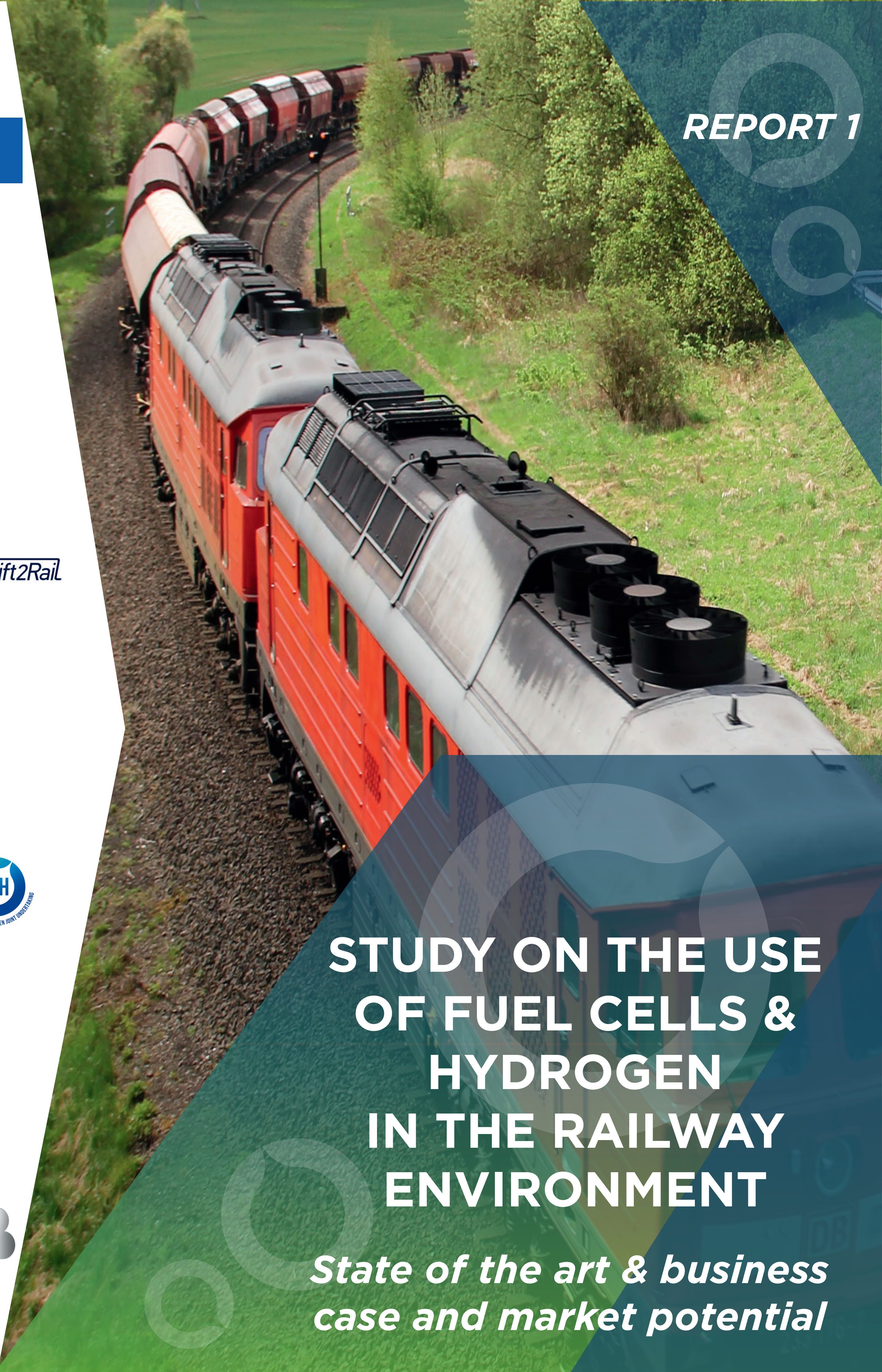


REPORT 1

STUDY ON THE USE OF FUEL CELLS & HYDROGEN IN THE RAILWAY ENVIRONMENT

State of the art & business case and market potential

STUDY ON THE USE OF FUEL CELLS & HYDROGEN IN THE RAILWAY ENVIRONMENT

REPORT 1

State of the art & business case and market potential

About this publication

Manuscript completed in April 2019.

Legal notice:

This document has been prepared by Roland Berger for the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Shift2Rail Joint Undertaking (Shift2Rail). The information and views set out in this study are those of the authors and do not necessarily reflect the official opinion of the S2R JU/FCH JU. The S2R JU/FCH JU does not guarantee the accuracy of the data included in this study. Neither the S2R JU/FCH JU nor any person acting on the S2R JU/FCH JU's behalf may be held responsible for the use which may be made of the information contained therein.

- More information on the FCH JU is available on the Internet www.fch.europa.eu
- More information on the Shift2Rail JU is available on the Internet www.shift2rail.org
- More information on the European Union is available on the Internet www.europa.eu

Authors:

Yvonne Ruf, Thomas Zorn, Pinar Akcayoz De Neve, Patrick Andrae, Svetlana Erofeeva, Frank Garrison

Contact:

Yvonne Ruf (yvonne.ruf@rolandberger.com)

Photos credits:

Cover © Deutsche Bahn AG, Page 4 © S2R JU, Page 5 © S2R JU, Page 6 © S2R JU, Page 7 © S2R JU, Page 8 © Deutsche Bahn AG, Page 11 © S2R JU, Page 15 © S2R JU, Page 18 © S2R JU, Page 19 © S2R JU, Page 22 and Page 23 © S2R JU, Page 30 © S2R JU.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF ABBREVIATIONS

AB	Advisory Board
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
FC	Fuel Cells
FCH	Fuel Cells and Hydrogen
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
IRG	Independent Regulators Group
Li	Lithium
LNG	Liquefied Natural Gas
NOx	Nitrogen oxides
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditures
PM10	Organic particles between 2.5 and 10 microns in diameter
PME	Proton Exchange Membrane
PSA	Pressure Swing Absorption
R&I	Research and Innovation
S2R JU	Shift2Rail Joint Undertaking
SMR	Steam Methane Reforming
TAC	Track Access Charges
TCO	Total Cost of Ownership
TSI	Technical Specifications for Interoperability
UK	United Kingdom
WACC	Weighted Average Cost of Capital


2
2 C
C 3
REGIO

ABSTRACT

The fuel cells and hydrogen (FCH) technology is a promising option to replace diesel combustion engines in rail transportation. The Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking launched this study to assess the state-of-the-art, the business case, the market potential, specific case studies and technical and non-technical barriers for FCH technology in different rail applications.

This first report covers Phase 1 of the study and the results achieved so far. The applications analysed are regional Multiple Unit, Shunter and Mainline Locomotive segments.

The technology has been tested for various rail application segments in 22 trials in 14 countries since 2005 globally. The trials have proven that the FCH solution can cope with the requirements of rail transportation. However, the technology is still at a prototype stage and requires further testing for increasing the scale of operations, improving availability, performance and cost expectations. The TCO analyses show that the technology can be cost competitive with the incumbent technologies if favourable conditions such as low energy prices can be achieved. The overall market potential until 2030 is estimated to be significant, especially for Multiple Units where FCH trains could potentially substitute 30% of diesel purchasing volumes.

EXECUTIVE SUMMARY

Fuel cells and hydrogen (FCH) have been suggested as a potential alternative powertrain technology in rail transportation. They offer one of existing reduced or zero emission options for rail transportation in various applications currently powered with diesel engines or expensive catenary electrification (other reduced or zero emission options include battery and LNG-powered trains). The Shift2Rail and Fuel Cells and Hydrogen Joint Undertakings have commissioned this study to analyse the potential of the FCH technology in rail and identify potential technical and non-technical barriers that prevent market introduction.

The review of the state-of-the-art of the technology shows that the FCH technology has been successfully trialled in different applications globally. 22 trials and demonstrations in 14 countries across Europe, Asia, North America, the Middle East, Africa and the Caribbean since 2005 have been identified and analysed. The technology has been tested in various applications from regional passenger trains, trams, trolleys to mining locomotives. The trials provide a good indication that the FCH technology can fulfil the requirements of rail applications. However, demonstration projects were often only conducted with single prototypes. First trials at scale with multiple standardised trains have been announced recently and shall start as of 2021 (e.g. North-East Germany regional passenger Multiple Units). The operational and cost performance for the commercial application of the technology has yet to be proven in practice. Furthermore, for some applications (e.g. mainline locomotives) prototypes have yet to be developed.

From a business case point of view, the FCH technology has the potential to become cost competitive with incumbent alternatives. For example, the results for the Multiple Unit case suggest a cost premium of the FCH technology of EUR 0.6 per kilometre in a conservative base case when applying a Total Cost of Ownership (TCO) perspective. However, the sensitivity analysis indicates that for instance low electricity prices of less than EUR 60 per MWh can make the FCH Multiple Unit cost competitive already today. These conditions could be achieved in some European regions, e.g. in Scandinavia. The business case of FCH Shunters and FCH Mainline Locomotives shows that the cost premium is higher than for Multiple Units in a conservative base case (EUR 1.6 per km, EUR 1.5 per km respectively) but also show the potential to become cost competitive. However, the latter two applications still require further analysis on a conceptual level and are yet to be tested with prototypes in Europe to solidify the TCO results. The revenue side of the business case is assumed to remain the same across all the technologies being considered.

