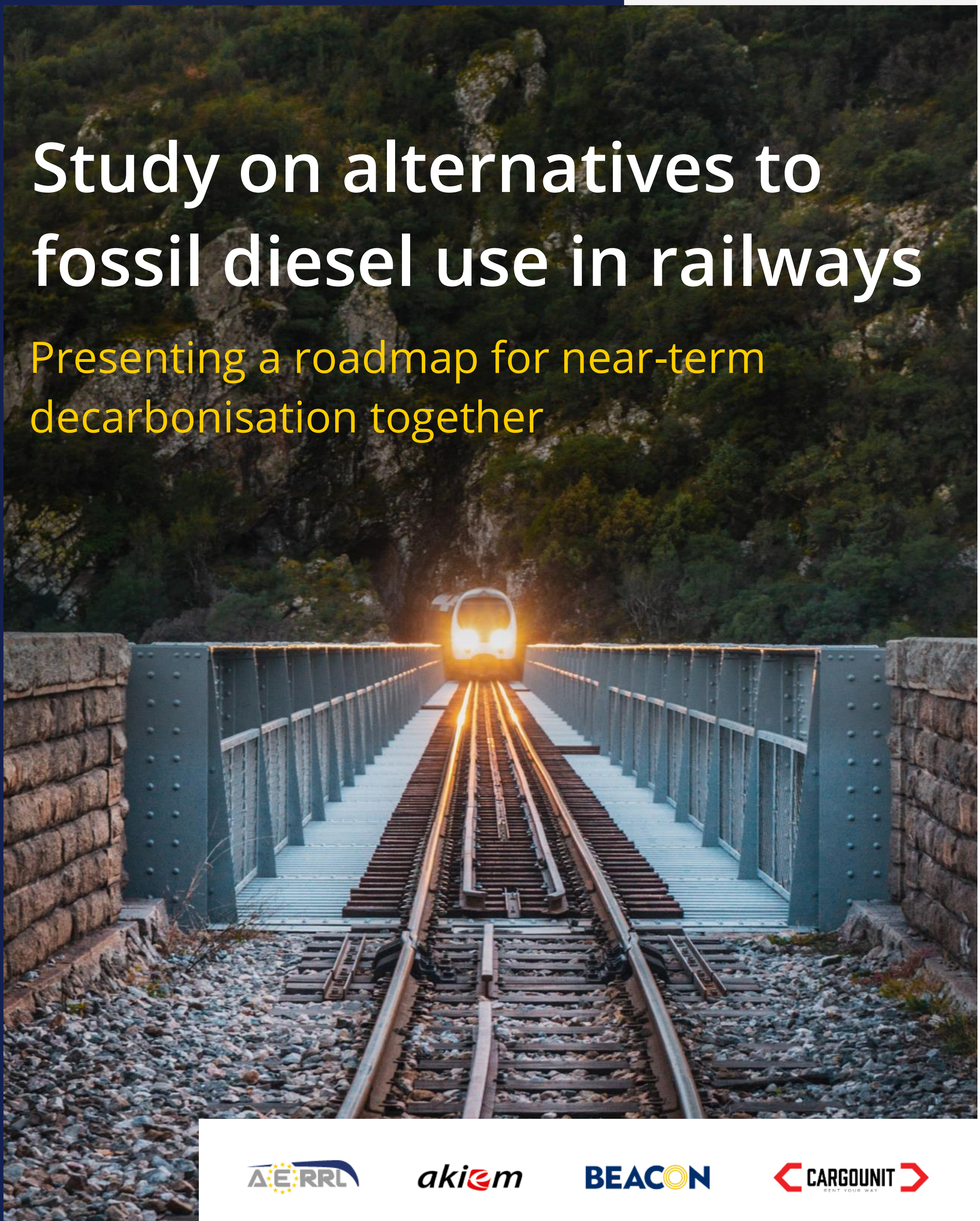
AERRL

Study on alternatives to fossil diesel use in railways

Presenting a roadmap for near-term decarbonisation together



AERRL akiem BEACON CARGOUNIT

SUPPORTED BY:

CRÉDIT AGRICOLE CORPORATE & INVESTMENT BANK ING KFW IPEX-Bank SOCIETE GENERALE

eolos
engineering the future®

December 2022

Table of Contents

Executive Summary

Moving towards net zero emission affects the European rail sector. In December 2019, the European Commission presented the EU Green Deal. Since then, it has been further substantiated by various compelling regulations and supporting funding programs. Against this background, the transport sector is bound to reduce emissions by 90 percent until 2050. The total freight carried by rail shall, however, increase by 100 percent for the same period, as the "Shift to Rail" approach is essential for the EU to reach its goals. Indeed, the rail sector is by far the most sustainable mode of land transport, representing less than 0.5 percent of total EU CO_2 emissions, although some rail operators still have diesel-powered fleets producing a significant portion of all their emissions. This is achieved thanks to the fact 60% of the European main lines network is already electrified and 80% of the traffic is running on these lines.

Ever-increasing rail demand, physical and economic limits to complete rail electrification, along with the rising competition over energy and resources, progressive taxation, and imminent ban of fossil fuels – many challenges are calling for coordinated efforts to strategically use available resources for a clean, competitive and efficient next-generation railway.

An aligned transition roadmap is essential to strengthen the railways' sector as part of the solution to decarbonise Europe. The Association of European Rail Rolling Stock Lessors (AERRL) commissioned this study to contribute to the overarching goal of a climate-neutral European Union (EU). Aware of the magnitude and urgency of this unparalleled green transition, AERRL reiterates the need to count on the rail sector for sustainable mobility and transport systems that can trigger a major change for society at large. The study specifically addresses the opportunities and challenges of phasing out of diesel-powered rolling stocks in the near future. It identifies promising alternatives meant to stimulate discussion and cooperation among all relevant stakeholders that lead to synchronised decisions and investment. The roadmap captures crucial milestones and provides orientation on the path towards climate neutrality.

Multidimensional and systematic analysis is required. This study examines the EU regulatory framework and selected national strategies and provides a preliminary evaluation of technology alternatives. The qualitative and quantitative research – including **extensive stakeholder consultations** and workshops with AERRL members – produced unique insights into the technological maturity as well as infrastructure and supply readiness.

While electrification remains the most efficient solution from a holistic perspective, complementary solutions can help to accelerate decarbonisation. HVO is rated as an immediate candidate. It can reduce CO_2 emissions by 85 to 90 percent and is easy to implement. Obstacles due to higher taxation can and should be adjusted by future regulation. RNG and Ammonia ICE are considered short- to medium-term options, though several operational challenges remain. Hydrogen has a high energy density (per kilogram), but "green production" is still very limited and requires high expenditure. It is an option for applications where no other solution is available (e.g. long non-electrified routes) and after substantial infrastructure improvements are achieved. Though major problems remain, battery technology is a solution for the rail sector. Especially Dual-Mode battery/electric trains combined with partial electrification for the longer term could become a game-changer.

Shifting perspectives to be successful in shifting to rail. This study provides clear recommendations for the EU Commission. To enable the sustainable transition of the rail sector, the different stakeholders need to come together in a "*freight transport system for efficiency*" organised either by the Commission or an appointed actor in the field. The investments between rolling stocks and infrastructure need to be balanced. To achieve maximum leverage for industrial decarbonisation, the rail sector should be, after pipelines, the first choice for green hydrogen transport. With such a position in a new supply chain, the rail sector can increase its freight market share and provide safe and reliable low carbon-emission energy to today's most emissive industries.

Disclaimer

This study is based on a high-level legal review of key EU regulations and national policies in selected EU member states followed by stakeholder consultations. All activities have been coordinated and led by eolos GmbH, an independent consulting company for industrial sustainability in the railway sector.

The views expressed in this study are those of the authors and do not necessarily reflect the official individual position of the AERRL members.

Nothing in this publication constitutes legal advice from eolos GmbH. The regulations mentioned and analysed in this study are based on current European legislation and on proposals for European directives and regulations as drafted at the date of publication of this study. These proposals may have been amended and entered into force after the date of publication of this study.

Acknowledgments

AERRL would like to thank its members, the authors, contributors, and reviewers for their contribution to the preparation of this study.

About AERRL

Our mission is to promote interoperable, sustainable, efficient, and safe passenger and cargo rolling stock for the European railways. Our association is addressing technical, operational, economic, legal and scientific issues and matters relating to locomotives and passenger trains operated in the European Union and Switzerland. **www.aerrl.eu.**

This report was authored by:

eolos
engineering the future®

On behalf of:

AERRL akiem BEACON CARGOUNIT RENT YOUR WAY

Supported by:

CRÉDIT AGRICOLE CORPORATE & INVESTMENT BANK
ING
KFW IPEX-Bank
SOCIETE GENERALE

Photo by **Gontran Isnard** on **Unsplash**

List of Acronyms

AERRL	Association of European Rail Rolling Stock Lessors
CFO	Catenary free operation
CO_2(e)	Carbon dioxide (equivalent)
DB	Deutsche Bahn, German national railway operator
Dual-mode	Combination of two types of motorisation or energy supply in the rolling stock
EC	European Commission
ETD	Energy Taxation Directive
EU	European Union, used interchangeably with Europe / European throughout the document
FFI	Fortescue Future Industries
GHG emissions	Greenhouse gas emissions
HVO	Hydrotreated vegetable oil (advanced bio diesel)
H2	Hydrogen
ICE	Internal combustion engine
LNG	Liquified natural gas
ÖBB	Österreichische Bundesbahnen, Austrian national railway operator
OEM	Original equipment manufacturer
RED	Renewable Energy Directive
RNG	Renewable natural gas
SBB	Schweizerische Bundesbahnen, Swiss national railway operator
TEN-T	Trans-European Transport Network
TTW	Tank-to-wheel
WTW	Well-to-wheel

1. Context of this Study

The Association of European Rail Rolling Stock Lessors (AERRL) has launched this study to identify and promote technologies to cut the climate impact of the existing diesel-powered rail fleets in the near future. A transition from diesel must encompass the technological readiness and application scenario as well as a proactive approach to include the European Union (EU) regulations prohibiting high-emissive practices.

The aim of this study is to start a conversation that takes up the EU's query about the most effective policy levers for a very low-carbon emission railway industry. Proper and detailed calculations with regard to the environmental impact of each solution should be addressed in the next phase.

Rail sector positioning in a Europe moving towards climate neutrality

In November 2018, the EU pledged to be the first climate-neutral continent by 2050, in line with the global climate action under the Paris Agreement. To meet its responsibility, the European Commission (EC) presented the EU Green Deal in December 2019. This set of directives strives to "transform the EU into a modern, resource-efficient and competitive economy, ensuring no net emissions of greenhouse gases by 2050 and economic growth decoupled from resource use"[1].

In its 2021-2027 budget of over €2.0 trillion, the EU allocates 30 percent of its financial resources to fighting climate change.[2] As a result, a complex ecosystem of compelling regulations and supporting funding programs has been formed, which industries must follow, adapt to and align their strategies with.

The rail sector is already by far the most sustainable mode of land transport, representing less than 0.5 percent of the EU total CO_2 emissions[3]. It is as such a key player to speed up the current decarbonisation efforts of European industries. Still, additional efforts are needed to deliver the next generation of railway, for passengers and freight, and accelerate the "Shift to Rail" in Europe.[4]

Although diesel rail freight emits significantly less greenhouse gas (GHG) emissions per load transported than heavy goods road transport[5], about 50 percent of the current fleet in Europe still operates on fossil diesel.[6] This study therefore focuses on exploring alternatives to the existing diesel propulsion, particularly in view of the very large increase in rail freight volume and the corresponding climate impact expected between now and 2050. Adding to the continuous demands on networks and services, the rail sector also faces unprecedented and oftentimes strict requirements from legislators like the gradual prohibition of fossil fuels.

---

1 European Union (n.d), A European Green Deal. More: Regulatory Landscaping Overview & related Sources

2 European Union. (n.d); https://climate.ec.europa.eu/eu-action/funding-climate-action/supporting-climate-action-through-eu-budget_en

3 European Environmental Agency (12/2019), Share of transport greenhouse gas emissions; https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2/#tab-googlechartid_chart_13

4 UNIFE and CER Position Paper (06/2016), Rail as a key to decarbonizing transport; https://www.unife.org/wp-content/uploads/2021/03/RAIL-AS-A-KEY-TO-DECARBONISING-TRANSPORT.pdf

5 Tank-to-wheel comparison: diesel rail freight 7.64 grams CO_2e per tonne-kilometres vs. heavy goods road freight 107 grams CO_2e per tonne-kilometres), see also: **https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccn/2021/Methodology%20for%20GHG%20Efficiency%20of%20Transport%20Modes.pdf**

6 Website European Union (01.07.2022); **https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Transport_equipment_statistics#Railway_transport_equipment:_more_electrical_energy.2C_fewer_seats**

Railway transport shall be further electrified according to the EC's "Sustainable and Smart Mobility Strategy", there will nevertheless be a need for catenary-free operations (CFO) for years to come.[7] Hence, stakeholders in the rail sector must explore alternatives to diesel and electrification that are readily available to be implemented in the fleet management in the coming decades.

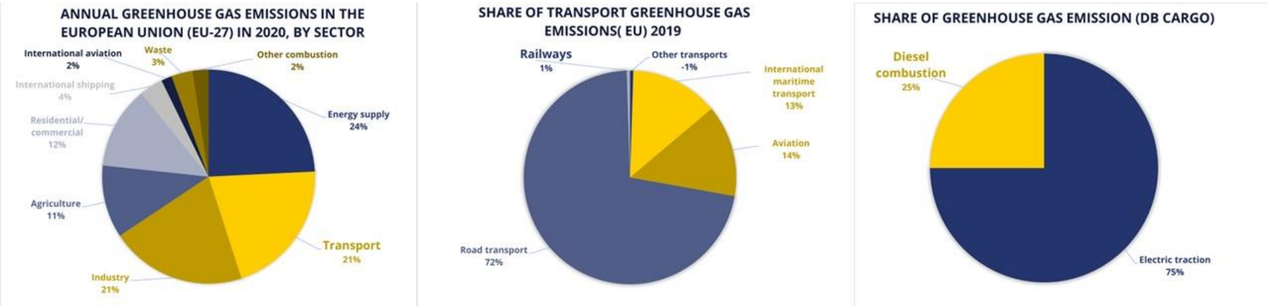


Figure 1: Distribution of greenhouse gas emissions (GHG), left to right: Europe[8], transport sector[9] and DB Cargo[10]

Scoping the rolling stock fleets concerned by diesel swap

In Europe, rail electrification remains the optimal solution, in particular for freight transport, and should be continuously driven forward. However, considering the length of implementation and the required physical, economic and strategic efforts to electrify the rail network, bridge solutions and technology alternatives can contribute to decarbonising the rail sector faster.

