due to the lower impact of BEMU and EMU. This positions SMR + CCS as a potential transitional solution, bridging the gap until large-scale renewable hydrogen becomes widely available. In the SMR-only scenario, emissions decrease by about 53% when current carbon intensities are applied, and by roughly 61% with future cleaner energy mixes. While this represents a substantial improvement compared to the diesel baseline, it also highlights the limited long-term sustainability of unabated fossil-based hydrogen, especially when compared with renewable electrolysis or SMR combined with carbon capture.

Overall, these results demonstrate that the choice of propulsion technology can already halve emissions under today's conditions, while full decarbonization can only be achieved through hydrogen, batteries, and electrification – provided that upstream energy supply is also

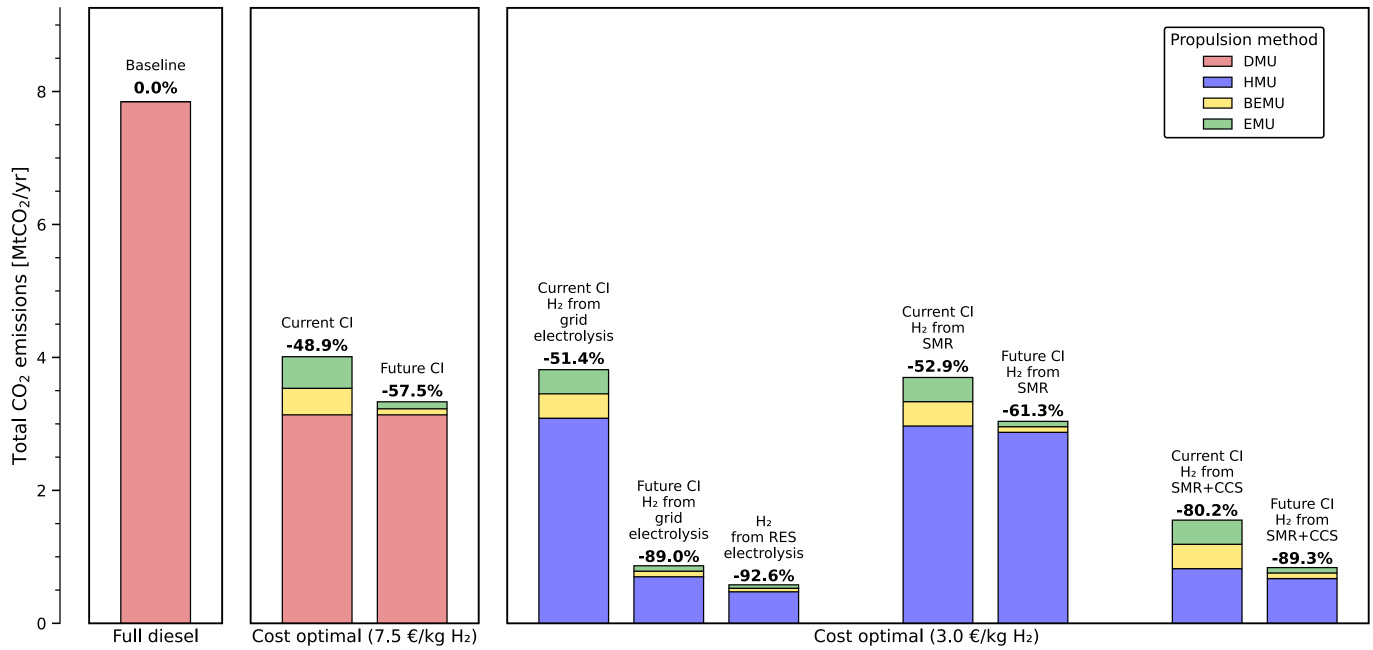

Fig. 7. Total CO_2 emissions (direct and indirect) of the cost-optimal scenarios, considering alternative electricity and hydrogen sources.

decarbonized. Substituting propulsion technologies alone is insufficient for complete decarbonization, as the overall impact ultimately depends on the carbon intensity of the upstream energy supply.