The market analysis for the three focus applications Multiple Units, Shunters and Mainline Locomotives suggests significant potential to replace diesel-powered trains in Europe until 2030. From all analysed rail segments, the potential is the highest in the Multiple Units segment (up to 30% substitution potential of diesel purchasing volumes in the base case for 2030). Overall, FCH trains can replace between 11 and 41% of the diesel purchasing volumes until 2030 depending on a low or high uptake scenario. This equals 546 – 1,753 standard units in line the UNIFE World Rail Market Study. The market potential could be even higher as industry stakeholders frequently cite the limited experience with FCH trains that prevents them from taking a more optimistic market view. Also a lack of commercial products in the Shunter and Mainline Locomotive segments currently suggests a slower market uptake in this area. Further concept design and product development is necessary to better assess the market potential.

The initial results of the TCO analysis and the related market potential need further validation. The TCO analysis might be further impacted by additional opportunities suggested by a synergy resulting from a multimodal approach. These opportunities are to be further investigated. The needs for specific research and innovation actions (R&I) to overcoming technical and non-technical barriers will be identified in close collaboration with industry stakeholders. Furthermore, additional optimisation potential will be assessed by applying location specific parameters to the business case. Furthermore, the location specific effect on emission reduction will be analysed.

1. BACKGROUND AND INTRODUCTION

The European Union and its member states have made a clear commitment to lead the way in environmental protection. At the same time, there is a need to ensure that European transport is safe and its industry remains competitive on the global market. One of the key pillars is reducing greenhouse gas emissions as well as other air contaminants and noise. The rail system has been a pioneer in this area with 80% of its traffic running on electrified lines (representing 60% of the mainline network). However, in order to achieve international climate protection targets in a sector with 30 year investment cycles, solutions for non-electrified tracks are needed today to replace incumbent diesel technology.

Hydrogen and fuel cell trains have been trialled globally and technology developers have moved beyond the proof-of-concept phase. However, in order to prepare a commercial roll-out at a larger scale, research and innovation (R&I) investments from the rail and rail supplier industry are needed. Moreover, it is important to ensure support from the state side. Additional subsidies could potentially be crucial for further technology development due to high costs associated with train prototypes and new infrastructure. Technological solutions need to mature and costs on the hydrogen supply side as well as on the rail powertrain side need to be reduced. Numerous stakeholders in Europe have shown interest in the potential of fuel cell and hydrogen technologies for trains. In order to obtain a fact-based analysis, the Shift2Rail and Fuel Cells and Hydrogen Joint Undertakings have commissioned this study. It provides insights on:

- Business cases and market potential per rail application and geographical area in Europe for the use of fuel cell and hydrogen technologies.
- Specific case studies by rail application with a concept design, a commercial analysis and a view on a multimodal approach.
- Technical and non-technical barriers for the implementation of fuel cell and hydrogen technologies in the rail sector and related needs for R&I, regulation and standards

The study results are being developed in close collaboration with an industrial Advisory Board (AB) that has expertise in all aspects of the fuel cell, hydrogen and rail value chain. In total the AB is comprised of 27 members of which four are rail OEMs, eight rail operators, one train and locomotive lessor, seven fuel cell suppliers, and seven hydrogen infrastructure suppliers.

Following a stakeholder consultation process in the first weeks, three rail applications stand in the focus of the study: Regional Multiple Units (i.e. Regional Trains), Shunters (i.e. Shunting Locomotives at shunting yards) and Mainline Locomotives (i.e. replacement of diesel-powered Mainline Freight or Passenger Locomotives). These have been considered most promising.

This document is the first report of the study. It presents findings on two topics: State of the art of existing initiatives as well as business cases and market potential for hydrogen and fuel cell rail applications. Results are based on data from the industry stakeholders, industry and research expert interviews as well as extensive desk research.

Please note that the TCO analyses presented in this report were conducted based on generic use cases. They represent findings based on a specific set of assumptions. The next phase of the study will analyse case studies more in detail. The focus will be on the different framework conditions that determine the business case, e.g. technological solution and design, operational requirements, cost of hydrogen, infrastructure solution etc. The analysis in Phase 1 of the study allows for a general orientation regarding the potential of the technology, while further specific analysis will be conducted in the next steps.

2. STATE OF THE ART AND EXISTING TRIALS AND DEMONSTRATIONS

2.1. OVERVIEW OF IDENTIFIED EXISTING TRIALS AND DEMONSTRATION ACTIVITIES

A comprehensive review of past, current and future rail trial and demonstration projects with hydrogen and fuel cell (FCH) powertrain solutions is the basis for the analysis. After a literature review (see literature list in Annex for further information), 22 trials and demonstrations in 14 countries across Europe, Asia, North America, the Middle East, Africa and the Caribbean were analysed. The majority of trials and demonstrations were conducted in Europe (10), followed by Asia (8) and North America (2). The picture below provides a geographical overview of the countries where trials and demonstration projects have been conducted.

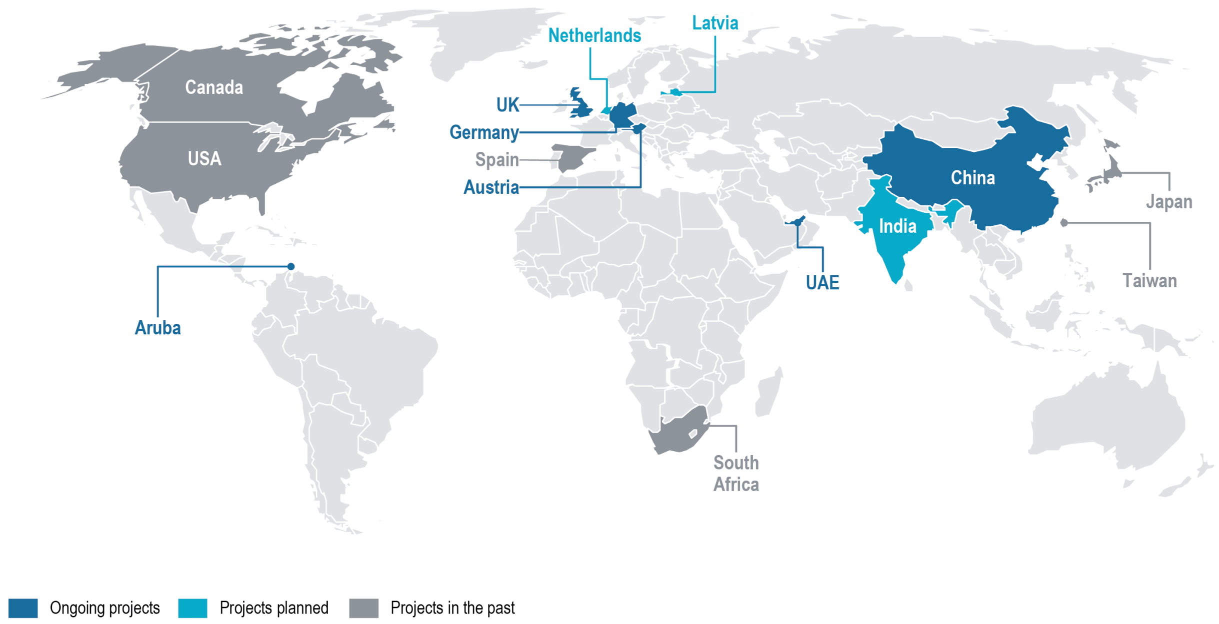


Figure 1: Countries with FCH train experience

FCH technology in the rail sector has been tested since 2001, typically with a single tractive unit being converted or retrofitted and a focus on a proof-of-concept. Amongst the train applications tested globally were: regional passenger trains (6), light rail (trams and trolleys; 5), shunting locomotives (5), mining locomotives (2) and proof-of-concept locomotives (4). These trials have proven that hydrogen and fuel cell technology can fulfil the performance requirements of different train applications in various operational scenarios. This forms the basis for necessary fleet tests that stimulate cost reduction and improve economies of scale of the refuelling infrastructure. Typically, the trials were conducted in a partnership of fuel cell providers and rail technology developers. Hydrogen supply and related hydrogen refuelling infrastructure was predominantly supplied with temporary refuelling solutions, mostly at 350 bars with no large-scale infrastructure tested yet. However, the new Multiple Units project in North-East Germany will be the first showcase for a large refuelling solution for fleets provided by The Linde Group. It is envisaged that 14 Multiple Units will be supplied with hydrogen at a single station as of 2021.

The latest developments have profited from the overall technological and cost progress of FCH technology. This results in a larger number of planned trials, while at the same time first companies are starting the commercial roll-out of their products. These envisaged trials are focused on the regional passenger train segment. First projects at a commercial scale have been announced in Germany, France and the UK.

The section below presents the main findings per rail application tested. Further detailed information is provided in the Annex of this document and a separate Annex presentation on the analysis conducted.

2.2. FINDINGS PER APPLICATION

The sections below provide a general overview of the conducted trials, the typical technical design and hydrogen supply chosen. They also provide first lessons for technology development and market potential.

2.2.1. REGIONAL PASSENGER TRAINS

GENERAL INFORMATION

Regional Passenger Trains also known as Regional Multiple Units (or Multiple Units) are the subject of six identified trials; with two trials already completed, two currently ongoing projects and two trial projects planned in the near term. The trials are spread globally with more recent concentration in Europe. New products are being announced or are already in commercial development with new technical designs (e.g. Alstom Coradia iLint, Siemens Mireo). Typically, the train OEMs partner with fuel cell suppliers for the development as it is the key innovative component of the trains' new traction system. Alstom has announced a partnership with fuel cell supplier Hydrogenics while Siemens chose Ballard as their fuel cell supplier for the time being.