This study estimates that more than 10.000 diesel-powered locomotives with an average remaining life of more than 20 years operating in Europe.[11]

	Operation scenario (status-quo of most common existing solutions)						
Traction System	**Locomotive Works**	**Locomotive Shunting**	**Locomotive Last Mile**	**Locomotive Mainline (Freight & Passenger)** (3000 kW)	**Locomotive Heavy-Freight** (> 4 to 6000 kW)	**Regional xMUs** (< 100 km)	**Intercity** (> 100 km)
Electric	⊗	⊗	⊗	☑	☑	☑	☑
Bimode (Elec/Diesel)	☑	☑	☑	☑	⊗	☑	☑
Diesel	☑	☑	☑	☑	☑	☑	☑

Figure 2: Overview of the current applicability of traction systems and operational scenarios[12]

---

7 60% of the European rail network is already electrified and 80% of traffic is running on these lines, see European Union, (22.01.2018), Electrification of the transport system, Expert group report; **https://op.europa.eu/en/publication-detail/-/publication/253937e1-fff0-11e7-b8f5-01aa75ed71a1/language-en**

8 Statista (n.a.), Annual greenhouse gas emissions in the European Union (EU-27) from 1990 to 2020, by sector; https://www.statista.com/statistics/1171183/ghg-emissions-sector-european-union-eu/

9 European Environmental Agency (12/2019), Share of transport greenhouse gas emissions; https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2/#tab-googlechartid_chart_13

10 DB Cargo (2022), Climate Protection and Energy (Jörg Schneider)

11 Retrieved from eolos' analysis locomotives of European railway operators (10.22)

12 Own illustration

Due to the desire and expectation to increase the total rail freight by 100 percent until 2050, the overall number of locomotives most probably will increase. Hence, decision-makers must explore alternative options as full electrification is not always possible.

Amongst those, we have considered different dual-mode propulsion systems and the following illustration clarifies them.

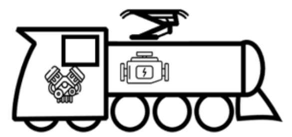
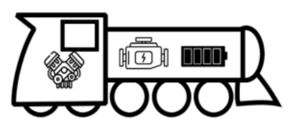
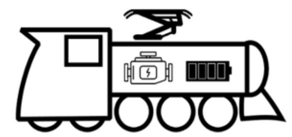
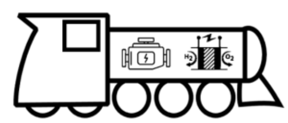
Dual-Mode Electric/Diesel	**Dual-Mode Diesel/Battery**	**Dual-Mode Electric/Battery**	**Hydrogen Fuel Cells**
			
Thermal motor + Electric motor powered by catenary	Thermal motor + Electric motor powered battery	Electric motor powered by catenary + Battery	Electric motor powered by a H2 fuel cell

Figure 3: Alternate dual-mode propulsion systems[13]

Tighter regulations limit the use of fossil fuels and stimulate alternatives

The analysis of new and revised EU regulations related to diesel fuel shows that the EU wants to drastically reduce the use of fossil fuels. The “Sustainable and Smart Mobility Strategy” sets out a roadmap with the objective to cut 90 percent of the emissions from the transport sector by 2050[14].

Beyond the ambitions related to carbon emissions driven by the EU Green Deal, the European Climate Law[15] or the “Fit for 55” package[16], the regulations currently worrying rail manufacturers and operators the most are recent revisions of the European Taxation Directive and the Renewable Energy Directive. These regulations are prompting changes around fossil fuel practices in other transportation sectors as well and have led to initiatives like “FuelEU Maritime” and “RefuelEU Aviation”.

At the same time, the EC also strives to develop alternatives to fossil fuels, especially for transport. This is the main purpose of a proposal to repeal the existing Alternative Fuels Infrastructure directive and replace it with a regulation ensuring an extensive coverage of alternative fuels infrastructure to (re)charge or (re)fuel vehicles across the EU. The revision of the Trans-European Transport Network (TEN-T) points in the same direction: to provide the appropriate infrastructure basis to reduce GHG emissions, to facilitate an increase in the share of rail and to foster multimodality and interoperability between transport modes.

Beyond these specific regulations, the EU Taxonomy Regulation[17], which entered into force in July 2020, clearly impacts the use of fossil fuels and the development of alternatives in the transport sector. With the EU Taxonomy Regulation and the EU Taxonomy Climate Delegated Act [18] adopted in June 2021, companies, investors, and policymakers can identify economic activities substantially contributing to the green transition and climate change adaptation and mitigation. Given its large share of very low-

13 Own illustration

14 European Union. (n.d.), Mobility Strategy. More: Regulatory Landscaping Overview & related Sources

15 Presentation of the European Climate Law by the European Commission. More: Regulatory Landscaping Overview & related Sources

16 European Parliament. Fit-for-55 package More: Regulatory Landscaping Overview & related Sources

17 EU Taxonomy Regulation More: Regulatory Landscaping Overview & related Sources

18 EU Taxonomy Climate Delegated Act. More: Regulatory Landscaping Overview & related Sources

carbon emissions (zero tailpipe emission / electric) assets, the rail industry will surely benefit from the taxonomy roll-out.

Addressing the rising need and competition for energy and resources

Beyond incentives to move away from the unsustainable exploitation of natural resources such as energy, metals, raw materials, and water, it is paramount to find solutions enabling EU industries to reduce their dependency on international supply chains. Disruptive crises like Covid-19 and the Russian invasion in Ukraine[19] have clearly demonstrated the possible negative impacts. Energy and resource efficient strategies must therefore form an essential part of future rail fleet management.

With its REPowerEU Plan, the EC addresses such risks by favouring the efficiency of energy usage and storage.[20] Similar approaches are outlined in the "Roadmap to a Resource-Efficient Europe" from 2011, which indicates the path to a low-carbon economy based on the Circular Economy principle.[21]

Positioning AEERL as a pragmatic implementer

In this context, AERRL and its members want to position themselves as a pragmatic implementer of very low-emissive solutions for the future railway. Through this study, the association wants to examine the high-level regulatory landscape and highlight existing opportunities and barriers for diesel alternatives.

AERRL's ambition is to discuss the study recommendations with its peers. A balanced representation of the rail sector is necessary to identify blind spots and to approach them pragmatically thereafter.

Therefore, AERRL is open to initiate, organise and implement projects together with other stakeholders, partners, and experts across the sector. The findings of this study are summarised in a roadmap (see **"Moving forward"**) to trigger further discussions and enable the convergence of the different stakeholders.

---

19 European Council of the European Union (n.d.), Impact of Russia's invasion of Ukraine on the market: **EU response https://www.consilium.europa.eu/en/policies/eu-response-ukraine-invasion/impact-of-russia-s-invasion-of-ukraine-on-the-markets-eu-response/**

20 European Commission (n.d.), REPower EU: affordable, secure and sustainable energy for Europe. More: **Regulatory Landscaping Overview & related Sources**

21 European Commission (n.d.), Resource Efficiency; **https://ec.europa.eu/environment/resource_efficiency/index_en.htm**

2. Methodological Approach

Complexity and scope of the green transition require a multidimensional and systematic analysis. This study encompasses qualitative and quantitative aspects necessary to identify appropriate and realistic scenarios for action. To achieve this, AERRL commissioned eolos GmbH to develop a methodological approach, engage in theoretical research and reach out to AERRL members, partners and other experts working on transport, sustainability and/or related issues. Stakeholder consultations took place during four workshops with AERRL and numerous topical interviews (see **List of Participants**).

The study focuses on two general areas:

1. Analysis of the EU regulatory framework and four national strategies

Given the importance of the EU regulatory framework in triggering significant change in the member states and major industries, an extensive evaluation of relevant directives and regulations was conducted ("regulatory landscaping"). This also included a non-exhaustive overview of related policies and EC communications. On the national level, the assessment mainly examined national strategies around diesel swaps in France, Germany, Poland and the United Kingdom. All policies and regulations referred to can be found in **Regulatory Landscaping Overview & Related Sources**.

2. Preliminary evaluation of bridge solutions and technology alternatives with a potential to replace or supplement diesel-powered rolling stocks

Five selected bridge solutions and technology alternatives were assessed in depth: biofuel hydrotreated vegetable oil (HVO); renewable natural gas (RNG); Ammonia internal combustion engine (ICE); hydrogen; and batteries. The operational readiness was examined by combining the four aspects technology maturity; existing infrastructure; available supply; and current regulatory landscape.

This focus was based on the applicability to different operation scenarios (with reference to Figure 2). Hydrogen ICE was not included because it can only be considered in retrofit use and has a much too low energy efficiency. Heavy freight was also neglected being a minor use case in Europe, but it should be addressed in and for countries like Australia, Canada, or India. Similarly, e-fuel technology was discarded as it currently is still under development, requires a lot of energy and has low WTW efficiency.

Though with varying levels of market readiness, there are many options to phase out diesel-powered locomotives and trains. For a systemic diesel swap to be successful, the transition must be thoroughly planned. In that sense, the following parameters are equally important to understand the specific conditions of AERRL members and other rolling stock operators and stakeholders: size and age of the diesel fleet and potential for upgrades; stage of development of low-carbon technologies; operational range requirements and forecast loads; environmental footprint and potential improvements.

Beyond technology readiness and its related environmental impacts, the methodological framework also considers existing and planned infrastructure developments as well as supply availabilities. The maturity graphs developed and shared as illustrations do not aim at providing detailed and accurate data points, but rather a holistic and integrated view. That way the gaps between technology, infrastructure and technology readiness are visualised and can illustrate important learnings.

Overall, the insights and recommendations blend theoretical research and quantitative analysis, stakeholder consultations and specific work environments in an integrated and systemic approach. The methodological framework of this study is designed to be future-proof and can be easily adjusted as new regulations and technologies emerge.

3. Findings and Recommendations

Examining and understanding every aspect of a certain bridge solution or technology alternative is far from easy. The methodological approach underlying this study helped to grasp up-to-date information from many different knowledgeable sources and relate it to the current regulatory landscape. On this basis, the following integrated findings and recommendations present a comprehensive overview of every technology along with its possible importance for a more sustainable transport system. Apart from technological innovation leading to low-emissive and more secure power supply for modern rail transportation, it is equally important to find new ways to use that power widely and more efficiently by providing support to operators and integrators and pushing the “Shift to Rail” approach forward.

3.1. Treating Rail separately from other Transportation Sectors

Representing less than 0.5 percent of the EU's total CO_2 emissions, the railway sector is a key component to speed up the decarbonisation efforts across European industries. In recent years, thanks to the efforts of major railway actors and the 2021 Year of Rail, unprecedented progress has been made towards effecting “Shift to Rail”.

Passengers traffic

Overall, ridership steadily increased prior to the COVID-19 pandemic thanks to the progressive upgrade and development of the infrastructure and procurement of new rolling stocks. Initiatives like the €1/day transport card in Austria[22] have motivated more passengers to choose rail transport. Though ridership has significantly decreased again during the pandemic, operators helped to implement social benefit programmes like the €9/month ticket in Germany[23] or the reduced ticket for commuters in Spain[24]. Although those new measures have proved to prompt passengers to make rail their mobility lifestyle, it raises questions regarding economic balance and sustainability.

Freight transport

Despite all the efforts deployed to “Shift to Rail”, it can be observed that the volume of rail freight transport has barely increased over the past 15 years. This contrasts with the overall increase in freight transport and logistic flows. A more detailed analysis suggests that a significant shift in the type of freight carried has taken place: decreasing transport of fossil fuels, increasing transport of other goods (including automotive). Today’s rail freight represents a mere 17 percent of the overall freight traffic in Europe, whereas the objectives set by the EU Sustainable and Smart Mobility Strategy aim at a 50 percent increase by 2030, and a 100 percent increase by 2050.

---

22 The Guardian, (2022), Vienna’s euro-a-day public transport model could waltz into Berlin; https://www.theguardian.com/world/2019/jul/09/vienna-euro-a-day-public-transport-berlin-365-annual-ticket

23 DW, (2022), Deutsche Bahn hails 9-euro public transport ticket; https://www.dw.com/en/deutsche-bahn-hails-9-euro-public-transport-ticket/a-62953716

24 Website the Guardian, (01.09.22), Free rail travel scheme begins in Spain to cut commuters’ costs; https://www.theguardian.com/world/2022/sep/01/free-rail-travel-scheme-begins-in-spain-to-cut-commuters-costs

Figure 4: Evolution of rail freight traffic volumes in Europe [25]

This study corroborates that achieving this volume of "Shift to Rail" is the major lever to decarbonising Europe. However, an increasing freight traffic market share is linked to the overall and current railway system performance, which is hindered by the below mentioned main root-causes.

