

## TOWARDS SUSTAINABLE RAIL MOBILITY: EMISSION REDUCTION STRATEGIES FOR MODERN RAIL OPERATIONS

Concettina MARINO, Marinella GIUNTA\*

*Department of Civil, Energy, Environmental and Materials Engineering, University Mediterranea of Reggio Calabria, via Zehender, 89100 Reggio Calabria, Italy*

Received 18 January 2026; revised 2 February 2026; accepted 5 February 2026

**Abstract.** Railway systems represent a cornerstone of sustainable transportation, providing an environmentally efficient means of moving both people and goods. Their ability to deliver high transport capacity with comparatively low greenhouse gas (GHG) emissions, combined with their contribution to reducing road congestion, positions rail as a key pillar of modern low-carbon mobility. The ongoing electrification of rail networks further enhances these benefits by enabling the use of renewable electricity along increasingly extensive corridors. However, despite these advancements, diesel locomotives, still essential for shunting operations, regional services, and non-electrified routes, remain a significant source of environmental impacts. The resulting emissions negatively affect air quality and pose health and climate change concerns, particularly in densely populated or high-traffic railway areas. To meet tightening emission standards, the rail sector is advancing multiple decarbonization strategies, including full electrification, hybrid propulsion technologies, and the adoption of low-carbon fuels. Among these, advanced biofuels, such as biodiesel and Hydrotreated Vegetable Oil (HVO) together with hydrogen used in fuel cell or combustion-based systems, are emerging as the most promising options. Building on established methodologies for assessing rail energy use and emissions, this study develops and applies a procedure for comparing the environmental burdens of conventional diesel traction with those associated with innovative propulsion and fuel solutions across a range of railway operations. The findings confirm that renewable fuels can substantially mitigate the climate impact of rail activities, while hydrogen-powered systems offer significant potential for deep and long-term decarbonization, particularly when supported by renewable energy sources. Nonetheless, the transition to hydrogen remains challenging due to the high energy requirements of its production, the need for dedicated storage and refuelling infrastructure, and uncertainties linked to large-scale deployment. These factors highlight the necessity of a comprehensive Well-to-Wheel (WTW) assessment to fully evaluate the environmental performance of emerging alternatives and ensure that their adoption results in genuine sustainability gains.

**Keywords:** sustainable rail transport, low-carbon fuels, hydrogen propulsion.

### 1. Introduction

Railway transport constitutes a key component of sustainable mobility systems, offering an energy-efficient mode for both passenger and freight transportation. Owing to its high transport capacity and comparatively low greenhouse gas (GHG) emissions, the train plays a crucial role in mitigating road congestion and reducing the environmental impacts associated with road-based transport. The ongoing expansion of rail network electrification further enhances these benefits, enabling the integration of renewable electricity and supporting the decarbonization of transport corridors on a large scale.

Despite these advances, diesel-powered locomotives remain an essential element of railway operations, particularly for shunting activities, regional services, and non-electrified lines. Consequently, they remain a

significant source of atmospheric pollutant emissions, which adversely affect local air quality and contribute to health risks and climate change, particularly in densely populated areas and along heavily trafficked railway lines (Sharma et al., 2023). Addressing the environmental impact of diesel traction therefore remains a critical challenge in the transition toward fully sustainable rail transport systems.

Figure 1 highlights the share of electrified railway lines across Europe in 2023, revealing substantial heterogeneity among national rail networks. While several countries have achieved high levels of electrification, a significant portion of the European railway infrastructure remains partially or largely non-electrified. In many cases, electrification rates remain below 50%, indicating that diesel traction continues to play a crucial role in daily railway operations. This uneven electrification

\* Corresponding author. E-mail: [marinella.giunta@unirc.it](mailto:marinella.giunta@unirc.it)

underscores the need for flexible and differentiated decarbonization strategies, particularly for corridors where electrification is limited.

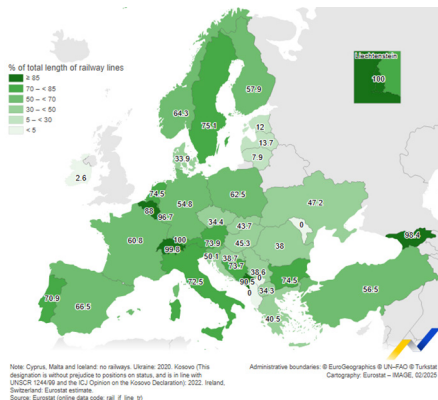


Figure 1. Electrified railway lines in 2023 (% of total length of railway lines) (source: Eurostat, n.d.)

These non-electrified segments are predominantly found on regional lines, secondary routes, and freight corridors, where full electrification may be economically or technically challenging in the short to medium term. As a result, diesel locomotives are expected to remain in service for the foreseeable future, reinforcing the importance of improving their environmental performance. To meet tightening emission standards, the rail sector is advancing multiple decarbonization strategies, including full electrification, hybrid propulsion technologies, and the adoption of low-carbon fuels. Technological advancements aimed at reducing emissions, increasing energy efficiency, and mitigating local air pollution from diesel traction, therefore, represent a key complementary pathway to electrification.