Generally, OEMs mirror diesel train performance and target operations in areas where today's rail track usage does not commercially justify catenary electrification at low utilisation rates (see also key learning section below). The FCH technology offers a zero-emission alternative with full route flexibility, long range and short refuelling times. This fits well with the drive profiles of passenger trains that offer regional commuter service and return to their home depot at night. The latter allows for cost optimised hydrogen refuelling infrastructure solutions at a single site. As such, FCH technology appear to be a good fit with the Multiple Unit segment to reduce emission from rail operations in European regional rail operations further.

TECHNICAL DESIGN, HYDROGEN AND INFRASTRUCTURE SOLUTIONS

Taking the currently Alstom Multiple Unit product as a basis, there is proof that the technology provides sufficient capacity, range and speed to mirror today's diesel-train technology. The train is equipped with a powerful hybridised powertrain, i.e. it combines a hydrogen fuel cell as the main energy source with batteries that are mainly used for the tractive effort of accelerating the train after a stop. This combination intends to optimise the overall system costs and allows the fuel cell to operate at a constant load in order to increase its performance and lifetime. The commercial offering bundles the vehicle purchase, long-term service and maintenance agreements, and a solution for the hydrogen supply. The refuelling station for Multiple Units fleet deployments will be amongst the largest stations built to date. A first reference station from industrial gases company, The Linde Group, will dispense up to 2 tons of hydrogen per day at 350 bar. Hence, the operational requirements regarding availability and performance are high.

The refuelling time for 100-300 kg of hydrogen is expected to be between 15 and 30 minutes. The hydrogen will be supplied by truck in the first phase of the project (e.g. produced by Steam Methane Reforming, chlorine-alkaline electrolysis or by central renewable electrolysis). An on-site electrolyser system operated with wind electricity will supplement the supply at a later stage of the development. The overall investment costs of the refuelling station are projected at EUR 10 m.

The chart below provides an overview of typical technical parameters as an example for the regional passenger train application.

	Characteristics	Value
Dynamics & capacity	> Maximum speed > Passenger capacity	> 140 km/h > 300/150[1)] seats
Consumption & range	> Fuel consumption > Average range per tank	> 0.25 kg/km > 1,000[2)] km
On board hydrogen system	> Storage pressure > Storage capacity > Fuel cell system > Fuel cell power	> 350 bar > 260 kg (1 tank[2)] of ~130 kg per car) > Hydrogenics HyPM™ Power Modules > 400 kW (200 kW module per car)
Powertrain	> Traction motors > Hybridization system > Energy storage capacity	> Alstom-power-management-system > Li-Ion batteries > 110 kWh
Costs	> Rolling stock costs > Infrastructure costs > Hydrogen fuel	> tbc > Included in hydrogen fuel cost > EUR 4-7 per kg

1) Seated seats 2) Latest modification of Coradia iLint – Each tank contains several pressurized bottles

State of the art elements

- Sufficient passenger capacity, range and speed
- Intelligent power management and energy management
- Complete solution offered consisting of rolling stock, maintenance services and H_2 infrastructure
- Powerful traction motors and FC- and battery-systems

Figure 2: Alstom Coradia iLint hydrogen train specifications

KEY LEARNINGS FOR FURTHER TECHNOLOGY DEVELOPMENT AND MARKET INTRODUCTION

Multiple Unit trials show that this is a very interesting application with significant potential to phase out global and local emissions in one of the rail applications that still often is powered by fossil fuels. The chosen technology configuration provides sufficient performance to replace existing diesel-based products and therefore gives rail operators access to a zero-emission technology that can phase out incumbent combustion engine-based trains. Out of all trials with FCH technology in rail, Multiple Units trials have taken a lead role for commercial deployment. The Multiple Unit segment could profit from applying FCH technology as today only limited feasible alternatives exist. Catenary electrification would require a high utilisation of rail tracks to become commercially feasible and purely battery-based trains would require large batteries.

Additionally, the trials are increasing the public visibility of the technology in Europe with a potential spill-over effect for adjacent rail applications like Shunting or Mainline Locomotives.

Looking ahead, the trains will have to prove their operational performance (e.g. acceleration), the durability of the installed fuel cell systems (e.g. sufficient full-load hours on fuel cell system before scheduled stack maintenance) and their fuel consumption (i.e. kg of hydrogen per km) on a larger scale. Additionally, the hydrogen refuelling infrastructure has to provide fuel at very high availability levels at competitive costs for commercial operation. Refuelling station systems will have to be designed with sufficient technical redundancy and storage capacity to supply FCH trains daily without major interruption of refuelling operations. This is especially important as limited refuelling alternatives will be available alongside railway tracks and in acceptable distance for rail operation, especially at the early stage of market introduction. Furthermore, the technical interoperability of hydrogen refuelling infrastructure adjacent to already existing rail infrastructure, e.g. catenary installation at central depots, will have to be analysed in further detail.

Currently, first projects are planned that will bring FCH Multiple Units into everyday commercial operation. According to industry stakeholders, multiple comparable projects are planned across Europe, indicating market demand for the technology solution. Furthermore, public announcements on hydrogen trains have significantly increased the visibility of the technology and currently put Europe at the forefront of FCH train development. Hence, there is a good chance that Multiple Units will become the first widely used FCH train application. First demonstration projects will probably still require public grant support to mitigate initial development cost and operational risk, however, commercial competitiveness on a Total Cost of Ownership (TCO) basis can be expected as multiple train OEMs have started developing commercial products. The market development and the market potential will depend upon the operational and commercial performance which needs to be validated in practice. Successful projects will require operations at scale to achieve low energy sourcing cost and a high utilisation of the assets, like the refuelling infrastructure. As such, the currently planned project based on Alstom's Coradia iLint platform in the North-West of Germany will provide a first test of operational performance. Multiple rail operators regard the train availability as their main concern when considering FCH trains besides the purchasing costs. Therefore, additional demonstration projects will be required to prove the technological readiness and the commercial offering. Ideally, the demonstrations are conducted under different geographic circumstances in Europe to address potential concerns from the rail operator's side.

2.2.2. LIGHT RAIL (TRAM AND TROLLEY)

GENERAL INFORMATION

Light rail is another focus application for FCH usage in rail transportation. Hydrogen-fuelled trams and trolleys are being tested in several countries around the world – with one past tram demonstration in Spain, one ongoing tram and two ongoing trolley trials in China, the UAE and the Netherlands. Furthermore, one tram trial is planned in China with the service starting in 2019. The tram trials typically involve local OEMs partnering with global fuel cell suppliers (e.g. CRRC and Ballard, Fenit Rail and Hydrogenics); for the two trolley trials an American manufacturer TIG/m was chosen to supply the vehicle.

The main motivation behind these trials is a public willingness to promote highly visible environmentally friendly and clean-energy transportation solutions. According to the public announcements, the planned tram project is addressing the significant air pollution in China. For example, the FCH trams in Foshan are expected to provide a 'green' transportation solution without the need of setting up a catenary-electrified infrastructure and having no local emissions in comparison to a diesel-powered alternative. All existing fuel cell trolleys are used exclusively within tourist areas. FCH-powered solutions avoid catenary electrification which is often undesired in tourist areas from an aesthetic perspective.

However, industry experts expect the market for the FCH light rail application to be limited in Europe due to a high level of tram line electrification within cities. While these trials are relevant for the state-of-the-art technology review, this specific application is not considered as a potential use case in the study due to its potentially limited commercial potential in the EU.

TECHNICAL DESIGN, HYDROGEN AND INFRASTRUCTURE SOLUTIONS

The FCH tram manufactured by CRRC Tangshan with a fuel cell supplied by Ballard is the first non-touristic light rail commercial trial and was launched in October 2017. Therefore, its technical parameters were examined as the state-of-the-art. The tram is equipped with both, a fuel cell and a battery complemented by supercapacitors, making the key technical features, such as speed, comparable to a diesel tram.

In the same way as for the Multiple Units application, the battery is mainly used for the tractive effort of accelerating after a stop. At the same time, other characteristics like the passenger capacity are comparable to a conventional diesel engine, making the FCH tram competitive from a technical point of view.

	Characteristics	Value
Dynamics & capacity	> Maximum speed > Passenger capacity	> 70 km/h > 336/66[1)] seats
Consumption & range	> Fuel consumption > Average range per tank	> 0.3 kg/km > 40 km
On board hydrogen system	> Storage pressure > Storage capacity > Fuel cell system > Fuel cell power	> 350 bar > ~12 kg > Ballard's FCvelocity® > 200 kW (2 x 100 kW)
Powertrain	> Traction motors > Hybridization system > Energy storage capacity	> ~373 kW > Li-Ion batteries, supercapacitors > 2 x 20 kWh, 2 x 45F

State of the art elements

- First tram application designed with fuel cell hydrogen technology introduced in commercial operation
- Fuel cell output is combined with a battery and supercapacitors
- Low-floor technology despite constraints from energy storage (H_2, batteries and supercapacitors)

Figure 3: Hydrogen fuel cell tram by CRRC and Ballard

The tram is equipped with additional customer-oriented features such as low-floor technology used for passenger boarding. The route is 14 kilometres long and the tram is served by a temporary 100-kilogram capacity portable hydrogen refuelling station at the depot. Another planned tram trial assumes a similar technical design with enhanced technical parameters (e.g. higher range). On the other hand, fuel cell trolley trials and demonstrations provide less powerful technical design with reduced passenger capacity.