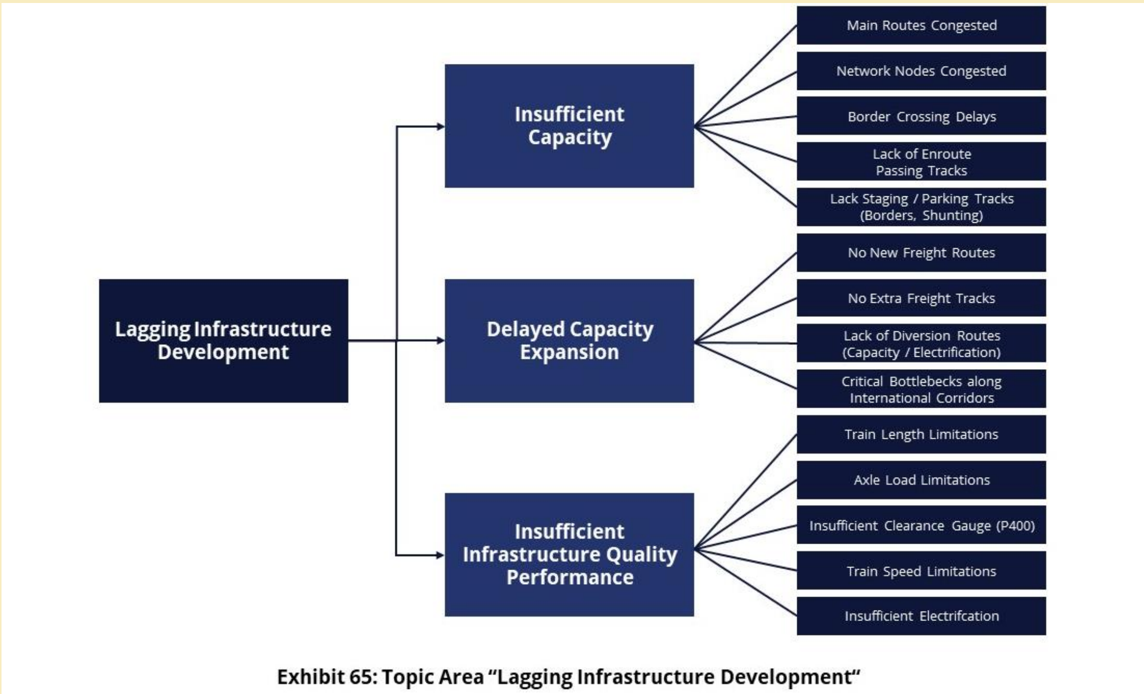


Figure 5: European rail freight market – competitive analysis and recommendations[26]

[25] ERFA Annual report 2021, page 7

[26] The European Rail Freight Market Competitive Analysis and Recommendations, Page 76; **https://erfarail.eu/uploads/The%20European%20Rail%20Freight%20Market%20-%20Competitive%20Analysis%20and%20Recommendations-1649762289.pdf**

3.2. Starting with basic Principles of Physics to Short-List Alternatives

First and foremost, two main physical features must be considered while assessing alternative technologies:

(1) the energy density of sources (see Figure below),

(2) and the efficiency of the overall WTW conversion (see Figure 7)[27].

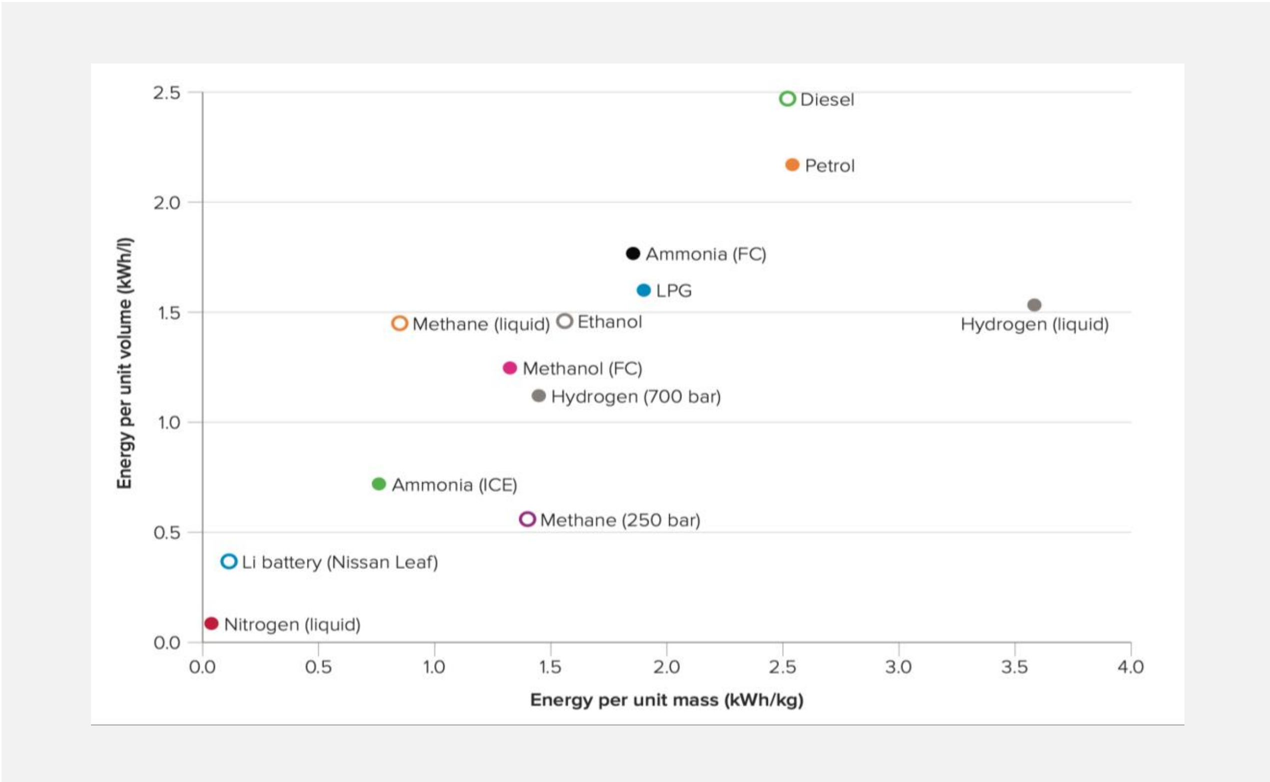


Figure 6: Energy density per technology alternative.[28]

---

[27] Please note: To better reflect GHG-related impacts, all CO2 emissions and energy-efficiency conversions mentioned are referring to "Well-to-wheel" calculations, except if mentioned otherwise.

[28] Retrieved from the **Royal Society, Policy Briefing, Ammonia: zero-carbon fertiliser, fuel and energy store**

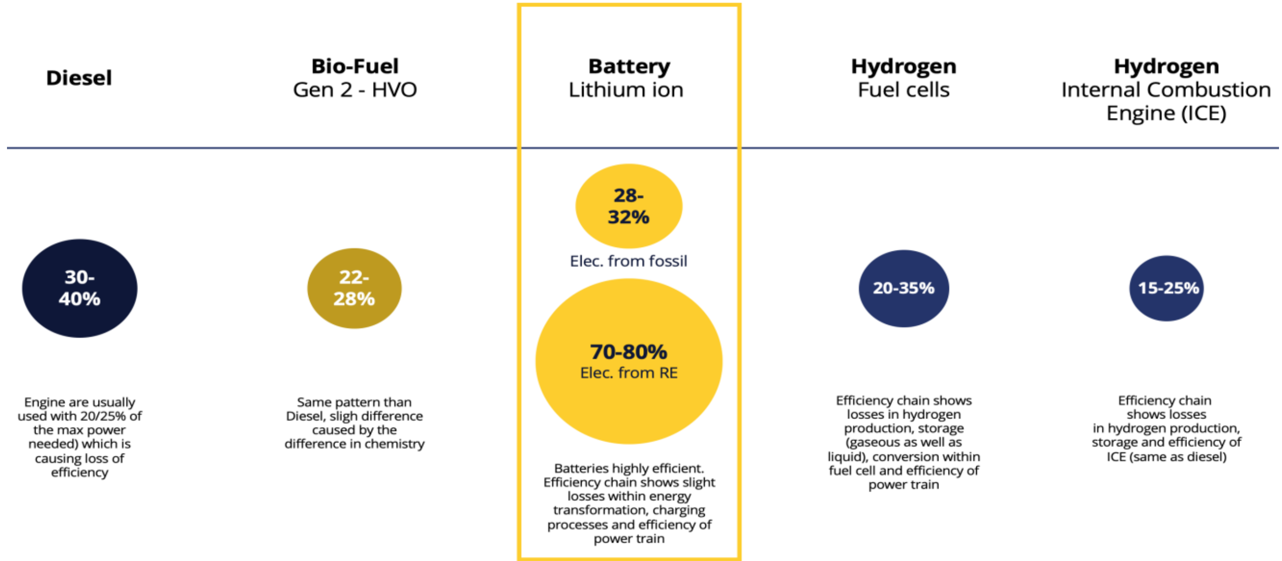


Figure 7: Well-to-wheel-efficiency per technology alternative compared to fossil diesel [29]

Considering the physical principles and the fact that energy is a limited resource, it can be preliminary concluded that:

1. battery cannot be applied as a solution for stand-alone heavy duty freight locomotives due to available integration space constraints versus its low energy density; and that
2. hydrogen ICE shall not be enlisted as a potential solution due to too low energy conversion efficiency. However, Ammonia ICE is captured as one of the potential bridge solutions to enable retrofit and maintain the original service life of some rolling stocks.

[29] Retrieved from Interview with TU Graz

As such, this study focuses on the following bridge solutions and technology alternatives.

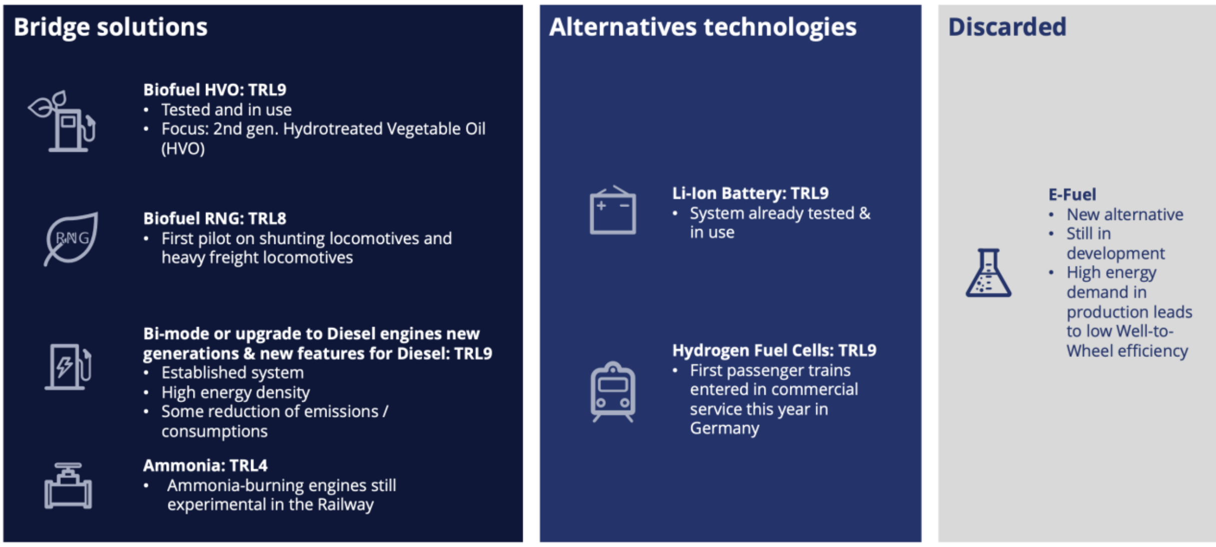


Figure 8: Considered Bridge solutions and technology alternatives[30]

These choices are substantiated by the conclusive comparison performed on the different solutions (see Figure below).

	Bridge solutions and technology alternatives					
	Diesel fossil fuel	**Bio-fuels**	**Ammonia**	**Hybrid Electric/Battery**	**Fuel Cells + Battery**	**Electrification**
Efficiency TTW (Tank to Wheel) WTW (Well to Wheel)	TTW : 36 to 46% WTW : 30 to 40%	TTW : 36 to 46% WTW : 22 to 28%	TBC	TTW : 80 to 85% WTW : 28 to 32% (Elec from fossil) WTW : 70 to 80% (Elec from RE)	TTW : 30 to 40% WTW : 20 to 35% (Green H2)	TTW : 85 to 95% WtW : 30 to 34% (Elec from fossil) WTW : 75 to 85% (Elec from RE)
TTW Emissions reduction	Not applicable	0%	TBC	-100%	-100%	-100%
WTW Emissions reduction	Not applicable	-80 to -85% (TBC as some studies state lower values)	TBC	-80% (on EU energy mix)	-80 to -90% (Green H2) -25 to -35% (Grey H2)	-80% (on EU energy mix)
Resources	No issue of supply so far	Secure the supply Strong competition with other transportation for HVO, Heating needs for RNG	No issue of supply	Necessary materials for Li-Ion	Secure the supply of Green H2 Strong competition with process industries	NA

Figure 9: Efficiency, emissions and resources per technology alternative [31]

The results are particularly noteworthy in terms of efficiency, differentiated by TTW and WTW. While looking at hybrid electric/battery and electrification, special attention should be paid to how the respective source affects the efficiency.

30 Own illustration

31 Own illustration

Although TTW efficiency of diesel engines (fossil or Bio) follows more than 100 years of innovation, and has now reached an asymptotic value, there are still some measures that need to be implemented to keep increasing the overall TTW efficiency of this proven technology like installation of anti-idling systems, installation of energy management systems, implementation of eco-driving modules, and optimizing train charges.

	Bridge solutions and technology alternatives				
	Bio-fuel HVO	**Bio-fuel RNG**	**Ammonia**	**Hybrid Electric/Battery**	**Fuel Cells + Battery**
TRL in the railway	**9**	**8**	**4**	**9**	**9**
Retrofit of existing locomotives	No need for HVO (*small adjustments on older engines*)	Upgrade for RNG (*positive business case*)	TBC	Possible but intrusive retrofit with negative business case	Possible but intrusive retrofit with negative business case
Operation & Maintenance Impact	None	RNG: safety measure for refuelling RNG: check maintenance impacts	TBC	Range and power Time for recharging and availability of recharging infrastructure	Availability of recharging infrastructure and safety
Main points to highlight	Price tag Traceability of refuelling	Availability of locally produced RNG	From the Marine sector, Still in development in the railway. Time to Market > 5 years	**Would lower the need for electrification (26 to 50%)**	To be considered for Heavy duty freight and long range with no electrification

Figure 10: Operation & maintenance impacts per technology alternative [32]

To address its own sectorial emissions, the railway sector needs to transform itself and leverage its strengths to concretely move away from diesel-powered operations. With this objective clearly stated by AERRL and its members, this study presents first bridge solutions that would immediately bring environmentally positive effects.