In this context, alternative low-carbon fuels represent practical interim solutions capable of delivering immediate emission reductions. Among these, biodiesel and hydrotreated vegetable oil (HVO) have attracted significant interest (Ababneh & Hameed, 2022; Di Blasio et al., 2022; Kokkinos & Emmanouilidou, 2023). Biodiesel, produced from renewable biological feedstocks, can substantially reduce lifecycle greenhouse gas emissions. HVO, a high-quality synthetic diesel fuel, ensures cleaner combustion and improved engine performance and is fully compatible with existing diesel engines. This compatibility enables a rapid reduction in emissions without requiring major modifications to current infrastructure.

More broadly, renewable fuels such as biodiesel, other biofuels, and hydrogen are increasingly recognized as promising alternatives to conventional diesel (D'Adamo et al., 2024; Ban et al., 2025). While these fuels provide effective short- to medium-term mitigation options, achieving deeper emission reductions in the rail sector is expected to rely on more transformative propulsion technologies.

Hydrogen-based traction is gaining increasing attention as a viable pathway for reducing the carbon

footprint of rail transport, especially on lines that are not electrified (D'Acerno et al., 2025). Recent progress in fuel cell technologies (Ahmed et al., 2023) has demonstrated their potential for railway applications, while also revealing several technical and systemic challenges. Compared with conventional diesel traction, hydrogen-powered trains can significantly reduce greenhouse gas emissions and enable operation without extensive electrification infrastructure.

Hydrogen can be classified according to its production pathway and the associated carbon intensity. The main categories include:

- Grey hydrogen, produced from fossil fuels through steam reforming without carbon capture, resulting in significant carbon emissions.
- Blue hydrogen, obtained via the same steam reforming process but coupled with carbon capture and storage (CCS) technologies to reduce carbon emissions.
- Green hydrogen, generated through water electrolysis powered by renewable energy sources such as wind or solar, yielding a low-carbon and environmentally sustainable fuel.
- Purple hydrogen, produced via water electrolysis using electricity generated by nuclear power plants, thereby leveraging nuclear energy for hydrogen production.

At present, Steam Methane Reforming (SMR) remains the dominant hydrogen production pathway, accounting for the majority of global production. This technology typically achieves efficiencies in the range of 74–85% (Younas et al., 2022). Despite its widespread adoption, SMR relies on high-temperature catalytic reactions, generally operating between 700 and 1000 °C, results in significant carbon dioxide emissions, underscoring the importance of considering hydrogen production routes when assessing its environmental benefits.

Several countries, including Germany, Spain, the United States, and more recently Italy, are actively assessing the deployment of hydrogen-powered rolling stock as part of their transition strategies for non-electrified rail networks. Nevertheless, critical issues related to hydrogen production pathways, storage solutions, refueling infrastructure, and on-board energy management remain to be addressed.

Despite the growing body of literature assessing rail transport emissions and evaluating alternative railway technologies from environmental, economic, and technical perspectives (Ahsan et al., 2023; Kapetanović et al., 2024; Giunta & Marino, 2026), comparative and operation-specific assessments of emerging propulsion and fuel solutions for non-electrified rail services remain limited. Building on established methodologies for assessing rail energy use and emissions, this study develops and applies a quantitative framework to compare the environmental burdens of conventional diesel traction with those associated with innovative propulsion technologies

and low-carbon fuels across a range of railway operating conditions.

## 2. Methodology

This section outlines the core principles and the modelling framework used for estimating energy consumption and emissions from rail transport. The emissions considered include all greenhouse gases generated by the use of fuel to power trains, notably CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and non-methane hydrocarbons. For assessment purposes, these gases are aggregated into a single indicator, carbon dioxide equivalents (CO<sub>2</sub>e), which is commonly used to quantify transport-related emissions (Piecny et al., 2012).

Transport emissions are conventionally categorized according to the stages of the energy life cycle: well-to-tank (WTT), tank-to-wheel (TTW), and well-to-wheel (WTW) (Figure 2).

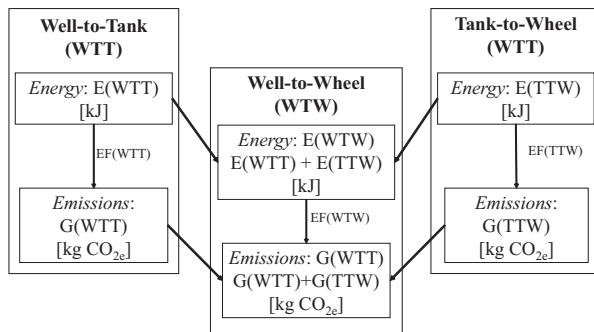


Figure 2. Conceptual structure for estimating energy consumption and greenhouse gas emissions in rail transport

WTT emissions,  $G(WTT)$ , arise from the production and distribution of energy, such as those generated at power plants or during fuel transport. TTW emissions,  $G(TTW)$ , refer to the direct emissions produced during vehicle operation, for example through fuel combustion in diesel locomotives. WTW emissions,  $G(WTW)$ , represent the combined effect of both stages.