4.5. What if a single propulsion system is chosen?

Table 3 summarizes the results of the European panorama when a single propulsion technology is imposed across all non-electrified lines, with a price of €3/kgH_2 and future network CI.

Full network electrification with EMUs would require an additional 7.2 TWh of electricity per year and yield a TCO of €35.83/km, i.e., +29% compared to the cost-optimal portfolio. This indicates that a fully electric strategy is not economically viable. The hydrogen-only and diesel-only scenarios are also not cost-efficient, resulting in similar TCOs (around +10% compared to the cost-optimal scenario). They would require about 0.5 MtH_2 and 2190 million liters of diesel per year, respectively.

In terms of CO_2 emissions, the cost-optimal scenario emits around 37% less than the HMU-only case, and 89% less than the DMU-only case. However, it still emits more than the EMU-only scenario since full electrification remains the most energy-efficient and low-carbon solution, but at the expense of the highest financial burden, driven by the need to electrify remote, low-traffic lines where overhead infrastructure is disproportionately expensive.

Table 3
Comparison of European single-solution strategies against the cost-optimal scenario. Electricity carbon intensities refer to future grid projections for each country. A low hydrogen price case is considered €3/kg).

Scenario	Results		Cost-optimal scenario comparison	
	Fuel demand (per year)	Average TCO	TCO	CO_2 emissions
Only HMU	17.1 TWh	€30.66/km	+10.6%	+36.7%
Only DMU	23.5 TWh	€30.45/km	+9.9%	+89.0%
Only EMU	7.17 TWh	€35.83/km	+29.3%	−175%

BEMUs were not included in this single-technology assessment, as their limited range restricts their applicability to a small fraction of the European railway network. Furthermore, transitional solutions such as low-carbon fuels like Hydrotreated Vegetable Oil (HVO) could provide interesting pathways to reduce the environmental impact of existing fleets while infrastructure for zero-emission technologies is being deployed.

4.6. Marginal abatement cost curve of the emissions

A Marginal Abatement Cost Curve (MACC) ranks mitigation options according to the cost of avoiding one tonne of CO_2, while also illustrating the corresponding abatement potential. In this analysis, abatement is computed based on tailpipe CO_2 emissions only, meaning that avoided emissions refer to DMU baseline tailpipe emissions. This choice was intended to facilitate a direct comparison with current carbon pricing benchmarks, such as the EU ETS, which are predominantly defined based on direct (Scope 1) emissions.

Fig. 8a presents the complete MACC for all non-electrified lines, with bars ordered by increasing €/tCO_2 and widths proportional to annual CO_2 reduction. A large tranche of negative-cost opportunities appears, mainly associated with EMU and BEMU solutions. These correspond to cases where decarbonization leads to both emission reductions and cost savings, in line with the cost-optimal scenario. On the right-hand side of the curve, a positive-cost tail emerges, largely dominated by HMUs, along with a few sizeable EMU contributions. The right panel (Fig. 8b) zooms in on this positive-cost segment: the dashed line indicates the current EU ETS (Emission Trading System) carbon price (€80/tCO_2 [75]). Under this threshold, approximately 500 ktCO_2/yr of abatement can be considered economically viable.

It should be noted that these results refer to the high hydrogen price case (€7.5/kg). Under a lower hydrogen price (€3/kg), the economics change significantly: hydrogen-powered lines would shift.

from positive to negative abatement costs, indicating that decarbonization relative to diesel becomes cost-saving rather than requiring a premium. In this regime, HMU deployments would fall within the low-cost tranche of the portfolio, expanding the pool of immediately financeable projects and reshaping the sequencing implied by the MACC.