3.3. Using HVO as a Bridge Solution: An immediate Opportunity

Hydrotreated vegetable oil (HVO) is a second-generation biofuel, which uses feedstock, unlike the first-generation biofuels using crops.[33] The use of HVO reduces CO_2 equivalent emissions by 85 to 90 percent while nitrogen oxide (NO_X) emissions remain in the same range.[34] It also reduces slightly the combustion noise levels.[35]

EU Taxonomy eligibility of HVO

Rolling stock using HVO in railway operations is not considered aligned with the EU Taxonomy as it is not "zero direct CO_2 emissions (at tailpipe)". Integrating HVO railway operations could improve financing conditions and help increase rail freight capacities for non-electrified transport routes. This would also be consistent, given that manufacturing biofuels and biogas for transport (activity 4.13) is identified as taxonomy-eligible with stringent criteria to ensure that the GHG emission savings is at least 65 percent compared to the manufacturing of fossil fuels and to ensure that food-and feed crops are not used for the manufacture of biofuels for use in transport (Source see **Regulatory Landscaping Overview & Related Sources)**

32 Own illustration

33 Oxford Academic, (n.d.), From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity; **https://academic.oup.com/af/article/3/2/6/4638639**

34 Science Direct, (01.03.2018), Particulate number and NOx trade-off comparisons between HVO and mineral diesel in HD applications; **https://www.sciencedirect.com/science/article/pii/S0016236117314151**

35 MDPI (01.09.2022), Utilization of Hydrotreated Vegetable Oil (HVO) in a Euro 6 Dual-Loop EGR Diesel Engine: Behavior as a Drop-In Fuel and Potentialities along Calibration Parameter Sweeps, Stefano d'Ambrosio, Alessandro Mancarella and Andrea Manelli

The main advantage of HVO for rail is the easy implementation in the existing diesel fleet: Using HVO does not require upgrading locomotives nor refueling stations. It does not impact the organisational processes linked to operation and maintenance of the rolling stock. Likewise, the mixed use of HVO and fossil diesel is possible during the migration phase while progressing supply availability across refueling stations. In this context, the decision by Deutsche Bahn (DB) Cargo Germany, part of the largest railway operator and infrastructure owner in Europe, is especially noteworthy.

According to DB Cargo GER, HVO remains a bridge solution especially for heavy freight locomotives due to the high power requirements with no economic and technological alternative in the medium term. In June 2022, the company endorsed the use of HVO on its entire fleet[36], following the self-initiated approval of two of its key engine suppliers: MTU[37] and Caterpillar.[38]

The following Illustration presents an integrated view of the technology, infrastructure, and supply availability readiness for HVO:

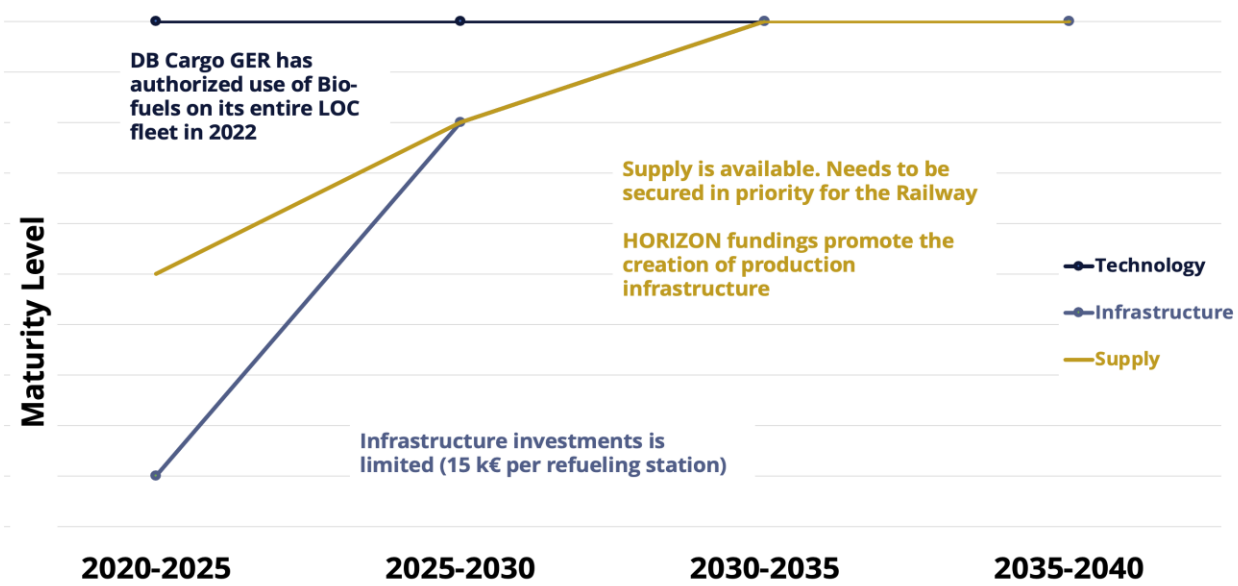


Figure 11: Technology, infrastructure, and supply availability readiness for HVO [39]

---

[36] Retrieved from stakeholders consultations. More: List of participants interviewed in the context of WP2 – technology alternatives; https://www.dbcargo.com/rail-de-de/logistik-news/auf-dem-gruenen-weg-db-cargo-testet-hvo-7327204

[37] MTU, (17.02.2022), HVO Fuel proven to be effective for Diesel Generator Sets; https://www.mtu-solutions.com/eu/en/technical-articles/2022/hvo-fuel-proven-to-be-effective-for-diesel-generator-sets.html

[38] Caterpillar (2021), Sustainability Report; https://www.caterpillar.com/en/company/sustainability/sustainability-report/focused-areas/energy-emissions/supporting-our-customers.html

[39] Own illustration

To fully exploit these advantages, the below-mentioned hurdles shall be addressed

1. Refueling stations must observe certain standards. For instance, in Germany, they must follow two different DIN standards depending on which type of fuel they dispense (DIN 15940 for HVO and DIN 590 for fossil fuels). This comes with administrative processes and requires specific authorisations to be obtained. Both DIN 15940 and DIN 590 also stipulate that a refueling station cannot be converted to HVO if a customer is still willing to use it for fossil diesel.
2. Currently, HVO costs ca. € 30ct/liter more than fossil diesel[40]. While the new Energy Taxation Directive (ETD) aims to tackle the risks of "overprice", and ultimately favor the use of biofuel over fossil diesel, concerns remain around the timely adoption of this Directive by the EU Commission, and consequently, the application by the member states.
3. HVO is an attractive bridge solution for other modes of transport, as promoted by the Renewable Energy Directive (RED). NESTE, the biggest European biofuel supplier, believes that the increase in supply shall meet the demand increase. Several funded projects under the HORIZON program are dedicated to support the development of the supply infrastructure. It is key for the rail industry to secure its necessary supply to implement this solution as an effective bridge solution.

Horizon Europe

"Horizon Europe is the EU's key funding programme for research and innovation with a budget of €95.5 billion. It tackles climate change, helps to achieve the UN's Sustainable Development goals and boosts the EU's competitiveness and growth."[41]

40 Based on eolos interview with DB Cargo, DB TecLab and Neste. More: List of participants interviewed on technology alternatives

41 European Union, (n.d.), Horizon Europe, **https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en**

Energy Taxation Directive (ETD)

	Rate at start of transitional period (01.01.2023)	Final rate before indexation (01.01.2033)
Petrol	10,75 (1000L of oil equivalent =42GJ)	10,75
Natural gas	7,17	10,75
Sustainable food and feed crop biofuels (1st generation)	**5,38**	**10,75**
Sustainable biogas	5,38	5,38
Advanced sustainable biofuels (HVO) and biogas (RNG to be confirmed)	**0,15**	**0,15**
Electricity	**0,15**	**0,15**

Figure 12: Future minimum levels of taxation for different fuels

With the current ETD, as the same tax rate applies, biofuels are disadvantaged by volume-based taxation. With this revision, minimum tax rates will now be based on the real energy content and environmental performance on fuels and electricity (€/GJ), rather than on volume (€/1000l). The most polluting fuels will be taxed the highest, as well as food and feed crop biofuels (1st generation) in 2033 after a 10-year transitional period. On the contrary, sustainable biofuels and advanced sustainable biofuels (2nd and 3rd generations) will have a lower level of taxation.

According to the article 17 of the revised ETD, Member States may apply under fiscal control reductions in the level of taxation, which shall not go below new minima to energy products and electricity used for the carriage of goods and passengers by rail, metro, tram and trolley bus, and for local public passenger transport.

Renewable Energy Directive

The Commission's proposal for a revised Renewable Energy Directive would increase the binding EU minimum share of renewable energy sources in final energy consumption to 40% by 2030. According to art. 25, the share of advanced biofuels (2nd and 3rd generations) from feedstocks that don't compete with food or feed will increase progressively, reaching at least 0,5% in 2025 and 2,2% in 2030.

On the contrary, according to art. 26, the maximum of the share of biofuels and bioliquids, as well as of biomass fuels consumed in transport, where produced from food and feed crops (1st generation), is limited to 7 % of final consumption of energy in the transport sector.

3.5. Upgrading to RNG or Ammonia ICE: Short- to medium-term Bridge Solution Options

Upgrading current diesel locomotives to use RNG

Renewable Natural Gas (RNG) is a biomethane produced by gasification and methanation processes of biomass, as well as through a process of upgrading and purification of biogas, which is mainly used for home heating.

It can take two different forms: Compressed Natural Gas (CNG) or Liquified Natural Gaz (LNG). Bio-methane is indistinguishable from natural gas and so can be used without the need for any changes in transmission and distribution infrastructure or end-user equipment and is fully compatible for use in natural gas vehicles. Today, worldwide biomethane production is 3,5 Mtoe, which represents 10% of the Biogas production and only 0.1% of Natural Gas demand. Operating locomotives with renewable natural gas (RNG) allows to reduce CO_2 emissions by 70 percent, NO_X by 30 percent, and particulate matter (PM) by 70 percent. [42]

To fully exploit these advantages, the below-mentioned hurdles shall be addressed

1. It requires new refueling stations and specific attention to safety with regards to storage and refueling operations. CNG / LNG requires to store gas in high pressure tanks, with periodic inspection and certification, and additional active cooling system for long term LNG storage
2. The availability of the supply for the rail sector remains to date unpredictable, mainly because Biogaz is primarily used for the ever-increasing demand of heating for housing. In the current socio-political context, member states are likely to favour heating over railway operations. Therefore, this technological alternative will probably depend on the gradual development of local supply and would require national and/or local initiative in the member states
3. Contrary to HVO, using RNG requires upgrading the locomotives. Successful pilots carried out by the Latvian company DiGas under the Horizon 2020 programme have demonstrated that the business case and the return on investment for locomotive owners and operators are positive, provided that local RNG supply is available and pricing of RNG is decoupled from the latest energy price increase. Under these conditions, financing should be facilitated to encourage locomotive owners and operators to upgrade (part of) their fleets and networks accordingly.

Upgrading current diesel locomotives to use Ammonia

Ammonia (NH3) is considered to be a hydrogen-derived fuel, it delivers higher volumetric energy density, up to three times higher than hydrogen.[43] Ammonia is now mainly used for fertilisers and therefore benefits from a global maritime infrastructure for its supply (both in terms of routes and terminals and ports), which will generate moderate costs for its expansion. There are 195 Ammonia terminals at over 120 ports, trading in total around 20 million tonnes per year (Mtpa). Green Ammonia is a green hydrogen-derived product, a zero-emission fuel.

The established infrastructure around Ammonia makes this an interesting fuel also for rail. Compared to Hydrogen, Ammonia is also easier to transport and store because it requires less cooling to liquify. It can therefore play an important role in the EU's supply of renewable energy.

---

[42] Retrieved from Digasgroup Test results based on bio-methane - Dual Fuel Technologies for Railway.

[43] Elsevier (10.05.2021), Ammonia as an energy vector: Current and future prospects for low-carbon fuel applications in internal combustion engines; **https://www.sciencedirect.com/science/article/abs/pii/S0959652621007824**

Ammonia can be used as fuel for three types of engines, and a phased approach can be considered depending on technological readiness:

1. A Diesel with 'drop-in' Ammonia ICE
2. A full Ammonia ICE
3. A fuel cell based on Ammonia

However, there are a number of constraints to consider:

1. Diesel engines need to be retrofitted to make them compatible with the addition of Ammonia to fossil fuel. The high corrosive power of Ammonia means that all sink and copper parts must be replaced
2. Ammonia is toxic and warrants proper handling and storage procedures
3. Ammonia used under ICE requires carrying 3 times the volume of diesel to cover the same distance

Building on successful pilots in the marine and trucks industries[44], the rail sector initiated R&D activities using Ammonia ICE compatible with existing types of diesel engine.

Deutsche Bahn recently initiated a partnership with the Australian energy company Fortescue Future Industries (FFI) to explore Ammonia solutions.[45] In addition to the development of emission-free propulsion technologies, the agreement also promotes cooperation in logistics and supply chains for green fuels.

The Karlsruhe Institute of Technology (KIT) and others carry out research on the potential application in the railway sector. They qualified a remaining gap of "five to ten years to bring it to market".[46]

3.6. Procuring new Dual-Mode Diesel/Electric Locomotives: an existing Solution to compensate today's Lack of Infrastructure and Supply Readiness

The introduction of Dual-Mode diesel/electric trains is a first significant progress as it results in drastically reducing the emissions compared to a diesel rolling stock.