For each life-cycle stage, a train's energy use and emissions on a given journey can be estimated using energy variables ( $E(WTT)$ ,  $E(TTW)$ ,  $E(WTW)$ ) and emission factors ( $EF(WTT)$ ,  $EF(TTW)$ ,  $EF(WTW)$ ) (ISO 14083:2023 (International Organization for Standardization, 2023)). Starting from the TTW energy consumption, direct emissions as well as upstream WTT and total WTW energy use and emissions can be calculated by applying the appropriate conversion factors. These coefficients describe the relationship between the energy required to move the train and the additional energy use and emissions generated along the energy supply chain.

Since such energy and emission factors are available in the literature for various train and engine types, total emissions can often be derived solely from TTW energy consumption. Accordingly, most emission estimation approaches, including the one adopted in this study,

primarily focus on modelling and estimating tank-to-wheel energy use.

Approaches for estimating emissions from railway systems are generally categorized into microscopic, mesoscopic, and macroscopic models.

Microscopic frameworks rely on a highly granular representation of physical mechanisms governing train dynamics (Lindgreen & Sorenson, 2005). In contrast, macroscopic methods utilize aggregated transport statistics and fuel usage data to derive emission factors (European Environment Agency, 2023; Intergovernmental Panel on Climate Change, 2006). Mesoscopic models, positioned between these extremes, incorporate selected micro-level details within broader macro-level trends (Hickman et al., 1999).

Existing models are commonly used to estimate energy consumption and emissions for railway services over varying distances, yet this study adopts a macroscopic framework based on the ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) model (Boulter & McCrae, 2007) to evaluate line-haul energy use and emissions.

This approach is well suited to representing the effects of aggregated operational characteristics on overall energy and emission performance and can be applied to different train types and operation conditions.

The conceptual rationale of the methodology is represented in Figure 3, which highlights the logical sequence through which operational conditions are translated into energy consumption and emissions.

The driving pattern of the train is established based on an operating matrix defined by discrete speed and acceleration intervals, constrained by element limits such as maximum and minimum speeds and admissible acceleration/deceleration values. These constraints ensure that the simulated operating conditions are consistent with real railway operations. The level of accuracy of the model is determined by the resolution of the speed and acceleration intervals, with finer discretization allowing a more detailed representation of train dynamics.

The next step describes the temporal and spatial distribution of operating elements, representing how different speed-acceleration states occur along the route and over time. This distribution captures the variability of train operation due to driving patterns, infrastructure characteristics, and service profiles.

These operating conditions are then combined with the element driving resistance, which accounts for the forces opposing motion, including rolling resistance, aerodynamic drag, and gradient resistance. By multiplying the occurrence of each operating element by the corresponding total resistance force, the methodology derives the total traction effort required for train operation.

Overall, the ARTEMIS methodology is based on a bottom-up modeling framework that integrates detailed descriptions of train operating dynamics with driving resistance formulations, enabling consistent and robust

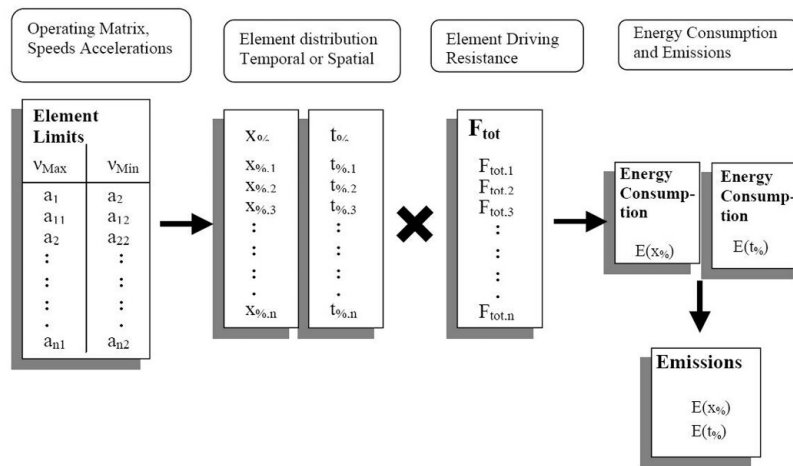


Figure 3. Basic principles of rail emissions and energy consumption model (source: Lindgreen & Sorenson, 2005)

estimations of energy consumption and associated emissions for the railway sector.

### 3. Case study

The ARTEMIS methodology was applied to the Crotona–Catanzaro Lido railway line (Figure 4), part of a key regional corridor in Calabria (the Calabrian Jonica railway route) that remains entirely non-electrified.