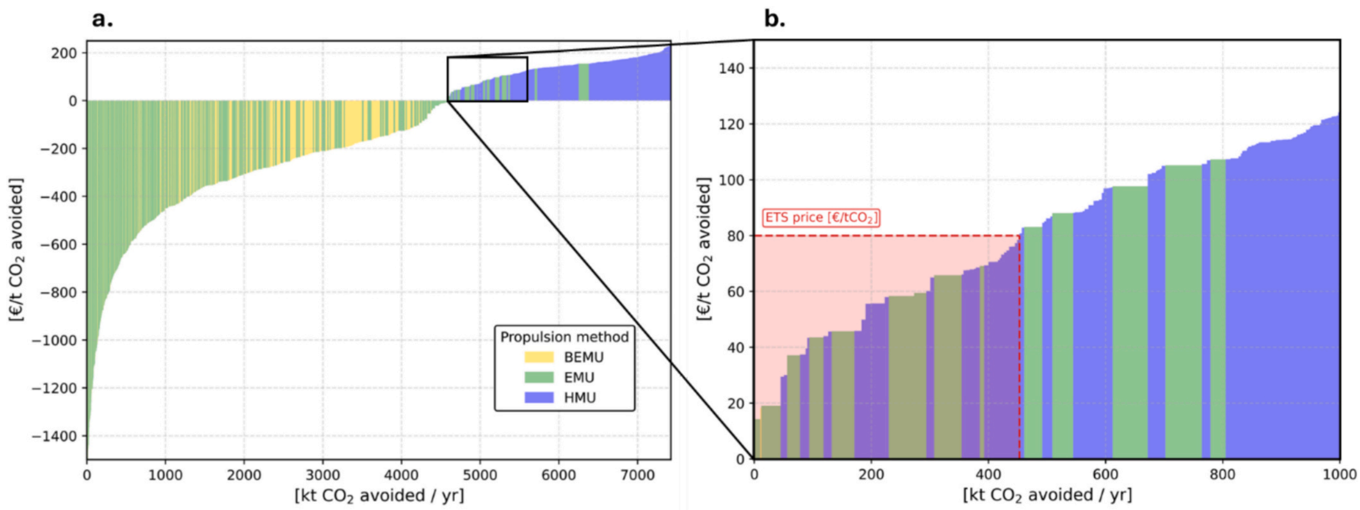

Fig. 8. Marginal Abatement Cost Curve (MACC) of direct emissions for non-electrified lines, with a zoom on positive-cost measures. A high hydrogen price case (€7.5/kg) is considered.

5. Conclusions

In this study, a continental-scale geospatial techno-economic framework was developed to identify cost-optimal decarbonization strategies for non-electrified European regional railways. The framework integrates dynamic train simulation, gravity-based demand estimation, lifetime cost modeling, and carbon emissions assessment.

Three recurring patterns emerge:

- Short low-traffic routes (typically below 60–70 km per leg) are optimally served by battery-based systems.
- Medium-to-long (>70 km) low-density lines become hydrogen-optimal when hydrogen prices fall below approximately €5–6/kg, whereas diesel remains the cost-optimal solution at higher hydrogen prices.
- High-traffic corridors justify full electrification despite high infrastructure costs.

Notably, enforcing a single-technology strategy leads to significant economic penalties, ranging from +10% to +30% in Total Cost of Ownership. These results confirm that effective railway decarbonization requires a diversified portfolio approach aligned with route-specific characteristics.

From an environmental perspective, under cost-optimal deployment and future electricity carbon intensities, well-to-wheel carbon emissions can be reduced by up to 90% relative to a diesel-only baseline. In this context, hydrogen produced via steam methane reforming with carbon capture and storage already enables substantial emission reductions and can represent a viable transitional pathway, bridging the gap until renewable hydrogen reaches full cost competitiveness.

Nevertheless, results remain sensitive to key parameters, including hydrogen price trajectories, electrification costs, and discount rates. While the framework provides a strategic planning tool at a continental scale, implementation decisions will require detailed local engineering assessments and infrastructure readiness evaluations. Future research should extend the methodology to other regions and further refine cost projections for hydrogen and battery systems under evolving market conditions.