Procuring new Dual-Mode Electric/Diesel locomotives (also called Bi-Mode), meets the special last mile needs of operators who currently operate diesel locomotives on mostly electrified corridors. These activities are taxonomy-aligned, as they concern devices using a conventional engine where electrified infrastructure is not available but have zero direct tailpipe CO_2 emissions.

---

44 For example CMB.Tech, CMB's HydroTug will be the first tugboat in the world to be powered by combustion engines that burn hydrogen in combination with diesel; https://cmb.tech/hydrotug-project

45 Rail Market (10.2022), Deutsche Bahn and Fortescue have partnered to develop an ammonia-hydrogen engine; https://railmarket.com/news/technology-innovation/1763-deutsche-bahn-and-fortescue-have-partnered-to-develop-an-ammonia-hydrogen-engine

46 INNOTRANS, round table DB Innovation Forum, (22.09.2022)

The German Government, for example, subsides the procurement of those types of rolling stocks.[47] Although upgrading diesel-powered locomotives is technically possible, its cost, which is likely to be higher than the corresponding bridge solutions, will be investigated at a later stage.

3.7. Considering the Integration of Hydrogen and Fuel cells in some specific Use Cases

This alternative technology can be adopted in specific operational scenarios such as heavy-duty freight or long-range passenger trains (above 200km with no electrification). Despite a great increase of projects, actual deployment may take time: currently, more than 95 percent of production is "grey hydrogen" (depending on gas/methane and resulting in carbon dioxide emissions).[48] In addition, using gas or steam methane reforming (SMR) is a very high carbon-emissive process with no positive impact on the environment.[49]

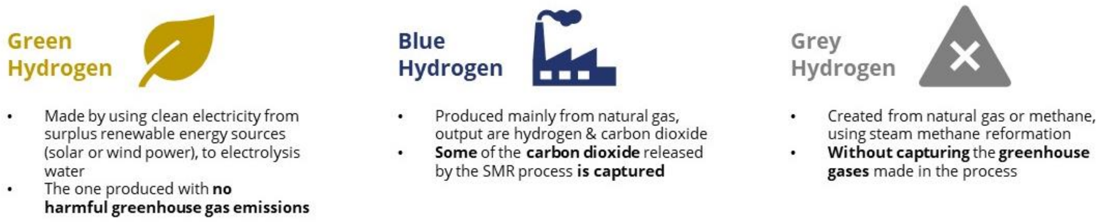


Figure 13: Different methods of production for hydrogen[50]

With only about one percent of today's hydrogen being produced using renewable energies ("green hydrogen")[51], the major challenge for a zero-emission application in the railway sector is the forecasted availability of sustainably produced hydrogen.

[47] Retrieved from eolos interviews with a German Think Tank, referring to a funding guideline published by the Federal Ministry for Digital and Transport (only in German available): https://www.now-gmbh.de/wp-content/uploads/2021/06/Richtlinie-zur-Foerderung-alternativer-Antriebe-im-Schienenverkehr.pdf

[48] IRENA (09.2018), Hydrogen from renewable power – Technology outlook for the energy transition; **https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf** and BELLONA (n.d.), Hydrogen from methane reforming + CCS; **https://www.frompollutiontosolution.org/hydrogen-from-smr-and-ccs**

[49] BELLONA (n.d.), Hydrogen from methane reforming + CCS; **https://www.frompollutiontosolution.org/hydrogen-from-smr-and-ccs**

[50] Own illustration

[51] IRENA (n.d.), Hydrogen overview **https://www.irena.org/Energy-Transition/Technology/Hydrogen**

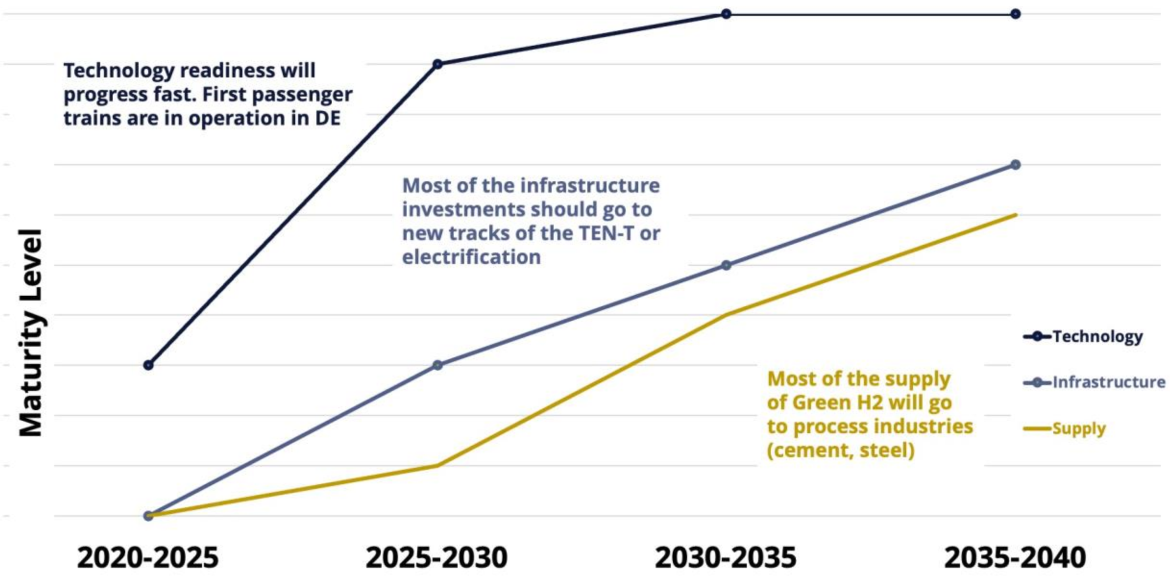


Figure 14: technology, Infrastructure and supply availability readiness for green hydrogen[52]

Low availability and poor infrastructure

In general, hydrogen comes with the risk of limited availability of supply in Europe and a high dependency on non-EU countries. This is especially true for low-cost green hydrogen, which would be needed to reach low-emissive status and maintain the competitiveness of the rail sector. The following map displays the potential global availability/production of low-cost green hydrogen. Sunny and windy areas not surprisingly are potentially the largest producers of renewable energy. Hydrogen or hydrogen derived fuels e.g. Ammonia are the only options to import this green energy. These imports will have a significant impact on economies. The port of Rotterdam already signed a MoU with Mauritania, equal to 5x the size of their current GDP.

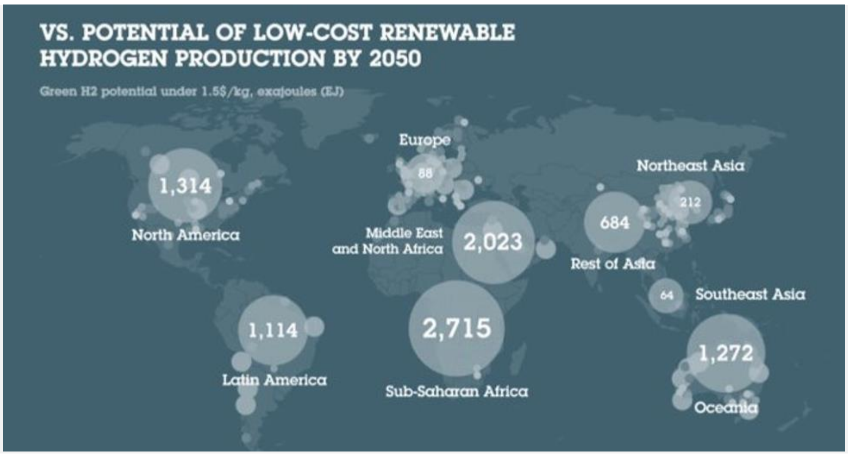


Figure 15: Overview of low-cost Green H2 production capabilities in the world[53]

---

52 Own illustration

53 Webinar Génération Hydrogen (28.09.2022) https://www.airliquide.com/generation-hydrogene

The RepowerEU plan, published in March 2022, aims for a significant amount of green hydrogen to be produced in Europe (ten million tons) and an equal amount imported from regions outside of Europe by 2030. The current annual demand in Europe is approximately ten million tons.

In line with the EU's decarbonisation objectives and national strategies on hydrogen development, the supply of green hydrogen will be primarily allocated to the most emissive industries, especially the process industry (i.a. cement, steel), as well as the transportation sector, especially aeronautics and road transportation (trucks). As green hydrogen is currently not a tradeable commodity, it is up to every industry itself to secure supply.

Apart from major investments in green hydrogen production, upgrading structural infrastructure must be planned in time to deploy sufficient refueling stations and storage capacity across the railway network. While it is possible to build upon legacy networks and optimise the location of upcoming refueling stations, major investment needs and lengthy installation time must be expected – when we observe the current insufficient capacity and delayed capacity expansion as well as low quality and performance of the existing infrastructure. It is foreseen that heavy industry sectors will transition to green hydrogen and will develop a hydrogen structure. Therefore, it should become possible to use hydrogen to fuel trains in the surroundings of heavy industry.

Entry barriers for the use of hydrogen in railway applications

A study on the use of fuel cells and hydrogen in the railway sector under the Shift2Rail program[54] identified many entry barriers to the use and scaling up of hydrogen. It was recommended to conduct further studies under European research and innovation (R&I) programs to facilitate its deployment for railway applications.

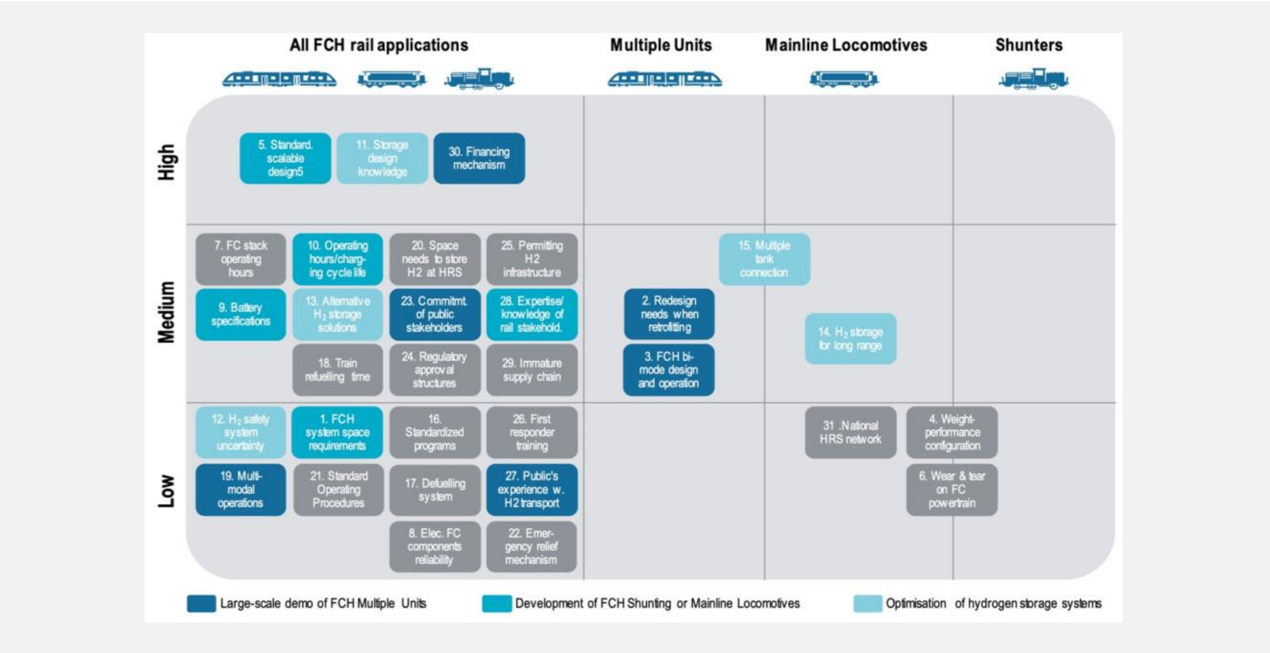


Figure 16: Entry barriers to hydrogen development for railway applications[55]

---

[54] Europe's Rail (2019), Study on the use of Fuel Cells and Hydrogen in the Railway Environment https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/

[55] Rail research (08.05.2019), Study on the use of Fuel Cells and Hydrogen in the Railway Environment, https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/

Economic considerations

Furthermore, the use of hydrogen for propulsion is currently not profitable. Projections show that in the future the total cost of ownership (TCO) of hydrogen fuel cells should significantly decrease and get closer to the TCO of battery operations (see figure below). It is unforeseeable how long it will take to close this gap.

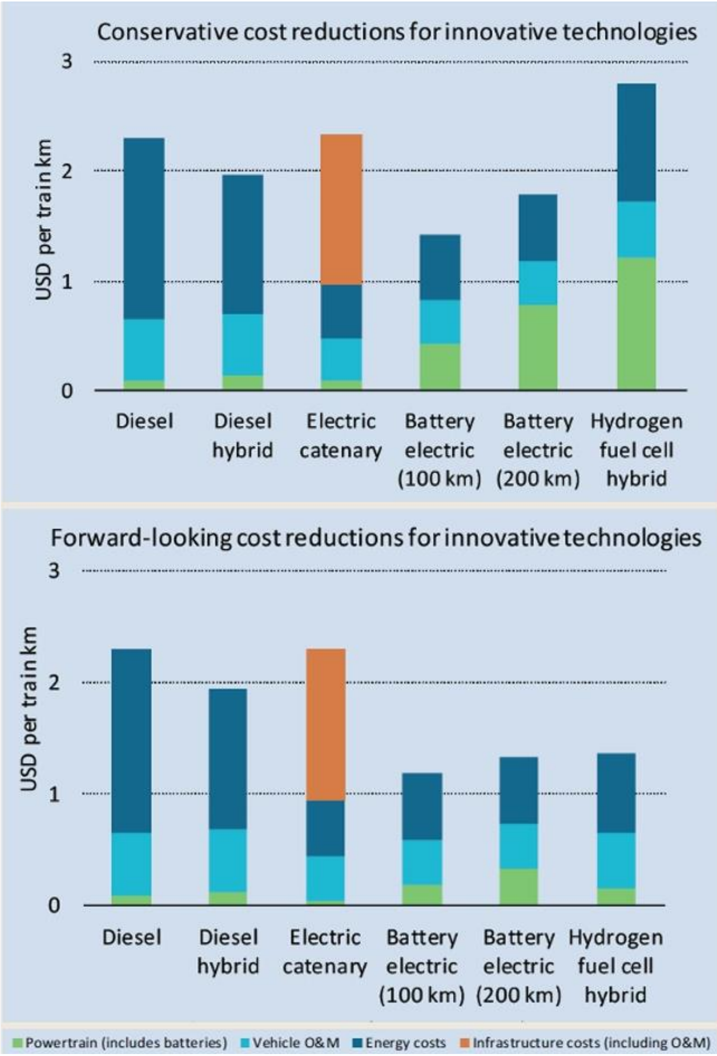


Figure 17: Comparison of cost-reductions scenarios for innovative technologies[56]

Alstom and Engie have partnered to bring hydrogen to European rail freight. Australia's largest rail freight operator, Aurizon, and mining company Anglo American have an agreement to conduct a feasibility study into using hydrogen-powered trains for bulk freight. Fortescue Future Industries, part of Fortescue Metals Group, has been testing zero-emissions locomotives, including the successful combustion of blended Ammonia fuel in a two-stroke locomotive. Further testing and demonstrations planned for 2022 will support Fortescue's aim to decarbonise its mining fleets.