The line extends for approximately 60 km and exhibits infrastructure characteristics typical of secondary Italian lines, including maximum speeds between 110 and 140 km/h, several gradient variations, and a high number of intermediate stops.

These features generate a highly variable driving profile, with frequent acceleration and braking phases that significantly influence the overall traction energy demand.

For the analysis, the HTR412 hybrid train was selected as the reference rolling stock. This unit, currently deployed on several regional services in Southern Italy, combines electric and diesel traction and is equipped with Stage V compliant engines and an advanced energy management system.

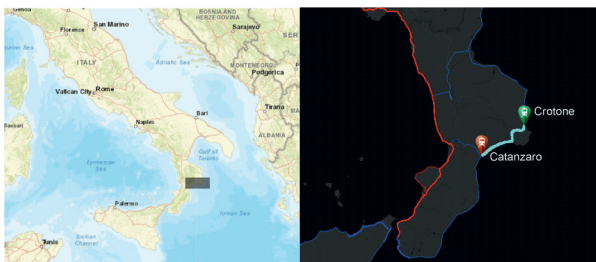


Figure 4. Geographical setting of the studied railway corridor (source: Portale Cartografico ePIR, n.d.)

With an empty mass of roughly 170 t, the HTR412 features multimodal electric traction architecture, based on a serial diesel-electric system integrated with

electrochemical energy storage and designed for operation both on electrified and non-electrified railway lines.

The traction system is organized around a common onboard DC link, which acts as the central energy bus interconnecting all power sources and loads. The DC link is supplied by: the overhead catenary system via pantograph, main circuit breaker, and DC/DC conversion stages; two independent diesel-generator sets ( $2 \times 650$  kW nominal power), installed in the end driving modules; two lithium-ion battery packs, connected through bidirectional power converters.

From the DC link, energy is distributed to the traction inverters feeding the traction motors and to the auxiliary power converters supplying onboard services. Traction is fully electric; no mechanical coupling exists between the diesel engines and the wheelsets.

On non-electrified lines, the primary source of energy is provided by the diesel-generator sets. Each diesel engine drives an electric generator whose output is directly connected to the DC link.

The generated electrical power is then converted by the traction inverters to supply the asynchronous traction motors. The presence of two independent diesel-generator units allows modular power management and functional redundancy.

Depending on operating conditions such as train load, line profile, and acceleration demand, one or both generator sets can be activated, improving overall efficiency and ensuring degraded-mode operability in the event of partial failures.

The onboard battery system is not intended as the primary energy source for sustained operation, but it plays a key functional role in the power balance of the traction system.

Specifically, the batteries:

- provide power boost during acceleration, covering short-term power peaks that exceed the continuous rating of the diesel generators;
- absorb energy recovered during regenerative braking.

- ing, thereby increasing overall energy efficiency;
- enable low-emission and low-noise operation in stations and environmentally sensitive areas;
- contribute to DC link stabilization during rapid load transients.

Battery recharging occurs preferentially through regenerative braking and, when available, from the overhead line. Charging from the diesel generators is limited to state-of-charge (SOC) management and safety requirements, as systematic charging via the thermal prime movers would result in reduced overall efficiency.

An onboard energy management system supervises the distribution of power among the available sources and controls transitions between catenary, diesel-electric, and battery-assisted operation.

These transitions occur automatically and without interruption of traction power. Power sharing between diesel generators and batteries is continuously optimized as a function of traction demand, battery SOC, and efficiency constraints.

As far as the vehicle configuration is concerned, the HTR 412 is a four-car articulated multiple units with 5 bogies and 10 axles (Figure 5). The two end cars are equipped with powered bogies (4 powered axles), while the intermediate cars share trailer bogies.



Figure 5. HTR 412 configuration

The maximum number of passengers is 300.

The operational profile of the Crotona–Catanzaro Lido line was discretized according to the ARTEMIS modelling structure, defining a matrix of speed–acceleration states consistent with infrastructure constraints and vehicle performance limits.

Specifically, the speed–acceleration matrices reported in the ARTEMIS final report were selected, choosing

those that best reflected the combined characteristics of the line and the HTR 412 train.

In particular, the matrices corresponding to the regional train profiles R03061 (Table 1) and R04557 (Table 2) were adopted (Lindgreen & Sorenson, 2005), with the latter providing smaller speed intervals and thus offering a finer representation of low-speed operating conditions. They will be referred to as simple distribution and detailed distribution respectively.

Table 1. Spatial distribution of speed–acceleration combinations of train R03061 – simple distribution

Acceleration interval (m/s <sup>2</sup> )	Speed interval (km/h)		
	150–100	100–50	50–0
1.0–0.9	0.00	0.00	0.00
0.9–0.8	0.00	0.10	0.20
0.8–0.7	0.00	0.00	0.00
0.7–0.6	0.00	0.00	0.00
0.6–0.5	0.00	0.20	0.40
0.5–0.4	0.00	1.50	0.80
0.4–0.3	0.00	0.20	0.10
0.3–0.2	0.80	3.80	2.40
0.2–0.1	1.90	8.50	2.30
0.1–0.0	2.90	21.00	2.70

By combining the occurrence of each operating state with the corresponding resistance forces, rolling, aerodynamic and acceleration, the total traction energy required for the service was estimated.