The chart below provides an overview of typical technical characteristics as an example for the light rail application by example of the CRRC tram.

KEY LEARNINGS FOR FURTHER TECHNOLOGY DEVELOPMENT AND MARKET INTRODUCTION

Multiple trials of FCH light rail application prove the interest of different countries and communities in introducing zero-emission transportation technologies in this segment. The current state-of-the-art technology suggests that the performance level of the vehicle is comparable to a conventional diesel engine. However, the main competitor for FCH trams and trolleys is still catenary electrification due to often already existing infrastructure. Thus, when considering FCH for a light rail application usage, the specific local framework conditions will be decisive, i.e. TCO competitiveness.

For further commercial usage, the technology will need to prove its operational performance in full commercial operation. While the performance appeared to be competitive in the trials, there is a need to further analyse key technical parameters such as hydrogen consumption, train acceleration after stops and costs related to fuel cell component maintenance (i.e. full load hours before stack refurbishment). As soon as more accurate data for technical parameters is available, a TCO-based comparison against alternatives should be conducted. Moreover, as environmental friendliness is one of the key rationales behind the fuel cell light rail solution trials, the actual environmental impact should be analysed in detail and assessed against alternative solutions (e.g. chosen hydrogen supply pathway and related emissions versus the emissions from electricity generation for catenary electrification). For the hydrogen infrastructure sufficiently large operational use cases should be identified before launching larger trials in order to achieve a high infrastructure utilisation. The latter will be decisive to reduce the overall cost of hydrogen supply (see also 0 for further information).

Currently ongoing trials of FCH trams and trolleys demonstrate the interest in investing into this application (which is mostly driven by the government or public companies). This might lead to the use of the technology in this segment in other countries as well. For instance, it could be attractive for operators with high pollution levels or in tourist areas as an attraction taking in public transportation. While several companies were involved in FCH tram and trolley trials, both from the OEM side and the fuel cell supplier side, the Total Cost of Ownership have not become competitive enough. This lack of competitiveness on the cost side is likely related to fact that multiple single prototype trials with different technical designs have been conducted that have not yet led to the required economies of scale for FCH technology.

In terms of the future market potential, the launch of the second commercial trial in China could be the next step towards commercialisation. Based on the results, the OEM (local CRRC subsidiaries) will decide on whether to continue investing in the technology further and proceed with its market introduction in the most polluted cities and regions in China. This could potentially provide the necessary manufacturing capacity at scale to drive costs down and enable a commercially competitive offering for public transport.

2.2.3. SHUNTERS

GENERAL INFORMATION

The FCH technology could potentially provide an environmentally friendly solution for Shunting locomotives. The operation of Shunters is often limited to the shunting yard with relatively constant operation over the year. Additionally they might be used for transfers on the distance of 30-70 km. Furthermore, a single hydrogen refuelling station is sufficient to supply a fleet of multiple Shunters at the yard which improves the hydrogen refuelling economics. Five Shunter trial projects have been identified of which three projects are finalised, one project is currently ongoing and one project is planned.

TECHNICAL DESIGN, HYDROGEN AND INFRASTRUCTURE SOLUTIONS

Within the segment of shunting locomotives, the technical characteristics of the FCH Shunter developed by BNSF and Vehicle Projects was selected as the state-of-the-art, since it is the heaviest and most powerful FCH Shunter to date. The trial indicates that FCH can provide sufficient power for very heavy duty shunting usage. The BNSF Shunter was equipped with a 240 kW fuel cell with transient power in excess of 1 MW. However, the hybridised powertrain had to provide between 40 to 100 kW of power on average as in most of the tested duty cycle the Shunter was idle 50 – 90 percent of the time.

	Characteristics	Value
Dynamics & capacity	> Maximum speed > Load capacity	> - > 200-1,800 tons
Consumption & range	> Fuel consumption > Average range per tank	> 5.6 kg/h > 8-16 hours operating shift[1)]
On board hydrogen system	> Storage pressure > Storage capacity > Fuel cell system > Fuel cell power	> 350 bar > 70 kg > Ballard's P5™ stacks modular design > 240 kW
Powertrain	> Traction motors > Hybridization system > Energy storage capacity	> 2,000 hp traction > - > -

State of the art elements

- The heaviest and most powerful hydrogen fuel cell locomotive (130 t weight with max. power of 1.5 MW)
- High power PEM fuel cell used (240 kW with power surges in excess of 1 MW)
- Low overall system weight – It requires a 9,000 kg steel-plate ballast placed in undercarriage bay

Figure 4: Hydrogen Shunter by BNSF and Vehicle Projects

The fuel consumption appears modest but limited information was published on the assumed operation cycle of the train. The hydrogen refuelling infrastructure has so far not been in the focus of the trials of shunting locomotives. The BNSF Shunter was designed with a 350 bar hydrogen tank system which suggests that similar refuelling station designs from regional passenger trains could be used in future trials or a commercial operation. During the trial phase the locomotive was supplied via a hydrogen tube trailer from a nearby industrial plant without setting up a hydrogen refuelling station. Demonstration projects would be required that specifically analyse the performance of the refuelling station in a real-life shunting environment with multiple Shunters in operation.

KEY LEARNINGS FOR FURTHER TECHNOLOGY DEVELOPMENT AND MARKET INTRODUCTION

FCH Shunters have been trialled and tested in practice. The FCH technology provided sufficiently high power for shunting operations. As such, the technology can be applied to this application and can compete with alternatives technically. FCH Shunters have the potential to save a significant amount of emissions (CO_2, NO_x, particulates) when replacing diesel Shunters (e.g. 2.81 kg of CO_2 for each litre of diesel saved). They would also avoid inefficient engine idling, e.g. when diesel-powered Shunters are waiting for the next shunting operation during their shift. This could contribute to a substantial local and global reduction of air pollutants and noise.

Currently, however, limited amounts of FCH shunting projects are ongoing and no project has been implemented with larger fleets of Shunters. Also, the experience with FCH Shunters in Europe is limited. Larger demonstration projects with fleets of Shunters in one depot are required to understand potential operational limitations (e.g. sufficient refuelling times, interoperability of rail and FCH infrastructure). A suitable level of hybridisation has to be defined (e.g. battery versus fuel cell capacity, integration of supercapacitors, size of hydrogen tank) and potential space limitations for integrating the technology on shunting locomotives needs to be clarified. Furthermore, options exist to retrofit existing diesel-electric Shunters with FCH technology. Respective prototype concepts need to be developed to test the retrofitting option (e.g. cost of integration, space constraints in shunting locomotive, and technical compatibility of existing installed electric equipment with retrofitted fuel cell powertrain).

The chosen design strategy of the Shunter will determine its fuel economy and subsequently impact the refuelling infrastructure. Depending on the actual use case (i.e. daily distance and operating hours), the fuel supply has to be optimised. Adjustments of the refuelling station technology will primarily depend on the Shunter manufacturers' technical design strategy. Deviations from the typical 350 bar refuelling pressure which is used in most FCH trains today could require significant alterations of the refuelling station design and refuelling operations (e.g. for 700 bar or liquid hydrogen stations).

An analysis of specific case studies for Shunters have to provide a more detailed insight into typical Shunter operations at shunting yards to identify additional technical and non-technical barriers before the application can be commercialised. Furthermore, European trials and consumption calculations should be based on a pre-agreed duty cycle for the comparison of FCH technology with diesel and other alternatives. The actual performance of FCH Shunters should be proven in demonstration projects under different operational requirements (e.g. different climate, different daily duty cycles, different loads hauled).

The realization of the market potential will depend on the commercial availability of shunting locomotives in Europe. Today, no commercial shunting locomotive product is available on the market but industry stakeholders are investigating the use of FCH technology for this rail application (e.g. retrofitting of diesel-electric Shunters). Commercial introduction in the market will require at least one successful demonstration project per supplier to provide potential customers with sufficient certainty about the technology performance. Therefore, FCH Shunter concepts need to be developed first, and then followed by a performance demonstration phase of prototypes. The latter shall reveal potential technical hurdles (e.g. space constraints for integrating FCH technology, shock vibration during shunting operations like coupling) and increase the visibility of the technology solution. Once the operational performance is satisfactory, demonstration projects in a larger shunting fleet setting with full daily operation should are advisable.

2.2.4. MINING LOCOMOTIVES

GENERAL INFORMATION

FCH technology has also been applied to mining locomotives with some conducted trials and demonstrations. FCH mining locomotives are used for a more environmental friendly process of underground mining. Up till now, two trials have been conducted – one in Canada in 2002, and the second one in South Africa in 2012. Both vehicles were manufactured by Vehicle Projects Inc., which has also provided the engineering design, fabrication and testing. The first vehicle was produced for Placer Dome for an underground gold-mining application in Quebec and is assumed to be the first FCH mining locomotive. The customer for the second one was Amplats, who purchased five FCH locomotives to be used for underground mining. The fuel cell for the latter project was supplied by Ballard.

TECHNICAL DESIGN, HYDROGEN AND INFRASTRUCTURE SOLUTIONS

As there are only two past initiatives on the FC mining locomotive both produced by the same manufacturer, the more recent one was considered for a state-of-the-art review (dated 2012). The locomotive was equipped with a Ballard fuel cell providing a continuous net power of 17 kW, and Li-Ion batteries. Maximum net power of 45 kW could be achieved from the traction battery. In comparison to a conventional purely battery-powered mining locomotive, it provided longer operating time, substantially faster refuelling and zero-emission at the tailpipe.