Despite the current communication and success of Alstom with the entry into service of their iLint[57], Siemens Mobility's programme to develop a passenger train and mobile hydrogen storage trailer, and

---

[56] IEA. "Global Hydrogen Review 2022." 2022. https://www.iea.org/reports/global-hydrogen-review-2022

[57] Alstom (n.d.), Alstom Coradia iLint – the world's 1st hydrogen powered train, https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-train

Stadler's project to enter service in California from 2024[58], major hydrogen projects in the rail sector are unlikely for the time being.

However, several other studies conclude hydrogen trains are no real alternatives to passenger diesel trains (DMU). For example, a recent study commissioned by the German federal state of Baden Wurttemberg concluded that hydrogen passenger trains are 80% more expensive than hybrid electric trains or extending the powered overlines, and therefore to discard the use of hydrogen fuel cells on all 16 non-electrified tracks[59] they had considered in their study.[60] Saxony, another German state reaches the same results.

As a conclusion, the technology readiness level for train fuel cells is high, while infrastructure and supply are still challenges at this point. Hydrogen and fuel cells are showcasing interesting advantages for rail applications for specific use cases and should be monitored for future implementation. Hydrogen has a high energy density unlike batteries, however, it has a high TCO (high OpEx and high CapEx). This means that it only is useful in situations where no alternatives exist e.g. on long unelectrified routes or for heavy-freight applications. Moreover, as the infrastructure demands are high, therefore most likely to start near large industry hubs that are expected to transition to hydrogen.

Making rail a key enabler for green hydrogen expansion

Opportunity lies also with making rail a response to the forecasted high European demand for low-cost hydrogen from other continents. The use of green hydrogen, as a substitute to fossil fuel in the most emissive sectors, is the way forward to speed up Europe's decarbonisation. There is a foreseeable increase of supply, prompted by massive production capabilities in countries such as Australia and Canada, which are building sea infrastructure to distribute their supply by giga-tankers to the rest of the world.

With the current production forecast, Europe will import a significant share of its needed supply. Ensuring an efficient and safe distribution across Europe, from harbours to the multiple points of industrial use, is a great challenge. After pipelines, Rail is the most appropriate mode of transportation, and at the same time this is a significant opportunity to achieve the EU objective of reaching approximately 35 percent of freight carried by rail until 2050.

The railway sector should mobilise and take a leading role in the design and implementation of such a new efficient and safe supply chain.

58 IEA (2022), Global Hydrogen Review 2022, p.49; https://www.iea.org/reports/global-hydrogen-review-2022

59 The study's scope only covered passenger trains, and the result is that, out of the 16 analysed tracks, 11 were recommended to be run via battery electric trains and 5 to be equipped with catenaries, see also Website Badische Zeitung **https://www.badische-zeitung.de/wasserstoffzuege-sind-in-baden-wuerttemberg-vorerst-kein-thema--220751826.html**

60 Website Ministry of Transport Baden-Württemberg (17.10.2022) https://vm.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/klimaneutral-auch-ohne-oberleitung/

3.8. Building on the Rail Legacy: Putting Batteries and Electrification at the Core of the System to maximize Rail Performance and Efficiency

Over the past 100 years, rail transportation and electrification have been a winning duo. Battery technologies are a natural choice for the rail sector and can be a game-changer in all aspects – technologically, economically and, not least, ecologically. This alternative for the future is also fully aligned with the EU Taxonomy.

The following illustration presents an integrated view of the readiness of technology, infrastructure and supply availability for batteries.

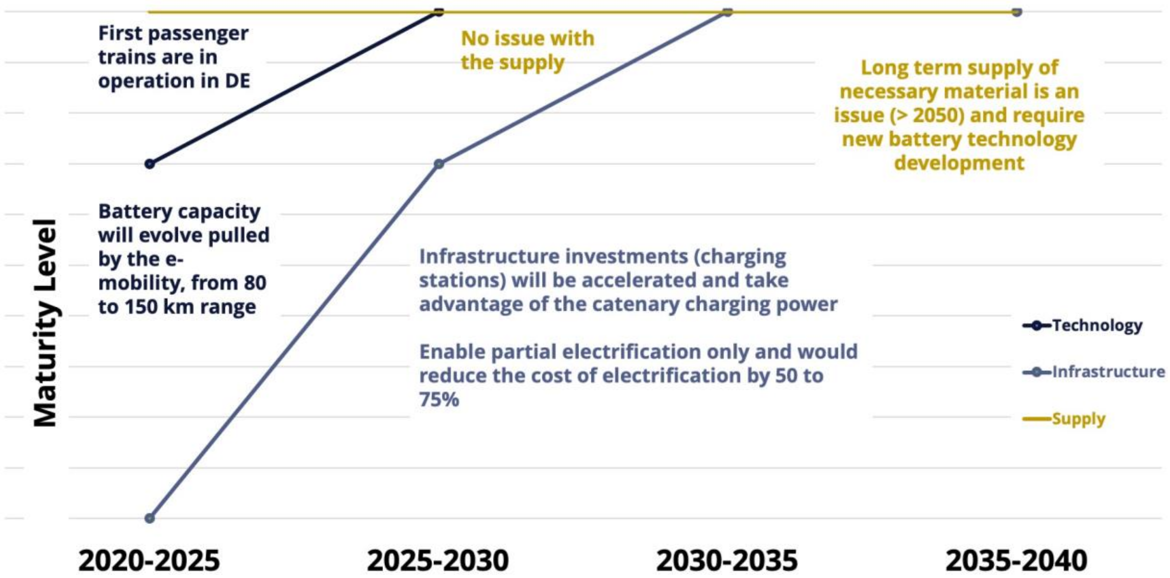


Figure 18: Technology, infrastructure, and supply availability readiness for Battery[61]

However, key operational constraints linked to the use of batteries remain and require the attention of stakeholders and decision-makers. These challenges are discussed in four thematic blocks, namely 1. Range and Power; 2. Charging infrastructure; 3. Scarcity of resources in the medium to long term (beyond 2050); 4. New recycling and traceability obligations resulting from the EU Battery Regulation.

1. Range and power

Today, successful battery use cases (including trains in revenue service) are associated with passenger trains covering a range of approximately 100 kilometers. The producers are major original equipment manufacturers (OEMs) such as Bombardier/Alstom, Siemens or Stadler. It is widely accepted across the rail industry that battery solutions cannot be applied to heavy freight. Although technologies like WABTEC FLXdrive[62] are emerging, they mostly contemplate the use of one battery-powered locomotive in between diesel ones. This battery unit is mainly used to store energy captured during braking, which will then be released if needed. The overall emission reduction is approximately ten percent.

---

61 Own illustration

62 Wabtec Corporation, (n.d.), FLXdrive, https://www.wabteccorp.com/locomotive/alternative-fuel-locomotives/flxdrive

There are various other pilot applications for freight and shunting battery-powered locomotives. The setup largely depends on the specific infrastructure and topography, as shown in recent examples of companies like BHP[63], Rio Tinto[64] and Fortescue.[65] Other existing projects are listed in the following table.[66] However, it has proven difficult to capture the main performance criteria associated with the use cases. Further studies are needed to better qualify the range of applications.

Czech Republic	Hybrid Shunter 400 locomotive
Germany	Prima H3, Hybrid AC Driving Shunting Locomotive, DE60 C Hybrid, Toshiba HDB 800
Japan	Mo 562, Class 602, Class 2103, Class 555, Toshiba HD300
Switzerland	Prima H4, Geaf 2/2
Turkey	HSL-700
UK	Class CBD90

Moreover, some applications in other modes of transport can be interesting for rail. For example, ZES is an ecosystem to charge, exchange and use 2 MWH battery containers. Currently used for inland shipping but can be used for any emission free heavy transport.[67]

2. Charging infrastructure

A key challenge in the automotive sector is the charging infrastructure due to the large quantity of cars charging at the same time. This results in a very high demand for local charging power. In contrast, the number of rail vehicles charging simultaneously is much lower and can be predicted based on in-service timetables.

Furthermore, high-voltage electricity, required for charging big batteries, is already available and in use on site or in catenaries, stations, surrounding industrial premises (among others). For example, companies such as Voltap or Railbaar provide high power recharging capabilities via catenary.

Figure 19: Charging infrastructure options and features[68]

---

63 Website bhp, (n.d.) BHP orders four battery-electric locomotives for WAIO rail network https://www.bhp.com/news/media-centre/releases/2022/01/bhp-orders-four-battery-electric-locomotives-for-waio-rail-network

64 Website riotinto, (11.01.2022), Rio Tinto purchases first battery-electric trains for the Pilbara, https://www.riotinto.com/news/releases/2022/Rio-Tinto-purchases-first-battery-electric-trains-for-the-Pilbara

65 Website raitech, (4.3.2022), Australian 'Infinity Train' uses gravity to recharge batteries, https://www.railtech.com/rolling-stock/2022/03/04/australian-mining-company-works-on-infinity-train-using-gravity-to-regenerating-batteries/?gdpr=deny

66 TU Graz (2022), M. Landgraf, Senior Scientist – Railway engineering

67 Website Engie, (01.06.21), **https://innovation.engie.com/en/news/news/green-mobility/zero-emission-services-first-emission-free-inland-shipping-vessel-on-energy-containers/26036**

68 Own illustration based on information from Sonnenseite, (04.03.21), **https://www.sonnenseite.com/de/mobilitaet/schnellladestation-fuer-batteriezuege/**

3. Scarcity of resources in the medium to long term (beyond 2050)

Many studies alert on the future scarcity of materials used to produce Li-ion batteries, for example Cobalt and Lithium. Concerns around dependencies from other countries and volatile supply chains, affecting their highly complex production system, motivated industries like automotive and communications to conduct R&D programs exploring alternatives. The following illustration presents the most promising approaches.

Sodium-Ion Batteries (SIB) also Natrium Battery NA-Ion	Lithium–sulfur batteries (Li-S)	Lithium–air batteries (Li-air) and Zinc-air batteries (Zn-air)	Solid-state batteries (SSB) using solid electrodes instead of liquid electrolytes
• Sodium-ion replaces Li-Ion. Easier to recycle as Sodium is not toxic. High natural abundance of sodium --> limited scarcity and low prices • Energy density lower • Kühnel et al. present a new solution for high-voltage sodium-ion batteries • Announced mass production in 2025 (CATL)	• Capacity of S cathode, will be the key to unlocking the door to a high energy density of 2500 Wh kg−1 • Sulfur also has the advantages of low-cost and high abundance • Research demand: Reduce shuttle effect in battery (leads to poor cycling stability and anode corrosion limiting service life and rechargeability)	• Comparable characteristics to Li-S but at the moment, with a low service life	• Toyota, Bosch, Panasonic, LG Energy Solution, and NGK Insulators lead patent activity, with more than 1000 patents each • Key developments include three promising solid electrolyte materials, organic polymer electrolytes, inorganic sulfide-based electrolytes, and inorganic oxide-based electrolytes • Available not before 2030 in transportation
Kühnel R, Reber D, Battaglia C; A High-Voltage Aqueous Electrolyte for Sodium-Ion Batteries, CS Energy Lett. 2017, 2-9 https://doi.org/10.1021/acsenergylett.7b00623	*Wang, Y., Sahadeo, E., Rubloff, G. et al. High-capacity lithium sulfur battery and beyond: a review of metal anode protection layers and perspective of solid-state electrolytes. J Mater Sci 54, 3671–3693 (2019). https://doi.org/10.1007/s10853-018-3093-7*		*Houache, M.S.E.; Yim, C.-H.; Karkar, Z.; Abu-Lebdeh, Y. On the Current and Future Outlook of Battery Chemistries for Electric Vehicles—Mini Review. Batteries **2022**, 8, 70. https://doi.org/10.3390/batteries8070070*

Figure 20: In-development alternate battery technologies to cope with resource scarcity[69]

It has to be noted that the next generation of Li-ion batteries is expected to double the current range of performance, i.e. from 80 kilometres to 150 kilometres range for a passenger electric multiple unit (EMU). The rail sector must continue to follow and analyse these research dynamics and assess how to potentially integrate a new generation of batteries into the railway environment.

69 Own illustration

4. New recycling and traceability obligations resulting from the EU Battery Regulation

The new regulation will significantly increase the recycling of Li-ion batteries and help to mitigate the risk of raw materials scarcity as well as the speedy development of recycling capabilities in the EU.