Energy consumption was evaluated assuming an overall efficiency of 0.35 (Lindgreen & Sorenson, 2005), which accounts for the combined efficiency of the diesel engine and the generation–traction system.

It is worth highlighting that ARTEMIS methodology does not consider local gradient. Gradient resistance is

Table 2. Spatial distribution of speed–acceleration combinations of train R04557 – detailed distribution

Acceleration interval (m/s <sup>2</sup> )	Speed interval (km/h)														
	150–140	140–130	130–120	120–110	110–100	100–90	90–80	80–70	70–60	60–50	50–40	40–30	30–20	20–10	10–0
1.0–0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9–0.8	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.13	0.10	0.06	0.02	0.06
0.8–0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7–0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10
0.6–0.5	0.00	0.00	0.00	0.08	0.05	0.02	0.00	0.00	0.10	0.13	0.05	0.11	0.08	0.16	0.19
0.5–0.4	0.00	0.00	0.03	0.00	0.06	0.00	0.13	0.10	0.11	0.19	0.32	0.65	0.55	0.39	0.00
0.4–0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.15	0.00	0.00	0.00	0.00	0.00	0.05
0.3–0.2	0.03	0.03	0.05	0.36	0.26	0.63	0.55	0.52	0.13	0.60	0.39	0.34	0.63	0.70	0.18
0.2–0.1	0.05	0.21	0.19	1.02	1.13	0.70	1.16	1.83	1.24	0.91	1.00	0.06	0.24	0.21	0.13
0.1–0.0	1.29	1.07	6.37	7.06	2.78	1.87	0.92	0.16	2.73	1.23	0.79	1.52	0.13	0.13	19.49

assessed on the basis of the height difference between origin and destination.

#### 4. Results and discussion

Energy consumption was assessed using both simple and detailed temporal (TD) and spatial distributions (SD) of speed-acceleration combinations.

The results are reported in Figure 6, which illustrates the consumption trend, in terms of kJ/pass-km as a function of the occupancy rate for both simple and detailed distribution approaches. With regard to spatial distributions, the difference between simple and detailed driving patterns remains within 8%. In contrast, the use of temporal distributions leads to significantly larger differences (about 33%), due to their higher sensitivity to the train's operational profile (e.g., number of stops and dwell times). Temporal distributions are more closely linked to the specific route-vehicle configuration and therefore introduce greater variability. For this reason, the spatial distribution will be adopted for the emission assessment phase. In particular, the detailed spatial pattern will be used.

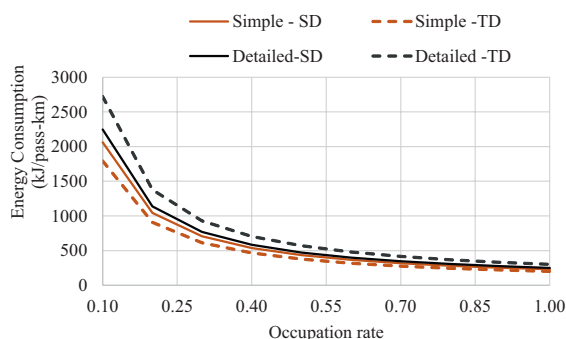


Figure 6. Energy Consumption of the HTR 412 train on the route Crotone Catanzaro for different distributions of speed-acceleration combinations and occupancy rates

Starting from the resulting TTW energy consumption, WTT and WTW emissions were computed for different propulsion and fuel scenarios: conventional diesel, HVO, biodiesel, and hydrogen (fuel-cell configuration). This comparative assessment provides a quantitative basis for evaluating the potential emission reductions achievable on the Crotone-Catanzaro Lido line through the adoption of low-carbon fuels or innovative propulsion technologies. The results offer valuable insights for regional decarbonization strategies, particularly for railway networks where full electrification remains economically or technically challenging in the short to medium term.

The emission factors used for the analysis are available in ISO 14083:2023 and in Lo Vullo et al. (2022).

The base case study considers the HTR 412 configuration powered by a diesel engine with battery boost. The resulting TTW and WTW emissions are shown in Figure 7.