The hydrogen storage system was designed by Vehicle Projects, allowed storing 3.5 kilogram of hydrogen at 200 bar and a refuelling within 10 to 20 minutes. The hydrogen stored on board could provide the system with approximately 50 kWh of tractive energy. The storage was designed to provide high level of safety and efficient usage of energy.

KEY LEARNINGS FOR FURTHER TECHNOLOGY DEVELOPMENT AND MARKET INTRODUCTION

A limited number of trials and demonstrations for this application indicate the niche interest of specific customers in funding and testing FCH mining locomotives (e.g. Amplats funded the project only from their corporate budget). Still, less expensive alternatives for the mining application exist, e.g. conventional diesel and battery-powered engines with the latter also running without local emissions.

Further technological development will depend on following: First of all, the operational performance of existing trials should be evaluated in a comprehensive way to identify any weaknesses and points for further improvement as limited information was published in that regard. Secondly, additional analysis on the performance needs from potential customers (i.e. mining companies) is required support identifying potential sweet spots for the FCH technology.

The past trials of FCH mining locomotives serve as a starting point for the market potential assessment. At the moment there are no publicly available indications of further fuel cell projects for this specific application. However, the market might be pushed by new customers seeking to reduce their corporate emissions as part of their corporate responsibility strategy via alternative zero-emission solutions. In comparison to other rail application segments like Multiple Units the market potential for FCH mining locomotive seems limited. This is especially important as the cost reduction of fuel cell system requires larger production volumes that cannot be expected from the mining locomotive market.

2.2.5. PROOF-OF-CONCEPT LOCOMOTIVES

GENERAL INFORMATION

Proof-of-concept locomotives refer to small-scale locomotives either developed for pure demonstration purposes or as a touristic attraction. For now there are four known proof-of-concept locomotive demonstrations – two past demonstrations in Taiwan and the UK, and two ongoing demonstrations in the UK and Austria. This type of FCH application is mostly developed and supported by local universities, research centres and other public organisations (e.g. Taiwan National Science and Technology Museum, University of Birmingham, Birmingham Centre for Rail Research and Education). The development is carried out either stand alone or in cooperation with local fuel cell promotion offices (e.g. Taiwan Fuel Cell Partnership). The only exception is a demonstration project in Austria, where numerous parties were involved (ÖBB Infra, TEMO, Air Liquide, Railway Competence and Certification Ltd. and Prosoft Süd Consulting GmbH) and the fuel cell was supplied by a global market player (Hydrogenics).

TECHNICAL DESIGN, HYDROGEN AND INFRASTRUCTURE SOLUTIONS

In terms of technological solution, proof-of-concept locomotives generally represent a scaled-down version of normal locomotives, which implies lower power rating, speed, capacity etc. Furthermore, the tests have generally been demonstrated and tested on narrow gauge tracks. In order to describe the state-of-the-art, the Austrian trial is being considered. The demonstration of a locomotive (‘Hydro Lilly’) was carried out on the 381 mm gauge Liliputbahn miniature railway. The 5-ton locomotive was powered by a modular, mobile FCH system providing an operating range of ~70 km and maximum speed of 25 km/h. The system ensures a continuous fuel cell rating of 8 kW with a peak output of 10 kW. The hydrogen tank capacity was 85 litres stored at 200 bar, which provides 38 kWh of energy. The hydrogen was supplied by Air Liquide in 200 bar hydrogen cylinders which were used to supply the train using the pressure differential between the supply cylinders and the hydrogen tank on the train.

KEY LEARNINGS FOR FURTHER TECHNOLOGY DEVELOPMENT AND MARKET INTRODUCTION

FCH proof-of-concept locomotives are being constructed from scratch, which offers good possibilities for customisation and integration of new powertrain technology. Systems are designed in a way so that they allow technology scale-up for trials and demonstration at a later stage in real-life operation. For example, the technology used within the current UK ‘Hydrogen Hero’ demonstration is planned to be scaled up at a later stage. These demonstrations indicate the interest for the technology and enable the industry to gain first experience with hydrogen and fuel cell technology.

This application is always a means to an end – not an application that will be pursued in its own sake. Technological development for a commercial market requires that learnings from proof-of-concept locomotives are transferred to full-scale products beyond scientific interest. Ideally, new technology development projects build on the past experiences of these proof-of-concept projects. Alternatively, further proof-of-concept trials could be conducted on a single platform basis with different levels of powertrain hybridizations and mirroring typical operations of large trains to draw conclusion for fuel cell lifetime, performance requirements and other operational characteristics in the rail segment. Furthermore, the hydrogen infrastructure aspect needs to be reviewed in further detail in order to evaluate if proof-of-concept projects could spur the development of novel hydrogen refuelling technologies, like compressors, valves, metering devices or refuelling couplings.

2.2.6. MAINLINE LOCOMOTIVES

Mainline Locomotives have not been trialled and tested with FCH technology so far. Both proof-of-concept type trials and prototype tests under real driving conditions are lacking. However, recent studies from Norway (SINTEF for NSB) and Canada (Jacobs Engineering Group for Metrolinx) suggest that the Mainline Locomotive application would be well suited to compete against diesel engine based systems. These first theoretical examinations should be tested with operational prototypes and demonstrated ideally at a larger scale within Europe to confirm theory in practice. In general, fuel supply for Mainline Locomotives appears to be more challenging as a full flexible operation across a country or region could require multiple refuelling stations depending on the specific use case. Currently, industry players suggest investigating the on-board hydrogen storage further in the first place as more hydrogen is required for Mainline Locomotives to cover larger distances. Here, also fuel storage on a separate tender trailer could be an option that requires further research. Besides the storage of hydrogen, a potentially large fuel cell system may be required to continuously supply the electric motors besides peak power supply for acceleration from batteries.

Mainline Locomotives are being analysed as one focus application in this study as rail operators and technology developers signalled interest in the application.

2.3. TRANSFERABILITY OF EXISTING TRIALS FOR LARGER MARKET INTRODUCTION

The majority of identified test and trial projects have been conducted outside of Europe. Europe's R&I should build on the international state-of-the-art and draw from existing experiences. Therefore, the transferability of trials is important to ensure that specific market needs and framework conditions are appropriately taken into account. The comparability of learnings is essential to assess future technological and non-technological development needs.

For a high-level assessment of the transferability, the existing trials were clustered and analysed in two categories: the first category encompasses passenger applications including Multiple Units, trams and trolleys, whereas the other category comprises Shunters and proof-of-concept locomotives. Here, the introduced state-of-the-art projects for Multiple Units and Shunters where used as an example for the two categories respectively. Mainline Locomotives were not trialled yet and therefore do not offer transferable information.

The transferability of trials was analysed based on the following criteria:

- Technical features, e.g. speed, range, power.
- Regulatory framework, e.g. geography, rail application, customisation.
- Likely TCO/cost, e.g. cost of technology (new vs. retrofitted).
- Stakeholders involved, e.g. participation of global suppliers and system integrators.
- Political motivation, e.g. degree of political support, availability of government funding.

REGIONAL PASSENGER TRAINS

Within the regional passenger segment, the Mireo train platform by Siemens and Ballard, the Alstom Coradia iLint, and the Stadler hydrogen multiple unit trains are all specifically designed for operations in Europe. Furthermore, the technology is in development for operations in Europe, addressing the specific regional technical and non-technical requirements (e.g. speed, acceleration, passenger capacity, HVAC requirements, drive profiles etc.) as well as the regulatory framework. Strategic partnerships between fuel cell suppliers and train OEMs show good involvement of experienced industrial companies (e.g. Siemens & Ballard, Alstom & Hydrogenics). First successfully tendered projects indicate that FCH Multiple Units can be TCO competitive although supported by public funding. The political support in all currently planned pilot projects is sufficient. Hence, the analysed projects are very transferable and ideally suited to provide valuable insights for a larger European market introduction. The above mentioned use cases also stand out internationally and provide a good basis for advancing Europe's technology development in that area.

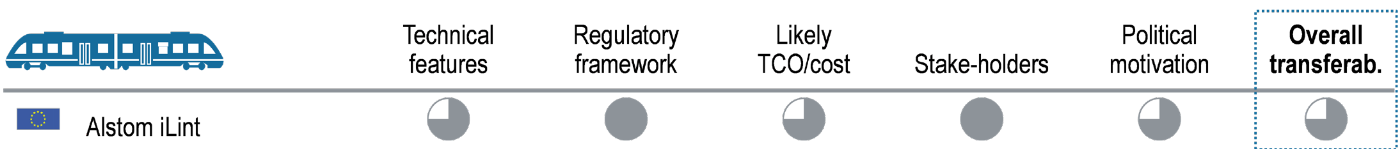


Figure 5: Transferability of Multiple Unit trial

SHUNTERS

For the Shunter segment, the U.S. American Shunter developed by BNSF and Vehicle Projects in cooperation with Ballard stands out as transferable to the European context. With its high power and application in heavy load shunting, the technical features prove the technological feasibility for similar use cases in Europe. Industry stakeholders indicated that lower power performance would be sufficient for European operations. Therefore, the TCO is estimated to be comparable or even lower as less fuel cell and battery power would be required. Furthermore, with Ballard as fuel cell supplier and BNSF as system integrator, the stakeholder involvement for this trial was high, which suggests that both rail and FCH specific know-how has been taken into account for the development. However, one has to consider that the regulatory environment in the United States varies from the European framework (e.g. performance requirements, TSI specifications). Hence, it is less comparable to the situation in Europe. The specific project was mainly driven by an individual corporate agenda to find alternative powertrains as a replacement for diesel. Politically, the topic has not been pushed further towards commercialisation. All in all, it provides a starting point for similar developments in Europe; however, actual demonstration projects based on latest technology progress are required to validate first results.