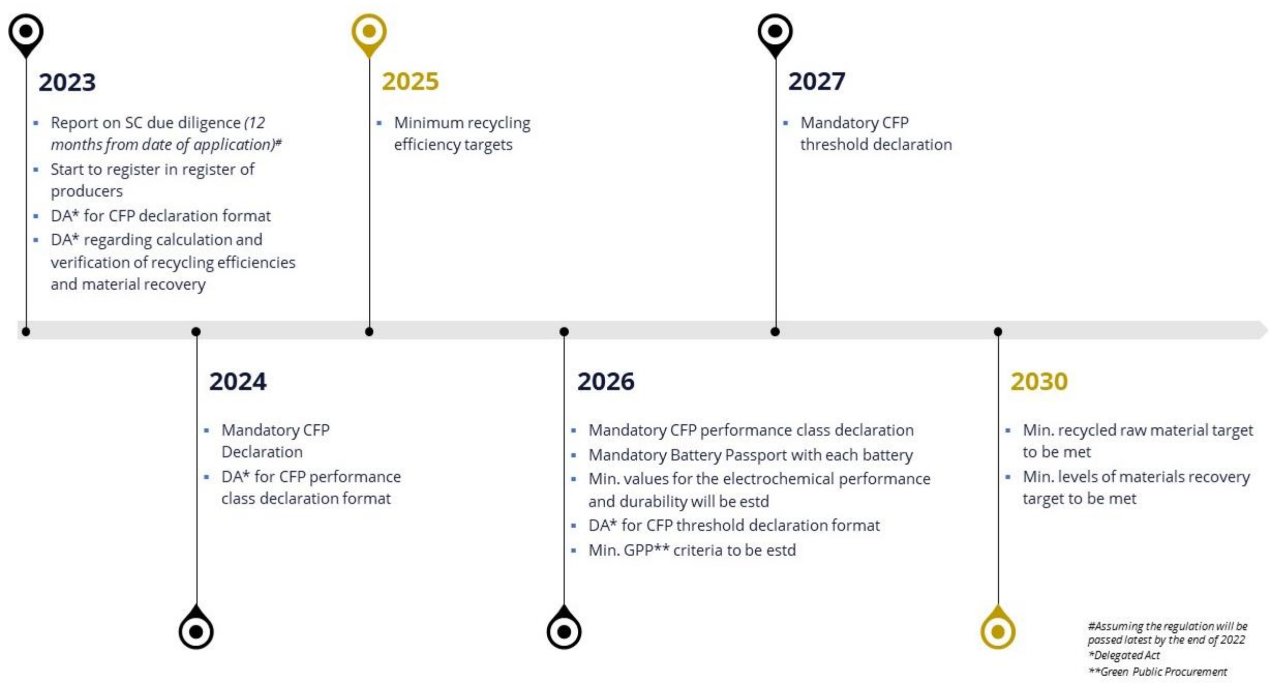


Figure 21: Timeline of major milestones in the new EU Battery Regulation[70]

Figure 22: Recycling and repurposing providers in Europe[71]

70 Own illustration

71 Retrieved from eolos study Recycling & Repurposing Solution providers Landscape

Europe is indeed financing the development of the recycling infrastructure significantly, and numerous new initiatives are being developed. Some battery suppliers such as the Swiss company Leclanché work directly with recyclers, proving that closing the loop is not only a possibility but already a reality.

Reducing the cost of electrification by at least 50 percent by using batteries

The study assumes that using batteries can reduce the cost of electrification by 50 to 75 percent.[72] This refers to conventional electrically powered train, equipped with batteries, running on lines with overhead catenary and switching to battery operation on non-electrified sections at station. Examples are the Talent 3 model with a traction battery capacity of 300 kWh, which equals a range of approximately 35 to 40 kilometres on a flat route, or the Desiro ML model with a capacity of 528 Kwh for up to 80 kilometres range.

This would apply for last-mile operations on low loaded feeder lines or non-electrified or partly electrified sections or areas where electrification is not possible. This combined alternative could significantly lower the costs of infrastructure upgrade in contrast to complete electrification. In the following example developed by the Österreichische Bundesbahnen (ÖBB), the electrification need would be limited to 26 percent.[73]

This study recommends supporting primarily the use of Dual-Mode Battery Electric trains combined with partial electrification for the long-term future. Removing diesel-only traction from modern operations and accelerating the rate of rail electrification is crucial to enabling a greener and cleaner transport network fit for our carbon-neutral ambitions.

[72] The exact reduction in infrastructure investments can only be confirmed after further in-depth studies on a given infrastructure.

[73] ZEVrail (2020), Betriebserfahrung mit dem ÖBB Cityjet eco, https://www.zevrail.de/artikel/betriebserfahrung-mit-dem-oebb-cityjet-eco

4. Moving Forward

4.1. Initial Roadmap for near-term Decarbonisation

The potential to reach the European targets lies primarily in shifting other modes of transportation to the railway sector. Less than one percent of the overall CO_2 emissions comes from the railway within the 21 percent of total emission in the transport sector across Europe. The success of the rail system convergence towards a safe, interoperable, more sustainable, and efficient network highly depends on increasing its capacity and performance, along with adequate policy decisions to support the development of its networks and infrastructures. By aligning all stakeholders around a simple and comprehensive roadmap, the rail sector can maximise its impact and contribute significantly to overarching goals – to be able to concentrate investments on meaningful areas and gain in effectiveness.

Jointly addressing the current development of rail infrastructure is the most important lever on the way to a decarbonised future – and this varies from region to region. Today major efforts are directed towards the electrification of networks to use electrical and other renewable sources as alternative energy to diesel. The European Union and its member states have announced an increase of electrification. Although the European average is quite high, major discrepancies among countries and regions do exist. Consequently, the current diesel fleet size varies widely and will require major investments in countries and regions where funds are not readily available nor structural and infrastructure changes possible.

Summarising the results and findings of this study in a transition framework and roadmap proposal to guide the convergence across railway stakeholders. The table below summarise the available options and recommendations based on operation scenario.

	Operation scenario						
Bridge solutions or alternatives for the future	**Locomotive Works**	**Locomotive Shunting**	**Locomotive Last Mile**	**Locomotive Mainline** (Freight & Passenger) (3000 kW)	**Locomotive Heavy-Freight** (> 4 to 6000 kW)	**Regional xMUs** (< 200 km)	**Regional xMUs** (> 200 km)
Bridge: Bio-fuels HVO	☑	☑	☑	☑	☑	☑	☑
Bridge: Retrofit Bio-fuels RNG	⊗	☑	⊗	⊗	☑	⊗	⊗
Bridge: Retrofit Ammonia ICE	⊗	☑	⊗	⊗	☑	⊗	⊗
Hydrogen Fuel Cells + Battery	☑	⊗	⊗	⊗	☑	⊗	☑
Dual-Mode Battery/Electric	⊗	☑	☑	☑	⊗	☑	⊗

☑ Preferred option ⊗ Not recommended / not possible

Figure 23: Summary of alternatives recommendations per operation scenario

The following roadmap further elaborates on the proposed timing and concrete fleet transition to be able to integrate the different investment phases.

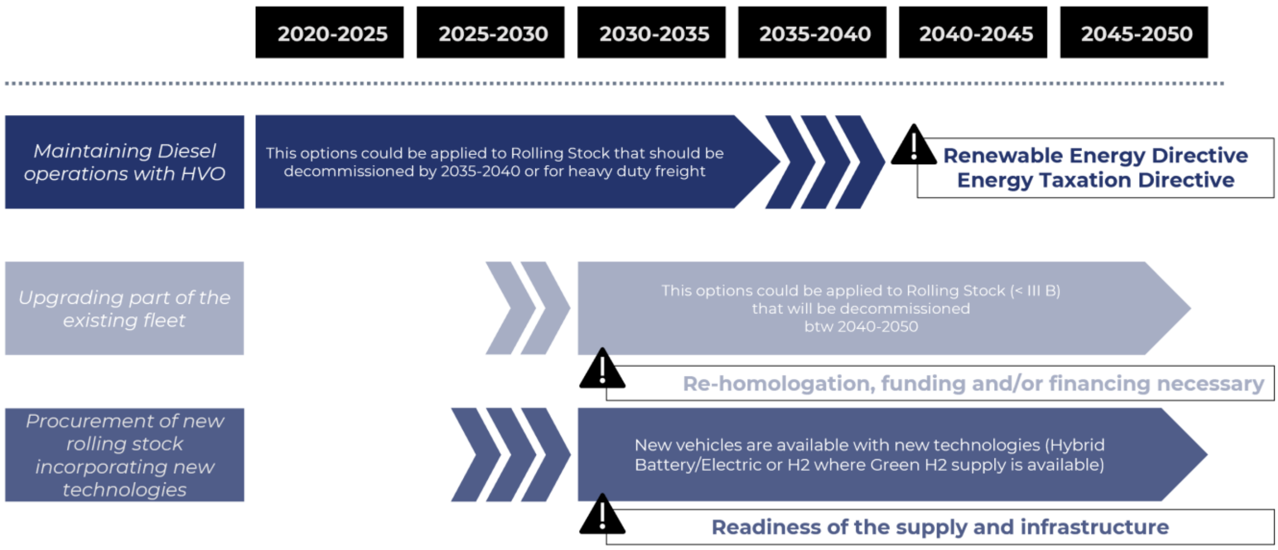


Figure 24: Initial roadmap – focusing on technological alternatives - to accelerate the further decarbonisation

Bringing immediate and pragmatic alternatives: using HVO, and potentially RNG and Ammonia with low(er) efforts. While operators and lessors face political, economic, and environmental issues in buying new assets that are matching European existing standards and forecasted regulations, further alignment across the rail sector and between its decision-makers is needed; namely in detecting the benefits of immediate bridge solutions and mid- to long-term technological alternatives to diesel engines. This study highly recommends replacing diesel with HVO wherever possible. Using HVO does not require upgrading the existing locomotives nor refueling stations. This alternative offers lower WTW CO_2 emissions.

Reducing the cost of electrification by at least 50 percent thanks to the use of hybrid electric/battery rolling stocks. This study has shown that using conventional electrically powered trains – equipped with batteries, running on lines with overhead catenary and switching to battery operation on non-electrified sections – could significantly lower the costs of infrastructure upgrades in contrast to uninterrupted electrification. It would cover for last-mile operations, low loaded feeder lines or where electrification is not possible.

Green hydrogen: focusing on making rail a key enabler for green hydrogen expansion and promoting green hydrogen for specific rail applications. Green hydrogen (including green hydrogen derived fuels like ammonia) in combination with fuel cells are showcasing interesting advantages for rail application for specific use cases and should be monitored for future implementation. A key opportunity lies with making rail a response to the forecasted high European demand for low-cost hydrogen from other continents.

Continue network electrification and research to ensure long-term carbon neutral rail freight transport. Currently, there are no solutions on the horizon that will enable a carbon neutral rail freight transport on non-electrified lines until 2050, unless enough green hydrogen can be secured for the rail industry. Research into alternative solutions and capacity building will be a crucial complementary component to electrification.

4.2. Key Expectations towards the European Commission and other Railway Stakeholders

Concentrating efforts on Shift to Rail initiatives

1. Further promoting the rail sector is a key element of Europe's decarbonisation.
2. Do not increase the burden on the rail sector to apply new standards designed for other transportation modes (automotive, aerospace, trucks).
3. Continue to subsidise the electrification and focus on projects promoting partial electrification combined with the use of battery-powered rolling stocks.
4. Build on the railway legacy and assets to boost the safe and efficient supply chain for green hydrogen across Europe.

Organising the convergence of the different stakeholders

1. Design and integrate a "freight transport system for efficiency" to balance investments between rolling stocks and infrastructure.
2. Upgrade the Technical Specifications for Interoperability (TSIs) requirements to consider alternative technology for the future, progressively tackle new safety aspects, and enable standardisation of operational procedures and systems.

Supporting the railway industry in implementing bridge solutions

1. Accelerate the entry into force of the new ETD and evolve it into a regulation.
2. Subsidise the increase of production capabilities and distribution of biofuels.
3. Promote and subsidise the upgrade of current locomotives into one of the solutions recommended by this study, whenever applicable.
4. Fund more research with regards to integrating RNG and Ammonia-ICE solutions.

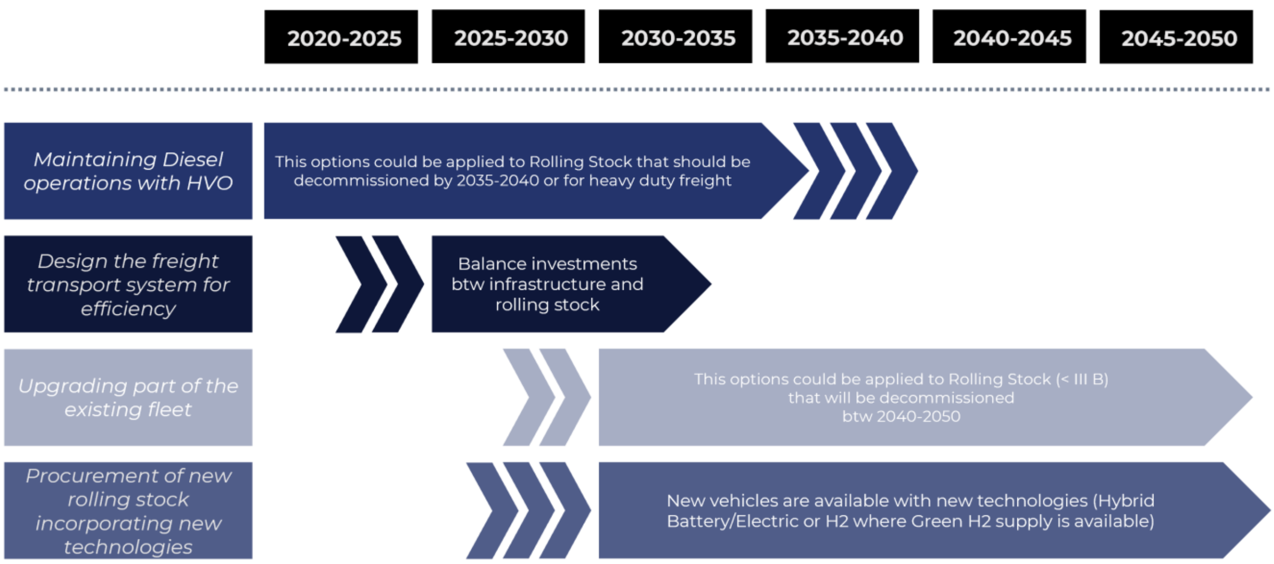


Figure 25. Initial roadmap to accelerate the further decarbonisation

Appendix

List of Participants interviewed on Technology Alternatives

General		
Allianz pro Schiene	Sören Gahrmann	**Transportation Policy Officer**
Alstom	Arnaud Fleurquin Joerg Schulze Adrien Kurz	**Head of Product Management** **Head of Platform** **Sales Manager Prima H3 / Prima H4**
Canadian Rail	Dominique Malenfant, Francois Belanger	**COO** **Senior Director Sustainability**
CER	Enno Wiebe	**Technical Director**
DB Energy	Martin Lemke Sebastian Zander	**Head of Business Unit Service Engineering** **Program Manager Energy Supply for Alternative Drives**
ERA	Josef Doppelbauer	**Executive Director**
ERFA	Conor Feighan	**Secretary General**
Europorte	François Coart Michel Karaghiosian	**Business Development Manager** **Project and Developments Director**
Europe's Rail Joint Undertaking	Carlo Borghini	**Executive Director**
German think-tank on Energie and mobility	Anonymous	**Project Manager, International Climate Policy**
Oberelbe Transport Association	Lutz Auerbach	**Head of Transport**
TU Delft	Marko Kapteanovic	**PhD Researcher - Transport and Planning Department**
TU Graz	Dr. Matthias Landgraf	**Senior Scientist – Railway engineering**
UIC	Alain Scherrer	**Head of Rolling Stock and Energy Management**
VOITH	Adelson Martins	**Head of Sales – Latin America**