CRediT authorship contribution statement

Gabriele Peyrani: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Marocco:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization. **Pierpaolo Cherchi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Massimo Santarelli:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Rail - IEA. https://www.iea.org/energy-system/transport/rail; 2025. accessed August 4, 2025.
[2] European Parliament. Reducing carbon emissions: EU targets and policies. https://www.europarl.europa.eu/topics/en/article/20180305STO99003/reducin

g-carbon-emissions-eu-targets-and-policies#cutting-emissions-from-transport-in-europe-10; 2018. accessed June 18, 2025.
[3] SNCF. Corporate social engagement report. 2018. p. 38. https://www.groupe-sncf.com/medias-publics/2024-03/sncf-rse_english.pdf. accessed August 4, 2025.
[4] Sabah Daily. German trains to stop using diesel by 2040. https://www.dailysabah.com/business/transportation/german-trains-to-stop-using-diesel-by-2040; 2022. accessed June 18, 2025.
[5] RIA. Rail Industry responds to announcement of phasing out of diesel-only trains. 2018. https://www.riagb.org.uk/RIA/ria/Newsroom/Press_Releases/Rail_Industry_responds_to_announcement_of_phasing_out_of_diesel-only_trains.aspx. accessed August 4, 2025.
[6] Zenith F, Isaac R, Hoffrichter A, Thomassen MS, Møller-Holst S. Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: case studies in Norway and USA. Proc Inst Mech Eng F J Rail Rapid Transit 2020; 234:791–802. https://doi.org/10.1177/0954409719867495.
[7] Eurostat. Statistics. https://ec.europa.eu/eurostat/databrowser/view/rail_if_line_na/default/table?lang=en; 2025.
[8] UIC. Global Rail Sustainability Report. 2022.
[9] Eurostat. Length of railway lines by number of tracks and electrification of lines. 2025. https://ec.europa.eu/eurostat/databrowser/view/rail_if_line_tr/default/table?lang=en. accessed September 5, 2025.
[10] IEA. The Future of Rail. 2019. https://www.iea.org/reports/the-future-of-rail. accessed August 20, 2025.
[11] Electric and Hybrid Rail Technology. Stadler sets world record with FLIRT Akku for longest distance travelled by a train in battery-only mode. 2021. https://www.electricandhybridrail.com/content/news/stadler-sets-world-record-with-flirt-akku-for-longest-distance-travelled-by-a-train-in-battery-only-mode/. accessed June 20, 2025.
[12] European Alternative Fuels Observatory. Stadler's FLIRT H2 sets new Guinness world record for hydrogen-powered trains. https://alternative-fuels-observatory.ec.europa.eu/general-information/news/stadlers-flirt-h2-sets-new-guinness-world-record-hydrogen-powered-trains; 2024.
[13] Alstom. Alstom and Verkehrsverbund Mittelsachsen present a new battery-powered electric train in Germany. 2023. https://www.alstom.com/press-releases-news/2023/8/alstom-and-verkehrsverbund-mittelsachsen-present-new-battery-powered-electric-train-germany. accessed July 29, 2025.
[14] Bahnen Elektrische. Akkumulator-Triebfahrzeuge Leipzig – Chemnitz. https://www.eb-info.eu/?view=article&id=1172:akkumulator-triebfahrzeuge-leipzig-chemnitz&catid=35:bahnen; 2024. accessed June 20, 2025.
[15] Nahverkehrsverbund. FLIRT AKKU 2-CAR UNIT. 2022. https://www.stadlerrail.com/api/docs/3aa54be0d4/2022_0919_media-release_innotrans_flirt-akku_en.pdf.
[16] Railvolution. FLIRT AKKUs for the Central Thuringia battery network | Railvolution. 2025. https://www.stadlerrail.com/en/media/media-releases/stadler-liefert-19-flirt-akku-fahrzeuge-fuer-das-mittelthueringer-akku-netz. accessed July 29, 2025.
[17] RailMarket. Stadler to deliver 19 BEMUs for DB Regio. 2025. https://it.railmarket.com/news/passenger-rail/32420-german-long-distance-rail-sets-new-delay-record. accessed July 29, 2025.
[18] Railway Gazette International. Danish battery train order signed. 2024. https://www.railwaygazette.com/traction-and-rolling-stock/danish-battery-train-order-signed/67574.article. accessed July 29, 2025.