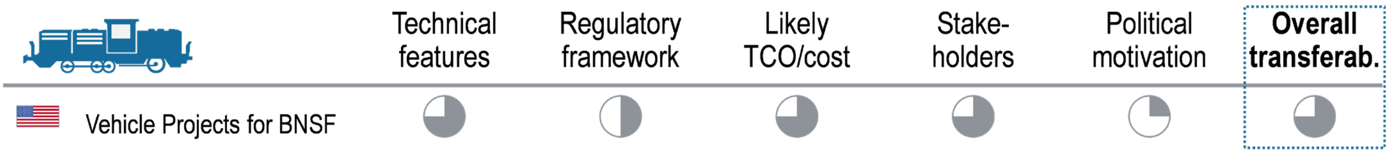


Figure 6: Transferability of Multiple Unit trial

In summary, past and current trials provide a good starting point for accelerated use of FCH technology in the rail segment. However, larger scale demonstration has just begun to be implemented in the Multiple Units segment. Here, first tests at scale have to provide further lessons. They potentially require further optimization and technology development to achieve full TCO competitiveness without public support. Furthermore, within the Shunter and Mainline Locomotive segment, new prototype products are missing. These could lay the foundation for larger fleet trials with an aim of providing an alternative for still large existing diesel fleets in Europe. In a first step, technical performance on both the train and refuelling infrastructure side have to be proven to repeat a similar positive development as for FCH Multiple Units.

3. BUSINESS CASE AND MARKET POTENTIAL

This chapter analyses the business case for FCH rail technologies. New technologies typically come at a cost premium to the market. Therefore, the Total Cost of Ownership (TCO) of the rail applications in question was analysed. The analysis is based on data provided by the industry and has been challenged and validated by FCH and rail experts. It is expected that the revenue side of the business case will in principle not be impacted by the introduction of FCH trains. The upside to the business case comes from the monetization of externalities (i.e. environmental costs). A brief perspective on this will be provided below. Please note that detailed and location specific business cases (incl. environmental benefits) will be analysed in detail in the second phase of the study. Furthermore, the chapter provides information on the market potential for FCH trains. Since costs are a strong driver for the demand, the results of the TCO analyses have been taken into account in the assessment. The market potential was estimated on the basis of existing market data, industry expert interviews and rail expert interviews. See chapter 3.2.5 for further details on the methodology applied.

3.1. FINDINGS OF THE TCO ANALYSIS AND BUSINESS CASE

OVERVIEW OF THE RESULTS

In order to assess the commercial competitiveness of FCH train solutions the TCO was analysed in comparison to incumbent technology options, mainly diesel combustion engine trains (for all applications) and catenary electrification (for Multiple Units). The TCO analysis is based on one generic use case per application that was defined to ensure comparability of the provided industry data, i.e. same assumptions for performance criteria, e.g. daily range, operating hours and power requirements were applied. The underlying energy consumption calculations were based on drive profiles from EN 50591 and a related concept of the S2R FINE project to enable comparability of the consumption data.

In the base case of the generic TCO calculation, a conservative approach on cost reduction and energy purchasing has been taken. The CAPEX assumptions were adjusted modestly over time to reflect the technological cost progress of the FCH technology. However, more specific analysis has to be conducted as part of the second phase of the study by investigating concrete case studies. A potentially higher CAPEX reduction can be justified in relation to higher deployment volumes or optimised technical designs in specific cases. In all cases an on-site hydrogen production facility was assumed using an electrolyser.

Generally, all applications indicate a pathway to commercial competitiveness under specific assumptions, i.e. mainly if low energy sourcing costs and high utilisation of the assets can be achieved (i.e. FCH trains and hydrogen refuelling infrastructure). The results for favourable conditions are presented as an optimistic case for the TCO analysis. However, if these favourable conditions cannot be realised a cost premium in the range of 7-19% to incumbent technology prevails.

• Multiple Units – Are generally within the range of the TCO of incumbent technology

Multiple Units have been analysed under the assumption that 15 trains are operated in a regional network and are refuelled at a single central depot. The trains are assumed to be in operation for 8 to 10 hours per day and to cover a distance of up to 800 kilometres per day. Due to low and peak load periods, the total annual mileage was assumed to be 200,000 kilometres (see chapter 3.1.1 for further information). The FCH cost premium is EUR 0.5-0.6 per kilometre under the specific case assumptions. However, assuming a reduced hydrogen price of EUR 3.4 per kilogram (excluding infrastructure) a Multiple Unit can become competitive on a TCO-basis (ceteris paribus). For instance, this would be possible in a scenario where the hydrogen is produced on-site via electrolysis and an electricity purchasing price of EUR 55 per MWh. Higher diesel prices, e.g. above EUR 1.5 per litre, would further increase the TCO spread for FCH trains by additional EUR 0.29 per kilometre. Hence, the Multiple Units are within the range of incumbent technology in terms of the TCO already today. Moreover, in a base case FCH Multiple Units have a competitive advantage over a catenary-electrified train under given base assumptions (100 kilometres of rail track to be electrified at an average cost of EUR 1.1 m per kilometre). Under the chosen assumptions, catenary-electrified Multiple Units are not competitive if more than 90 kilometres require new electrification.

• Shunters - Have the potential to become TCO competitive

The Shunter use case is based on operations in a shunting yard where 10 Shunters are operated at one location. The Shunters are assumed to be in operation for 12 to 16 hours per day and consume 3.9 kilograms of hydrogen per hour. Under these assumptions and a hydrogen price of EUR 5.8 per kilogram, the Shunter can potentially become competitive on a TCO-basis (with a premium of EUR 1.6 per kilometre in the base case). As fuel and infrastructure costs are important for the FCH technology TCO results, an upside exists for larger fleets of Shunters with more intense daily operations as it is the case at large, central shunting yards supplied by only one hydrogen station. Also a shared use of the hydrogen refuelling infrastructure with other modes of transport (e.g. FCH trucks) can improve the hydrogen fuel supply economics and reduce the FCH Shunter TCO accordingly.

- ## Mainline Locomotives – Are currently not TCO competitive, need for further analysis

The Mainline Locomotive TCO was calculated based on a scenario in which 7 trains are operated in long distance service covering 1,000 kilometres per day. The use case assumes a hydrogen consumption of 0.9 kilogram per kilometre and hydrogen price EUR 5.6 per kilogram. The train fleet is supplied by a hydrogen refuelling station in each of two hypothetical mainline freight hubs. Under these assumptions the FCH Mainline Locomotive is currently not TCO competitive against conventional diesel locomotives (with a cost premium of EUR 1.5 per kilometre in the base case). The main driver is an underutilised refuelling infrastructure.

The illustration below depicts the results of the TCO analysis in range (based on more optimistic data points on the lower end of the range and more conservative data points in the base case) for the TCO on a EUR per kilometre basis. In all cases FCH trains can be TCO competitive against incumbents in a favourable scenario. Advancements of the FCH technology through R&I can further decrease the TCO (see section below).

The TCO spread between the FCH and conventional technologies can reach up to 19%, applying different input parameters. The analysis assesses the main TCO drivers such as hydrogen consumption per application, electricity price, diesel price and FCH train purchasing cost.

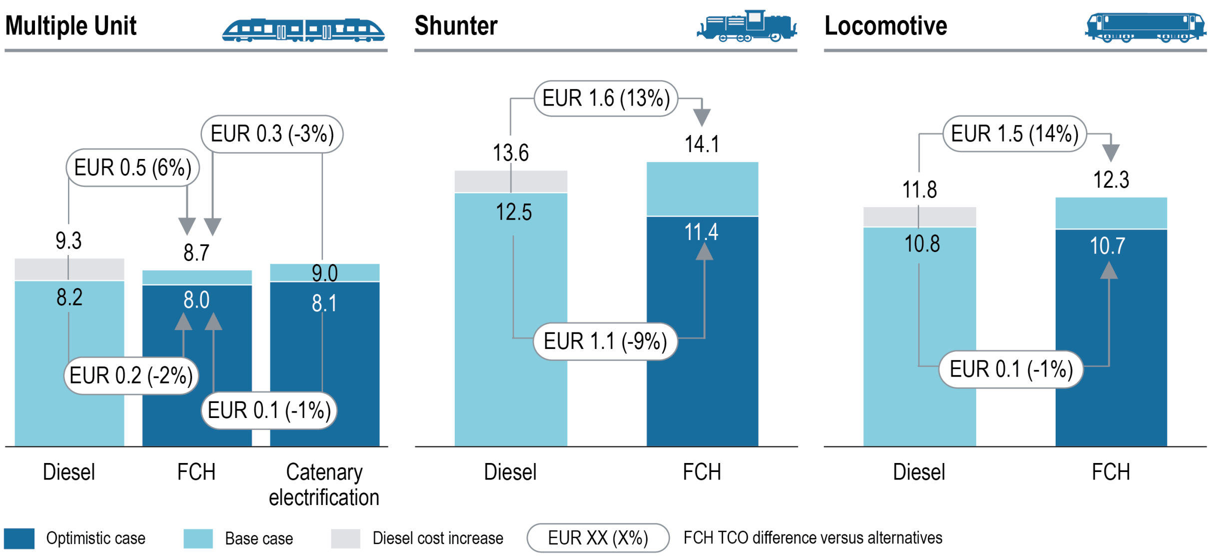


Figure 7: Projected TCO in 2022 [EUR/km]

The TCO of FCH trains is mainly driven by three categories that impact different elements of the business case:

- ## CAPEX and OPEX costs:

The TCO for FCH trains is mostly driven by the energy OPEX, i.e. the electricity price obtainable for on-site production of hydrogen or the external purchasing costs of trucked-in hydrogen fuel. Secondly, the CAPEX for FCH refuelling infrastructure, the hydrogen on-site production facility and the FCH trains is decisive for competitive TCO. The CAPEX is also impacted by economies of scale (see below). The illustration below depicts the CAPEX (on average ~22% for FCH, ~12% for diesel, and ~32% for catenary) and OPEX share of the TCO for all three applications.