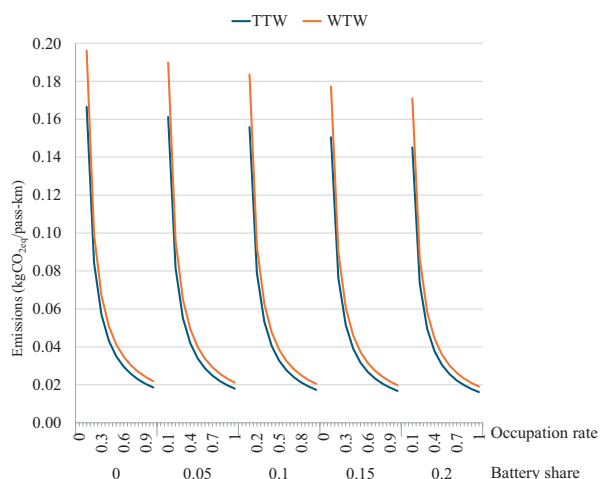


Figure 7. Emission rates of the HTR 412 train on the route Crotone Catanzaro for different occupancy rates and battery share values

The battery contribution was assessed by simulating partial energy coverage during acceleration phases, based on predefined battery share values ranging from 0 to 0.20. For each battery share, the traction energy demand was proportionally split between diesel and battery sources, assuming that battery power is primarily employed to support acceleration phases of the driving cycle. This approach reflects realistic hybrid operation strategies and allows quantification of emission reductions under varying occupancy rates and battery utilization levels.

With a battery share of 20% the reduction in both TTW and WTW emissions remains within approximately 13%.

With a view to assessing the effectiveness of different emission reduction strategies the following propulsion and fuel scenarios were analysed:

- conventional diesel;
- HVO;
- biodiesel;
- hydrogen (fuel-cell configuration).

For the hydrogen scenario, a fuel-cell electric train configuration was considered. A tank-to-wheel efficiency of 0.40 was assumed for the PEM fuel-cell hybrid system, accounting for fuel-cell conversion, battery charge-discharge losses, and electric traction efficiency.

In addition, different hydrogen production pathways were considered: Steam Methane Reforming (SMR) and electrolysis. For the latter, electricity-related emission factors were applied, assuming an efficiency of 0.60 (Bičáková & Straka, 2012), and several scenarios of renewable energy penetration in electricity generation were included, in accordance with the projections reported by Falchetta (2014).

The results are reported in Figures 8 and 9 and refer to the scenario with no battery contribution. This assumption was adopted to ensure a consistent comparison among the different fuel and propulsion options, isolating the effect of the primary energy carrier. In the

fuel-cell configuration, the battery is considered an intrinsic component of the propulsion system and is therefore used exclusively for power smoothing and transient management, rather than as an additional energy boost for traction.

Figure 8 shows that, at the Tank-to-Wheel level, renewable liquid fuels such as HVO and biodiesel lead to a significant reduction in direct emissions compared to conventional diesel, due to their lower carbon content and cleaner combustion characteristics. The hydrogen fuel-cell configuration exhibits zero TTW emissions, confirming its potential to completely eliminate local exhaust pollutants during operation. This feature is particularly relevant for regional services operating in urban areas or environmentally sensitive zones.

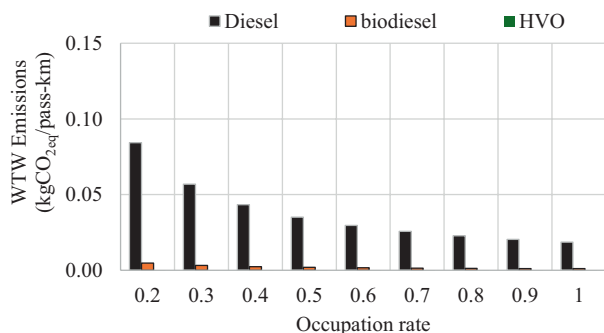


Figure 8. TTW emissions rates for several fuel scenarios

When the full Well-to-Wheel perspective is considered (Figure 9), the differences among the various energy pathways become more pronounced. Although HVO and biodiesel provide substantial emission reductions relative to diesel traction, it is worth underscoring that any ultimate assessment should rely on a broader analysis that accounts for the sustainability of the entire supply chain, including upstream production pathways, feedstock origin, land-use impacts, and other related factors.

Hydrogen produced via SMR shows no WTW benefits, whereas hydrogen generated through electrolysis becomes increasingly advantageous as the share of renewable electricity increases. This clearly highlights the strong dependence of hydrogen sustainability on the decarbonization of the power sector.

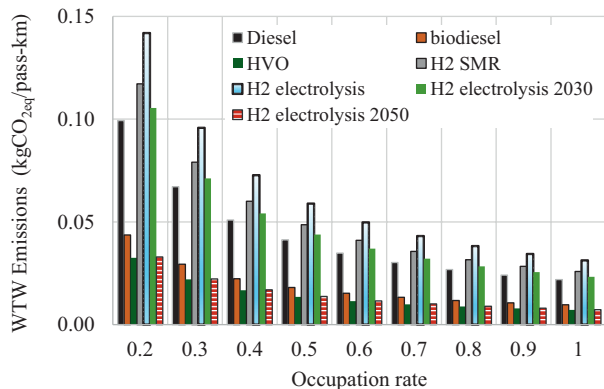


Figure 9. WTW emissions rates for several fuel scenarios

Figure 10 summarizes the relative emission reductions with respect to the diesel baseline. It shows no variation with the occupation rate, so a unique value is reported.