[19] Railvolution. FLIRT AKKUs for Chicago.. 2024. https://www.railvolution.net/news/flirt-akkus-for-chicago. accessed July 29, 2025.
[20] Railvolution. ÖBB orders 16 FLIRT AKKU trains. 2023. https://www.railvolution.net/news/obb-orders-16-flirt-akku-trains. accessed July 29, 2025.
[21] Hitachi. Battery Commuter Trains. 2023. https://www.hitachirail.com/products-and-solutions/rolling-stock/battery-powered-trains/battery-commuter-trains/.
[22] Hitachi. The People of Hitachi: Leader in the Development of Europe's First Tribrid Train, Achieving a 50% Reduction in CO2 Emissions. 2024. https://www.hitachi.com/en/insights/articles/people-blues/. accessed July 29, 2025.
[23] Siemens. Mireo Plus H and B datasheet. 2024. https://assets.new.siemens.com/siemens/assets/api/uuid:0a451202-2be4-485d-a736-974d74263e63/siemens-mobility-mireo-plus-b-mireo-plus-h-en.pdf. accessed June 23,2025.
[24] Siemens. Siemens Mobility to supply 28 Mireo regional trains for Baden-Württemberg. 2023. https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-28-mireo-regional-trains-baden-wurttemberg. accessed July 29, 2025.
[25] Siemens. East Brandenburg rail network gets 31 battery-electric trains. 2021. https://press.siemens.com/global/en/pressrelease/east-brandenburg-rail-network-gets-31-battery-electric-trains. accessed July 29, 2025.
[26] Siemens. First battery trains for North Rhine-Westphalia enter service in 2026. 2024. https://press.siemens.com/global/en/pressrelease/first-battery-trains-north-rhine-westphalia-enter-service-2026. accessed July 29, 2025.
[27] Siemens. Siemens Mobility to supply first battery powered Mireo Plus B trains to Denmark. 2022. https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-first-battery-powered-mireo-plus-b-trains-denmark. accessed July 29, 2025.
[28] ABB. ABB and Škoda Group power up Czech railways with new battery-electric trains. 2025. https://new.abb.com/news/detail/122888/abb-and-skoda-group-power-up-czech-railways-with-new-battery-electric-trains. accessed July 29, 2025.
[29] ALSTOM. Hydrogen Coradia stream description. 2020. https://www.alstom.com/sites/alstom.com/files/2021/09/17/Alstom_Product_Sheet_Hydrogen_Train_EN.pdf.
[30] ALSTOM. Alstom to supply first hydrogen trains to the Italian region of Puglia and second order of trains in the framework agreement with Lombardy. 2023. https://www.alstom.com/press-releases-news/2023/12/alstom-supply-first-hydrogen-trains-italian-region-puglia-and-second-order-trains-framework-agreement-lombardy.
[31] Peyrani G, Marocco P, Gandiglio M, Cherchi P, Santarelli M. Techno-economic modeling framework to assess the feasibility of hydrogen-powered trains on non-electrified routes. J Power Sources 2025;652:237677. https://doi.org/10.1016/J.JPOWSOUR.2025.237677.
[32] Stadler. Automotrici ad idrogeno (HMU) A scartamento 950 MM - alghero. 2023. https://www.stadlerrail.com/api/docs/x/f913ace532/tailor-made-arst-hmu-it.pdf.
[33] Int Railway J. Italian operators order world's first narrow-gauge hydrogen rolling stock 2023. 2025. https://www.railjournal.com/fleet/italian-operators-order-worlds-first-narrow-gauge-hydrogen-rolling-stock/. accessed June 20.
[34] Stadler. Hydrogen multiple unit for FDC. 2023. https://www.stadlerrail.com/en/solutions/references/tailor-made-hydrogen-multiple-unit-arst. accessed June 20,2025.
[35] Ballard. Stadler Flirt H2 zero-emission train breaks Guinness world record. 2024. https://blog.ballard.com/rail/stadler-flirt-h2-zero-emission-train-breaks-guinness-world-record. accessed June 23, 2025.
[36] Hydrogen Technology Expo North America. Stadler has received another order from California worth $127m. 2024. https://www.hydrogen-expo.com/industry-news/stadler-received-another-order-california-worth-127m. accessed June 23, 2025.