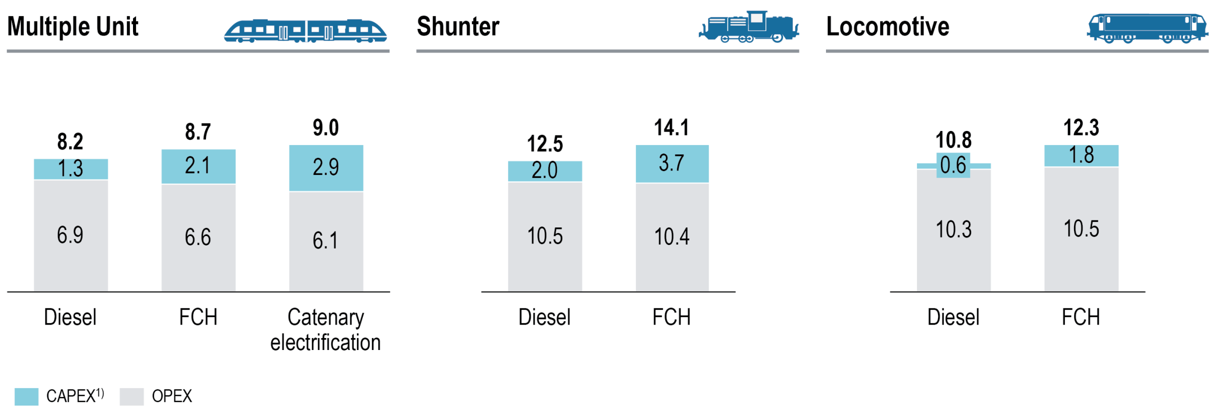


Figure 8: Projected CAPEX and OPEX in 2022 in the base case [EUR/km] [1]

- ## Economies of scale:

The TCO of FCH trains profits significantly from economies of scale on the hydrogen infrastructure side. This is especially the case for larger and higher performing refuelling station systems and H2 production facilities that disproportionally increase in costs with increasing refuelling and production capacity, i.e. the specific costs per kilogram of hydrogen supplied to trains are lower. Additionally, lower purchasing cost on the FCH train side can be expected if larger batches of trains are purchased in one single order. Especially FCH train specific components like the fuel cell stacks show significant cost reduction potential if produced at larger volumes (e.g. by moving from manual via semi-automated to fully automated production). As an example, the illustration below provides the CAPEX costs for the hydrogen refuelling infrastructure depending on the size. It indicates that the rate of the cost increase is lower than the rate of capacity increase.

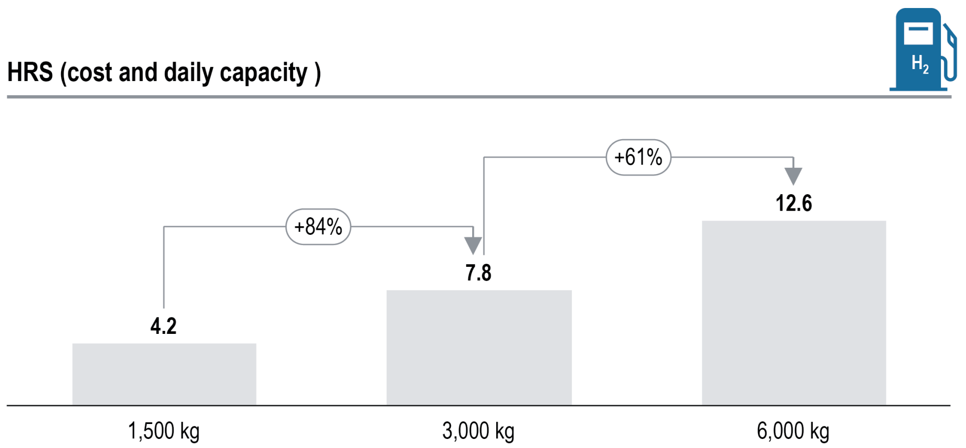


Figure 9: Example for lower cost increase of hydrogen refuelling station with capacity increase in the base case in 2022 [EUR m]

[1] CAPEX includes financing cost and depreciation cost for the train, the required infrastructure, e.g. investment and installation of catenary electrification or e.g the H2 production facility.

- ## Asset utilisation:

This category is important for the FCH train fuel cell system and the hydrogen refuelling infrastructure. The fuel cell system will degrade over time based on utilisation, i.e. full-load hours performed. Hence, heavier utilisation of the fuel cell system will decrease the service and maintenance intervals leading to higher costs. This is an important aspect for FCH heavy duty applications like trains and offers good potential to reduce TCO further if the operational lifetime of the fuel cell stack can be extended before refurbishment is necessary. In contrast, the infrastructure for fuel supply is ideally frequently utilised by the trains without significant hourly, daily, weekly or seasonal peaks, i.e. similar amounts of hydrogen dispensed per time period. As such, inefficient overcapacity in the HRS system can be avoided. If the infrastructure (HRS and H2 production facility) is utilised for 100% versus 50% the TCO can be reduced by EUR 0.5 per kilometre.

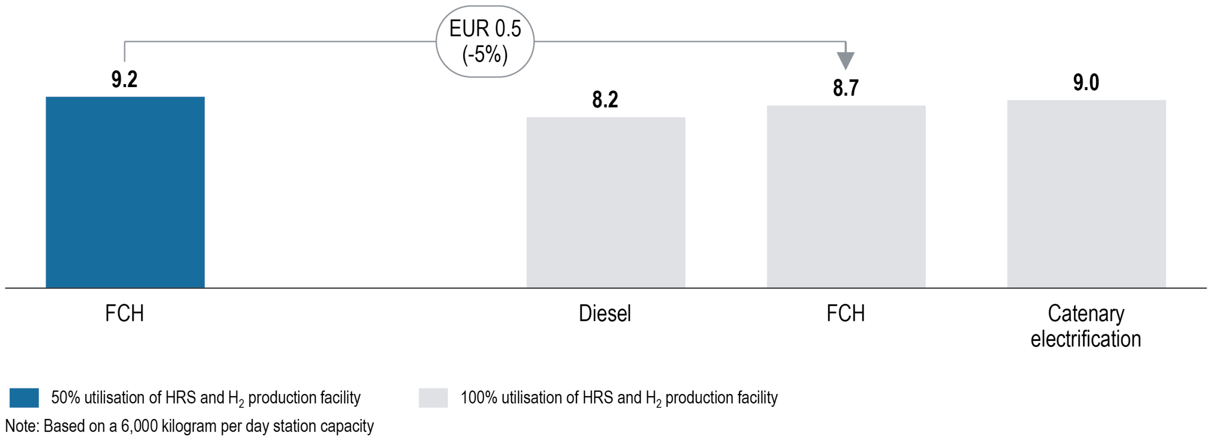


Figure 10: Example for TCO sensitivity to infrastructure asset utilisation [EUR/km]

A more detailed breakdown of the cost elements per segment is provided in chapters 3.1.1 to 0. Levers to optimise the business case in relation to the main cost drivers for the TCO analysis are presented in chapter 0 below.

As a starting point for the analysis, all cases have been calculated with on-site production of hydrogen via electrolysis to present a feasible but not too optimistic scenario for renewable hydrogen supply. In reality, lower infrastructure costs can be achieved if off-site hydrogen supply via trucks or pipelines is considered. An example for this supply route is presented as part of the sensitivity analysis. The level of CO2 reduction potential will then depend on the source of hydrogen chosen (e.g. industrial by-product from chlorine-alkaline plants, central steam methane reforming) and the emission from truck transportation.

3.1.1. REGIONAL PASSENGER TRAINS (MULTIPLE UNITS)

The use case for Multiple Units assumes a deployment of 15 FCH trains. Additional technical parameters for the use case are described in the illustration below.