Renewable liquid fuels deliver moderate but immediately deployable benefits, while hydrogen-based solutions exhibit the highest long-term mitigation potential, especially under scenarios characterized by high renewable energy penetration. However, these benefits are contingent upon the availability of low-carbon hydrogen production pathways and dedicated refuelling infrastructure.

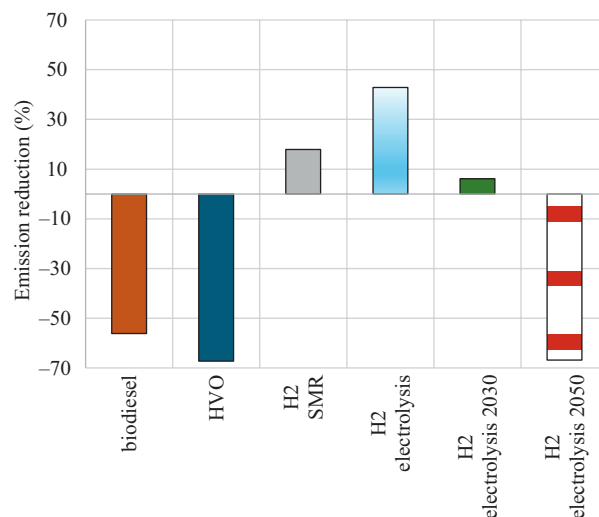


Figure 10. Emission Reduction with respect to the base scenario (diesel propulsion)

### 5. Conclusions

This study presented a comparative Tank-to-Wheel and Well-to-Wheel assessment of emission reduction strategies for non-electrified regional rail services, using the Crotona–Catanzaro Lido line as a representative case study. By applying the ARTEMIS modelling framework to a modern hybrid multiple units, energy consumption and emissions were quantified under different operating assumptions and fuel pathways.

The results indicate that, under the hypotheses of the methodology, battery assistance in diesel-hybrid configurations yields only modest emission reductions, demonstrating that batteries alone cannot deliver deep decarbonization when fossil fuels remain the primary energy source. In contrast, renewable liquid fuels such as HVO and biodiesel represent an effective short- to medium-term mitigation option, as they can be deployed with minimal changes to existing rolling stock and infrastructure while achieving meaningful WTW emission savings.

Hydrogen-based propulsion emerges as the most promising long-term solution for non-electrified railway lines. Fuel-cell configurations allow the complete elimination of local emissions and, when hydrogen is

produced from low-carbon electricity, can substantially reduce lifecycle emissions. Nevertheless, the environmental performance of hydrogen is highly dependent on the production pathway, and current reliance on fossil-based hydrogen significantly limits its immediate benefits.

Overall, the findings underline the importance of adopting a comprehensive Well-to-Wheel perspective when evaluating alternative rail propulsion technologies. A phased transition strategy appears most appropriate, combining the near-term deployment of renewable fuels with targeted investments in hydrogen technologies and renewable electricity generation, in order to ensure that future rail decarbonization pathways deliver genuine and sustained environmental benefits.

## Acknowledgements

This research was carried out as part of the MOST – Sustainable Mobility National Research Center, with financial support from the European Union’s Next-Generation EU (Piano Nazionale di Ripresa e Resilienza (PNRR) – Missione 4 Componente 2, Investimento 1.4 – D.D. 1033 17/06/2022, CN00000023). The views and opinions expressed in this manuscript are solely those of the authors and neither the European Union nor the European Commission can be held responsible for its content.