[37] Stadler. FLIRT H2 technical datasheet. 2022. https://www.hydrogen-expo.com/industry-news/stadler-received-another-order-california-worth-127m. accessed June 23, 2025.
[38] Saft. Saft delivers innovative LTO traction batteries to power Siemens Mobility's hydrogen trains. 2024. https://saft.com/en/media-resources/press-releases/saft-delivers-innovative-lto-traction-batteries-power-siemens. accessed June 23, 2025.
[39] Siemens. First Mireo Plus H hydrogen trains from Siemens Mobility in passenger service. 2024. https://press.siemens.com/global/en/pressrelease/first-mireo-plus-h-hydrogen-trains-siemens-mobility-passenger-service. accessed June 23, 2025.
[40] Ballard. Ballard 200kW fuel cells power Siemens Mireo test drive. 2023. https://blog.ballard.com/rail/ballard-200kw-fuel-cells-test-drive-siemens-mireo. accessed June 23, 2025.
[41] Andreas Sebayang. Mireo plus B/H: Battery and hydrogen powered trains tested on Siemens' rail test facility. 2023. https://www.notebookcheck.net/Mireo-Plus-B-H-Battery-and-hydrogen-powered-trains-tested-on-Siemens-rail-test-facility.726579.html. accessed October 10, 2025.
[42] Ogawa K. Development of traction system for rolling stock using hydrogen fuel cells. 2024. https://www.hitachihyoron.com/rev/papers/2024/02/02/index.html.
[43] Toyota Media Site. Toyota Announces Hydrogen Transport Partnership Projects to Develop Fuel Cell Trucks and Trains. 2020. https://media.toyota.co.uk/toyota-announces-hydrogen-transport-partnership-projects-to-develop-fuel-cell-trucks-and-trains/. accessed June 23, 2025.
[44] East Japan Railway Company, ENEOS Corporation. Partnership agreement signed to expand CO-free hydrogen use to decarbonize railways-first joint study for social implementation of hydrogen-hybrid trains in Japan. 2022. https://www.jreast.co.jp/e/press/2022/pdf/20220530.pdf.
[45] Toyota. Toyota fuel cell modules-A SUSTAINABLE ZERO-EMISSION SOLUTION. 2022. https://www.toyota-europe.com/brands-and-services/toyota-fuel-cell/fuel-cell-technology.
[46] FCH2RAIL. Fuel Cell Hybrid PowerPack for Rail Applications. 2025. https://fch2rail.eu/. accessed June 20, 2025.
[47] Holger D. FCH2RAIL final event. 2024. https://fch2rail.eu/project-results/fch2rail-final-event-presentation/.
[48] 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 Manage 2022;23:100338. https://doi.org/10.1016/j.jrtpm.2022.100338.
[49] Parola N, Peyrani G, Marocco P, Gandiglio M, Santarelli M. Impact of control strategies on the degradation of hybrid hydrogen-battery powertrains in railway applications. Int J Hydrog Energy 2025;177:151529. https://doi.org/10.1016/j.ijhydene.2025.151529.
[50] 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 2024;160:110094. https://doi.org/10.1016/J.IJEPES.2024.110094.
[51] Hernandez A, Ng MTM, Siddique N, Durango-Cohen PL, Elgowainy A, Mahmassani HS, et al. Evaluation of rail decarbonization alternatives: framework and application. Transp Res Rec 2024;2678:102–12. https://doi.org/10.48550/arXiv.2501.01614.
[52] Bakker SJS, Martin J, van Beesten ER, Brynildsen IS, Sandvig A, Siqveland M, et al. STraM: a strategic network design model for national freight transport decarbonization. Transp Res Part E Logist Transp Rev 2025;197:104076. https://doi.org/10.1016/J.TRE.2025.104076.
[53] Heat Roadmap Europe. EU28 fuel prices for 2015, 2030 and 2050. 2017. https://heatroadmap.eu/wp-content/uploads/2020/01/HRE4_D6.1-Future-fuel-price-review.pdf.
[54] Fedele E, Iannuzzi D, Del Pizzo A. Onboard energy storage in rail transport: review of real applications and techno-economic assessments. IET Electrical Systems in Transportation 2021;11:279–309. https://doi.org/10.1049/ELS2.12026.
[55] Attinà M, Basilico A, Botta M, Brancatello I, Gargani F, Gori V, et al. Assessment of unit costs (standard prices) of rail projects (CAPital EXpenditure). 2018. https://ec.europa.eu/regional_policy/sources/studies/assess_unit_cost_rail_en.pdf.