HVO & RNG

BSR	Norbert Pauluweit	**Head of Strategic Energy, Material Flow and Plant Mgt**
DB	Dr. Tobias Fischer	**Head of Technology TecLab**
DB Cargo GER	Jörg Schneider	**Head of Climate Protection and Energy**
DB Energy	Mistil Kilicarslan	**Head of Sales Tank Services**
DiGas	Peter Dumenko, Robert Strods	**CEO** **Head of Business development**
NESTE	Jörg Hübeler	**Head of Market development**

Battery

ABB	Martin Deiss	**Head of Sales at ABB Traction Division**
ACTIA	Jérôme TRIPOZ	**Business Development Manager**
Alstom	Stefan von Mach	**Former Chief Engineer of Talent 3 BEMU**
LECLANCHE	Gerardo Gimeno Cyril Carpentier	**VP Sales Commercial Vehicles** **Head of Sustainability**
SAFT	Pierre Prenleloup	**Railway Application Expert**
TU Berlin	Julia Kowal	**Prof. Dr.-Ing. (FG Electrical Energy Storage Technology; Institute for Energy and Automation Technology)**

Hydrogen

Alstom	Stephane KABA	**Alstom smart and green mobility director, president SpeedInnov JV**
	Thierry Tournier	**Alstom Belfort site innovation director, project developer on hydrogen and autonomous freight rail**
Fortescue Future Industries	Rubim de Moura	**Head of Business Development**
NOW GmbH	Frederik Wewetzer	**Programme Manager Hydrogen and Fuel Cell**
Sciences Po / HEC Paris	Mikaa Mered	**Adjunct lecturer on hydrogen markets and geopolitics, Sciences Po / HEC Paris - member of the steering committee, French Hydrogen Task Force**

Involved parties in this study

AERRL staff & AERLL members active in the management of the project

AERRL	Carole Coune	SG	WG Chair, Project Manager
AERRL	Fabien Rochefort	Chair	Alternate WG Chair
AERRL	Martin Weber	Chair AERRL WG 4 Diesel swap	WG Vice-Chair, representing AERRL
AKIEM	Philipp Megelin	ESG Program Coordinator	
BEACON	Franziska Schmuecker	Technical Manager	Alternate WG Vice-Chair
CARGOUNIT	Rafal Hejmo	COO	
Partially active in the management of the project, particularly for the first part "Regulatory framework"			
AKIEM	Michaël Grosmaire	Head of Asset Management – Diesel and Hybrid	
BEACON	Ian Scothon	Technical Manager	
CARGOUNIT	Lukasz Boron	CEO	

Supporting Banks

CACIB	Michel Cusenza	Executive Director - Rail Finance Group	Alternate WG Vice-Chair
CACIB	Eloise Boutin	Director Sustainable banking	
ING	Robert van Duuren	Lead Land Transport - Germany	WG Vice-chair, representing banks
ING	Tom Groenewoud	Intern	
KfW-IPEX	Frank Hermandung	Director – Land-based Transportation	
KfW-IPEX	Simon Schüder	Associate – Land-based Transportation	
Société Générale	Denys Bierré	Director – Global Land Transportation	
Société Générale	Thomas Losay	Head of Land transportation	

Eolos

Pierre-Yves Cohen	Founder & CEO, Railway Expert
Leena Jäger	Principal, Project Manager Railway
Helene Isermeyer	Governance Expert
Baptiste Grüss	Policy Expert

Regulatory Landscaping Overview & related Sources

EU Taxonomy Regulation	Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance) (PE/20/2020/INIT) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32020R0852**
EU Taxonomy Climate Delegated Act	Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives (Text with EEA relevance) (C/2021/2800) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R2139**
European Climate Law	Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law") (PE/27/2021/REV/1) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R1119**
Energy Taxation Directive	Proposal for a COUNCIL DIRECTIVE restructuring the Union framework for the taxation of energy products and electricity (recast) (COM/2021/563 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0563**
Renewable Energy Directive	Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (COM/2021/557 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557**
Alternative Fuels Infrastructure	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council (COM/2021/559 final) **https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559**

EU Battery Regulation	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 (COM/2020/798 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020PC0798**
TEN-T	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Union guidelines for the development of the trans-European transport network, amending Regulation (EU) 2021/1153 and Regulation (EU) No 913/2010 and repealing Regulation (EU) 1315/2013 (COM/2021/812 final) **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM%3A2021%3A812%3AFIN**
FuelEU Maritime	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC (COM/2021/562 final) **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:562:FIN**
RefuelEU Aviation	Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport (COM/2021/561 final) **https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561**
Sustainable and Smart Mobility in EU	COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy – putting European transport on track for the future (COM/2020/789 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789**
EU Hydrogen Strategy	COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe (COM/2020/301 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301**
RePower EU	COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS REPowerEU Plan (COM/2022/230 final) **https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN**

Bibliography

The international Council on Clean Transportation (09.04.2021); **https://theicct.org/transport-could-burn-up-the-eus-entire-carbon-budget/**

UNIFE and CER Position Paper (06.2016), Rail as a key to decarbonizing transport; **https://www.unife.org/wp-content/uploads/2021/03/RAIL-AS-A-KEY-TO-DECARBONISING-TRANSPORT.pdf**

TU Delft & Fraunhofer ISI (2020); **https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccn/2021/Methodology%20for%20GHG%20Efficiency%20of%20Transport%20Modes.pdf**

Statista (n.d.), Annual greenhouse gas emissions in the European Union (EU-27) from 1990 to 2020, by sector (Ian Tiseo); **https://www.statista.com/statistics/1171183/ghg-emissions-sector-european-union-eu/**

European Environmental Agency (12/2019), Share of transport greenhouse gas emissions **https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2/#tab-googlechartid_chart_13**

European Council of the European Union (n.d.) Impact of Russia's invasion of Ukraine on the market: EU response; **https://www.consilium.europa.eu/en/policies/eu-response-ukraine-invasion/impact-of-russia-s-invasion-of-ukraine-on-the-markets-eu-response/**

European Commission (n.d.), Resource Efficiency; **https://ec.europa.eu/environment/resource_efficiency/index_en.htm**

Oxford Academic (04.2013), From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity; **https://academic.oup.com/af/article/3/2/6/4638639**

Science Direct, (1.3.2018), Particulate number and NOx trade-off comparisons between HVO and mineral diesel in HD applications; **https://www.sciencedirect.com/science/article/pii/S0016236117314151**

Retrieved from stakeholders consultations. More: **List of participants interviewed in the context of WP2 – technology alternatives; https://www.dbcargo.com/rail-de-de/logistik-news/auf-dem-gruenen-weg-db-cargo-testet-hvo-7327204**

MTU (17.02.2022), HVO Fuel proven to be effective for Diesel Generator Sets; **https://www.mtu-solutions.com/eu/en/technical-articles/2022/hvo-fuel-proven-to-be-effective-for-diesel-generator-sets.html**

Caterpillar (2021), Sustainability Report; **https://www.caterpillar.com/en/company/sustainability/sustainability-report/focused-areas/energy-emissions/supporting-our-customers.html**

European Union, (22.01.2018), Electrification of the transport system, Expert group report; **https://op.europa.eu/en/publication-detail/-/publication/253937e1-fff0-11e7-b8f5-01aa75ed71a1/language-en**

European Union, (n.d.), Horizon Europe, **https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en**

Uabio (2020), European Biogas association statistical report; **https://uabio.org/en/materials/7524/**

Elsevier - Ammonia as an energy vector: Current and future prospects for low-carbon fuel applications in internal combustion engines (10.05.2021) - **https://www.sciencedirect.com/science/article/abs/pii/S0959652621007824**

For example CMB.Tech, CMB's HydroTug will be the first tugboat in the world to be powered by combustion engines that burn hydrogen in combination with diesel; **https://cmb.tech/hydrotug-project**

Rail Market (10/2022), Deutsche Bahn and Fortescue have partnered to develop an ammonia-hydrogen engine; **https://railmarket.com/news/technology-innovation/1763-deutsche-bahn-and-fortescue-have-partnered-to-develop-an-ammonia-hydrogen-engine**

Retrieved from eolos interviews with a German Think Tank, referring to a funding guideline published by the Federal Ministry for Digital and Transport (only in German available); **https://www.now-gmbh.de/wp-content/uploads/2021/06/Richtlinie-zur-Foerderung-alternativer-Antriebe-im-Schienenverkehr.pdf**

Alstom (n.d.), Rolling Stock – Alstom Coradia iLint – The world's 1st hydrogen powered train; **https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-train**

Air Liquide (09.2022), Webinar Génération Hydrogen ; **https ://www.airliquide.com/generation-hydrogene**

Webinar Génération Hydrogen (28.09.2022); **https ://www.airliquide.com/generation-hydrogene**

Website Ministry of Transport Baden-Württemberg (17.10.2022) ; https ://vm.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/klimaneutral-auch-ohne-oberleitung/

IEA (2022), Global Hydrogen Review 2022; https://www.iea.org/reports/global-hydrogen-review-2022

IRENA (n.d.), Hydrogen overview; https://www.irena.org/Energy-Transition/Technology/Hydrogen

IRENA (09/2018), Hydrogen from renewable power – Technology outlook for the energy transition; **https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf**

Europe's Rail (2019), Study on the use of Fuel Cells and Hydrogen in the Railway Environment; https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/

Rail research (08.05.2019), Study on the use of Fuel Cells and Hydrogen in the Railway Environment, https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/

Badische Zeitung (17.10.2022) https://www.badische-zeitung.de/wasserstoffzuege-sind-in-baden-wuerttemberg-vorerst-kein-thema--220751826.html

Wabtec Corporation (n.d.), FLXdrive; https://www.wabteccorp.com/locomotive/alternative-fuel-locomotives/flxdrive

MDPI, (1.9.2022), Utilization of Hydrotreated Vegetable Oil (HVO) in a Euro 6 Dual-Loop EGR Diesel Engine: Behavior as a Drop-In Fuel and Potentialities along Calibration Parameter Sweeps, Stefano d'Ambrosio, Alessandro Mancarella and Andrea Manelli

Website bhp (n.d.), BHP orders four battery-electric locomotives for WAIO rail network; https://www.bhp.com/news/media-centre/releases/2022/01/bhp-orders-four-battery-electric-locomotives-for-waio-rail-network

Website riotinto (11.01.2022), Rio Tinto purchases first battery-electric trains for the Pilbara; https://www.riotinto.com/news/releases/2022/Rio-Tinto-purchases-first-battery-electric-trains-for-the-Pilbara

Website raitech (04.03.2022), Australian 'Infinity Train' uses gravity to recharge batteries; https://www.railtech.com/rolling-stock/2022/03/04/australian-mining-company-works-on-infinity-train-using-gravity-to-regenerating-batteries/?gdpr=deny

Website Engie, (01.06.2021), **https://innovation.engie.com/en/news/news/green-mobility/zero-emission-services-first-emission-free-inland-shipping-vessel-on-energy-containers/26036**

Own illustration based on information from Sonnenseite (04.03.2021); https://www.sonnenseite.com/de/mobilitaet/schnellladestation-fuer-batteriezuege/

ZEVrail (2020), Betriebserfahrung mit dem ÖBB Cityjet eco; https://www.zevrail.de/artikel/betriebserfahrung-mit-dem-oebb-cityjet-eco_

The Guardian, Vienna's euro-a-day public transport model could waltz into Berlin https://www.theguardian.com/world/2019/jul/09/vienna-euro-a-day-public-transport-berlin-365-annual-ticket

DW, Deutsche Bahn hails 9-euro public transport ticket; https://www.dw.com/en/deutsche-bahn-hails-9-euro-public-transport-ticket/a-62953716

Website the Guardian, (01.09.2022), Free rail travel scheme begins in Spain to cut commuters' costs; https://www.theguardian.com/world/2022/sep/01/free-rail-travel-scheme-begins-in-spain-to-cut-commuters-costs

ERFA Annual report 2021

The European Rail Freight Market Competitive Analysis and Recommendations, Page 76; https://erfarail.eu/uploads/The%20European%20Rail%20Freight%20Market%20-%20Competitive%20Analysis%20and%20Recommendations-1649762289.pdf

AERRL (2022), Press Release: Very Low carbon Rail Traction for the future (C. COUNE); https://aerrl.eu/wp-content/uploads/2022/10/PR-Very-low-carbon-rail-traction-for-future-F.pdf

List of Figures

SUPPORTED BY:

Produced by and with