## References

- Ababneh, H., & Hameed, B. H. (2022). Electrofuels as emerging new green alternative fuel: A review of recent literature. *Energy Conversion and Management*, 254, Article 115213. <https://doi.org/10.1016/j.enconman.2022.115213>
- Ahmed, H., Adebayo, P., Ahmed, M., & Arbab, A. I. (2023). Hydrogen Fuel Cell technology: Benefits, challenges, and future potential. *Journal of Energy Technologies and Policy*, 13, 48–56. <https://doi.org/10.7176/JETP/13-1-06>
- Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023). A critical review of sustainable rail technologies based on environmental, economic, social, and technical perspectives to achieve net zero emissions. *Renewable and Sustainable Energy Reviews*, 185, Article 113621. <https://doi.org/10.1016/j.rser.2023.113621>
- Boulter, P. G., & McCrae, I. S. (Eds.). (2007). *ARTEMIS: Assessment and reliability of transport emission models and inventory systems* (report PPR350). TRL Limited. <https://www.trl.co.uk/uploads/trl/documents/PPR350.pdf>
- Ban, L., Wu, D., Sun, D., Zhou, H., Wang, H., Zhang, H., Xu, C. C., & Yang, S. (2025). Sustainable production of bio-fuels from biomass feedstocks using modified montmorillonite catalysts. *ChemSusChem*, 18(1), Article e202401025. <https://doi.org/10.1002/cssc.202401025>
- Bičáková, O., & Straka, P. (2012). Production of hydrogen from renewable resources and its effectiveness. *International Journal of Hydrogen Energy*, 37(16), 11563–11578. <https://doi.org/10.1016/j.ijhydene.2012.05.047>
- D’Acerno, L., De Matteis, L., & Stefanelli, R. (2025). Adoption of hydrogen in railway traction: Opportunities and limits in the case of non-electrified railway lines. *Transportation Research Procedia*, 90, 130–137. <https://doi.org/10.1016/j.trpro.2025.06.044>
- D’Adamo, I., Gastaldi, M., Giannini, M., & Nizami, A.-S. (2024). Environmental implications and leveled cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen. *Environmental Research*, 246, Article 118163. <https://doi.org/10.1016/j.envres.2024.118163>
- Di Blasio, G., Ianniello, R., & Beatrice, C. (2022). Hydrotreated vegetable oil as enabler for high-efficient and ultra-low emission vehicles in the view of 2030 targets. *Fuel*, 310, Article 122206. <https://doi.org/10.1016/j.fuel.2021.122206>
- European Environment Agency. (2023). *EMEP/EEA air pollutant emission inventory guidebook 2023* (pp. 1–23). <https://www.eea.europa.eu/publications/emep-eea-guidebook-2023>.
- Eurostat. (n.d.). *Electrified railway lines, 2023*. [ec.europa.eu/eurostat/cache/statistics\\_explained/maps/transport/electrified-railway-lines-2023.html](https://ec.europa.eu/eurostat/cache/statistics_explained/maps/transport/electrified-railway-lines-2023.html)
- Falchetta, M. (2014). *Fonti rinnovabili e rete elettrica in Italia: Considerazioni di base e scenari di evoluzione delle fonti rinnovabili elettriche in Italia* (RT/2014/8/ENEA). Agenzia Nazionale per le Nuove Tecnologie, l’Energia e lo Sviluppo Economico Sostenibile.
- Giunta, M., & Marino, C. (2026). Sustainable railways and the impact of freight trains: The case study of the shunting area of the Strait of Messina. In *Sustainable landscapes across the Mediterranean (CrossMED 2024—V1). Interdisciplinary approaches in cultural landscape management in the built environment*. Springer.
- Hickman, J., Hassel, D., Joumard, R., Samaras, Z., & Sorenson, S. (1999). *Methodology for calculating transport emissions*. (Project report SE/491/98). Transport Research Laboratory.
- Intergovernmental Panel on Climate Change. (2006). Chapter 2.3: Mobile combustion. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (pp. 1–78). <https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>
- International Organization for Standardization. (2023). *Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations* (ISO 14083:2023).
- Kapetanović, M., Núñez, A., van Oort, N., & Goverde, R. M. P. (2024). Energy use and greenhouse gas emissions of traction alternatives for regional railways. *Energy Conversion and Management*, 303, Article 118202. <https://doi.org/10.1016/j.enconman.2024.118202>
- Kokkinos, N. C., & Emmanouilidou, E. (2023). Sustainable rail fuel production from biomass. In *Transportation energy and dynamics* (pp. 3–6). Springer Nature Singapore. <https://www.springerprofessional.de/en/sustainable-rail-fuel-production-from-biomass/25483750>.
- Lindgreen, E., & Sorenson, S. C. (2005). *Simulation of energy consumption and emissions from rail traffic evaluation traffic* (report MEK-ET-2005-04). Technical University of Denmark, Department of Mechanical Engineering. [lindgreen\\_sorenson.pdf](https://lindgreen_sorenson.pdf)
- Lo Vullo, E., Monforti-Ferrario, F., Palermo, V., & Bertoldi, P. (2022). *Greenhouse gases emission factors for local emission inventories* (EUR 31168 EN). Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/776442>

- Portale Cartografico ePIR. (n.d.). Retrieved December 21, 2025, from <https://epir.rfi.it/arcgis/apps/sites/#/epir>
- Sharma, A. K., Sharma, M., Sharma, A. K., & Sharma, M. (2023). Mapping the impact of environmental pollutants on human health and environment: A systematic review and meta-analysis. *Journal of Geochemical Exploration*, 255, Article 107325. <https://doi.org/10.1016/j.gexplo.2023.107325>
- Piecyk, M., Cullinane, S., & Edwards, J. (2012). Assessing the external impacts of freight transport. In A. McKinnon, M. Browne, & A. Whiteing (Eds.), *Green logistics: Improving the environmental sustainability of logistics* (2 ed., pp. 31–50). Kogan Page Limited.
- Younas, M., Shafique, A., Hafeez, A., Javed, F., & Rehman, F. (2022). An overview of hydrogen production: Current status, potential, and challenges. *Fuel*, 316, Article 123317. <https://doi.org/10.1016/j.fuel.2022.123317>