[56] Eurostat. Electricity prices by type of user. 2025. https://data.europa.eu/data/datasets/o0kgq8bifnbvc85xzncga?locale=en. accessed July 2, 2025.
[57] GOV. Prices of electricity purchased by manufacturing industry. 2025. https://www.gov.uk/government/statistical-data-sets/prices-of-fuels-purchased-by-manufacturing-industry. accessed October 10, 2025.
[58] European Commission. Weekly Oil Bulletin. https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en; 2025. accessed September 3, 2025.
[59] GOV. Weekly road fuel prices. 2025. https://www.gov.uk/government/statistics/weekly-road-fuel-prices. accessed October 10, 2025.
[60] European Central Bank. Data services. https://www.ecb.europa.eu/stats/accessing-our-data/html/index.en.html; 2025. accessed September 3, 2025.
[61] Tax Foundation Europe. VAT Rates in Europe. 2025. https://taxfoundation.org/data/all/eu/value-added-tax-vat-rates-europe/. accessed August 18, 2025.
[62] Comité national routier. Excise duties and mechanisms for RFT partial refunds on excise duties on diesel in Europe. 2025. https://www.cnr.fr/en/excise-duties-and-mechanisms-rft-partial-refunds-diesel-europe-march-2026.
[63] Open Spatial Demographic. Data and Research - WorldPop. n.d.. 2025. https://www.worldpop.org/. accessed September 3
[64] Copernicus. CORINE Land Cover. 2025. https://land.copernicus.eu/en/products/corine-land-cover. accessed July 24, 2025.
[65] Lomonossoff GV. Problems of railway mechanics. In: Proceedings of the Institution of Mechanical Engineers. 120; 1931. p. 643–59. https://doi.org/10.1243/PIME_PROC_1931_120_024_02.
[66] Gardner H, Brambilla M, Matheus D. Perspectives for the rolling stock supply in the EU. 2023. https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2023)747263.
[67] Zhang Y, Tian Z, Roberts C, Hillmansen S, Chen M. Cost optimization of multi-mode train conversion for discontinuously electrified routes. Int J Electr Power Energy Syst 2022;138:107993. https://doi.org/10.1016/J.IJEPES.2022.107993.
[68] Electricity Maps. Emissioni di CO_2 in tempo reale del consumo elettrico. https://app.electricitymaps.com/zone/IE; 2023. accessed November 13, 2023.
[69] Hamels S. CO_2 intensities and primary energy factors in the future European electricity system. Energies 2021;14:2165. https://doi.org/10.3390/EN14082165.
[70] European Commission. Study on actual GHG data for diesel, petrol, kerosene and natural gas. 2015. https://energy.ec.europa.eu/publications/study-actual-ghg-data-diesel-petrol-kerosene-and-natural-gas_en.
[71] Trapani D, Marocco P, Gandiglio M, Santarelli M. Hydrogen leakages across the supply chain: current estimates and future scenarios. Int J Hydrog Energy 2025; 145:1084–95. https://doi.org/10.1016/J.IJHYDENE.2025.06.103.
[72] IEA. Indicative production costs for hydrogen via electrolysis in selected regions compared to current references. 2023. https://www.iea.org/data-and-statistics/charts/indicative-production-costs-for-hydrogen-via-electrolysis-in-selected-regions-compared-to-current-references-2. accessed August 4, 2025.
[73] Office of Rail and Road. Rail Emissions April 2022 to March 2023. 2023. https://www.gov.uk/government/statistics/rail-emissions-april-2022-to-march-2023.
[74] European Environment Agency. Transport Emissions Analysis. https://www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobility-systems/climate; 2025.
[75] Trading Economics. EU carbon permits - index Price. https://tradingeconomics.com/eecxm:ind; 2025.