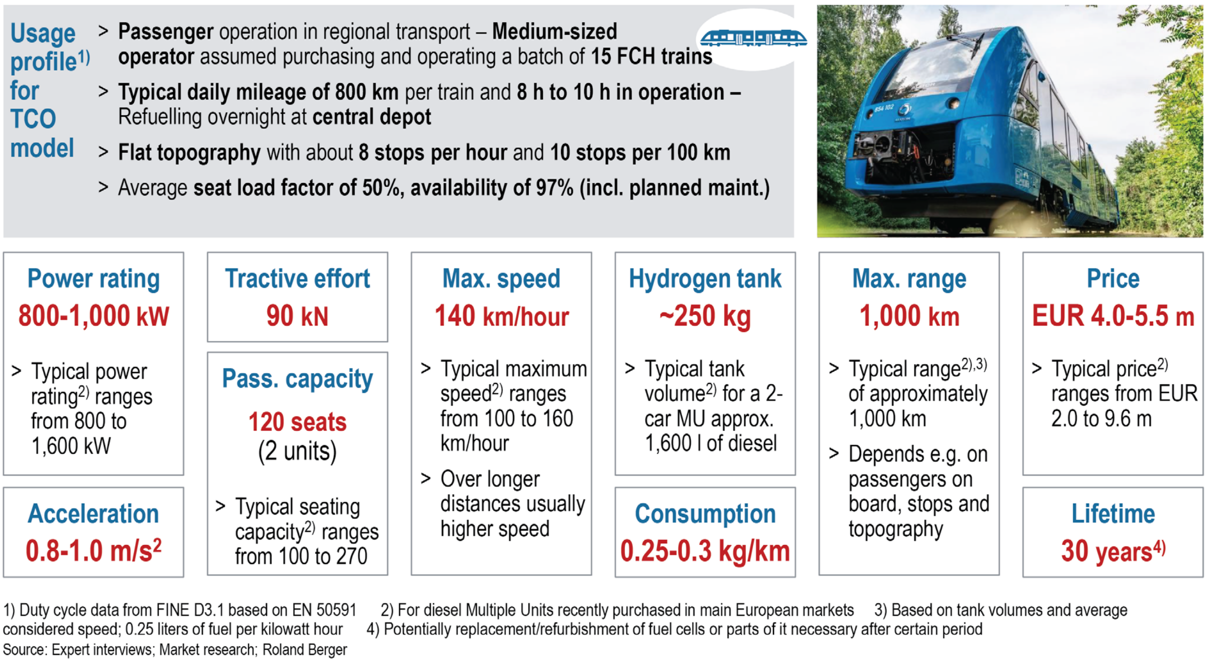


Figure 11: Use case – FCH Multiple Units

TCO ANALYSIS AND COMPARISON TO INCUMBENT TECHNOLOGY

The analysis shows a TCO spread of +6% between the FCH and conventional diesel technology and up to –4% in comparison with catenary electrification. The analysis is based on the key TCO drivers such as diesel price (EUR 1.3 per litre of diesel), electricity price (EUR 90 per MWh), route length (100 kilometres) and energy consumption (1.45 litre of diesel per kilometre and 0.27 kg H2 per kilometre). It is assumed that hydrogen is produced at the on-site production facility using an electrolyser. The infrastructure cost includes a hydrogen refuelling station and a production facility. For the catenary electrification it was assumed that 100 km of rail track are being electrified.

The illustration below indicates the detailed TCO in a base case in 2022 in comparison with other technologies.

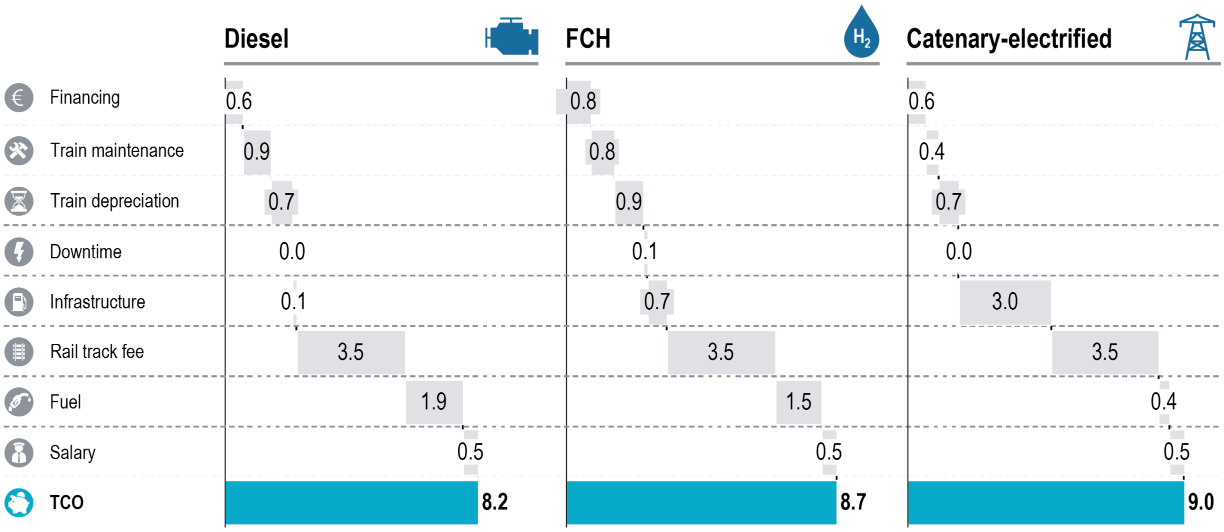


Figure 12: Detailed TCO – Multiple Units in base case [EUR/km]

SUITABILITY OF THE FCH TECHNOLOGY FOR THE APPLICATION

The FCH technology provides an interesting powertrain option for a Multiple Unit application under favourable economic conditions, e.g. low energy OPEX and reduced CAPEX of FCH technology (trains and infrastructure) that can potentially become TCO competitive. The commercial competitiveness can be achieved under the applied assumptions. However, if these assumptions cannot be achieved in a real deployment case, the cost premium might be up to EUR 0.5 per kilometre (6%) for a FCH Multiple Unit over a conventional diesel. The cost premium is mainly driven by the fuel prices (EUR 5.6 per kilogram of H2 and EUR 1.3 per litre of diesel) and infrastructure operating costs (mainly electrolysis-based H2 production facility). The sensitivity analysis described in 3.1.4 concludes that a 30% change in diesel cost, a 38% change in H2 consumption and a 38% change in electricity price lead to FCH being at par with diesel.

3.1.2. SHUNTERS

USE CASE

The use case for yard Shunters assumes the deployment of 10 FCH Shunters per shunting yard. Additional technical parameters for the use case are presented in the illustration below.

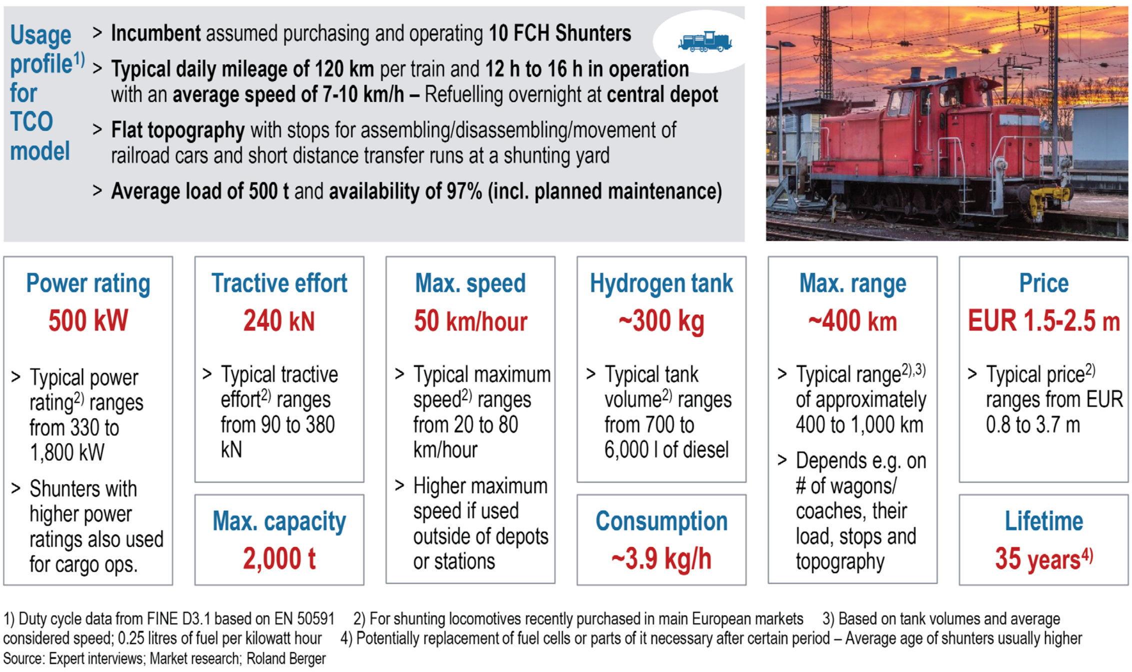


Figure 13: Use case – FCH Shunter

TCO ANALYSIS AND COMPARISON TO INCUMBENT TECHNOLOGY

Compared to a conventional diesel-powered Shunter, the FCH technology offers a potential for competitiveness if the technology is matured and favourable conditions can be achieved, i.e. low hydrogen cost and larger Shunter fleets supplied by a single hydrogen station. In the base case, the analysis suggests a higher TCO (+13%) for the FCH technology that is mainly driven by a difference in fuel (EUR 0.7 per kilometre) and infrastructure costs (EUR 1.2 per kilometre). The analysis is based on a diesel price of EUR 1.3 per litre, an electricity price of EUR 90 per MWh, and an energy consumption of 13 litre of diesel per hour and 3.9 kg H2 per hour respectively.

The illustration below indicates the detailed TCO in a base case in 2022 in comparison with conventional diesel.

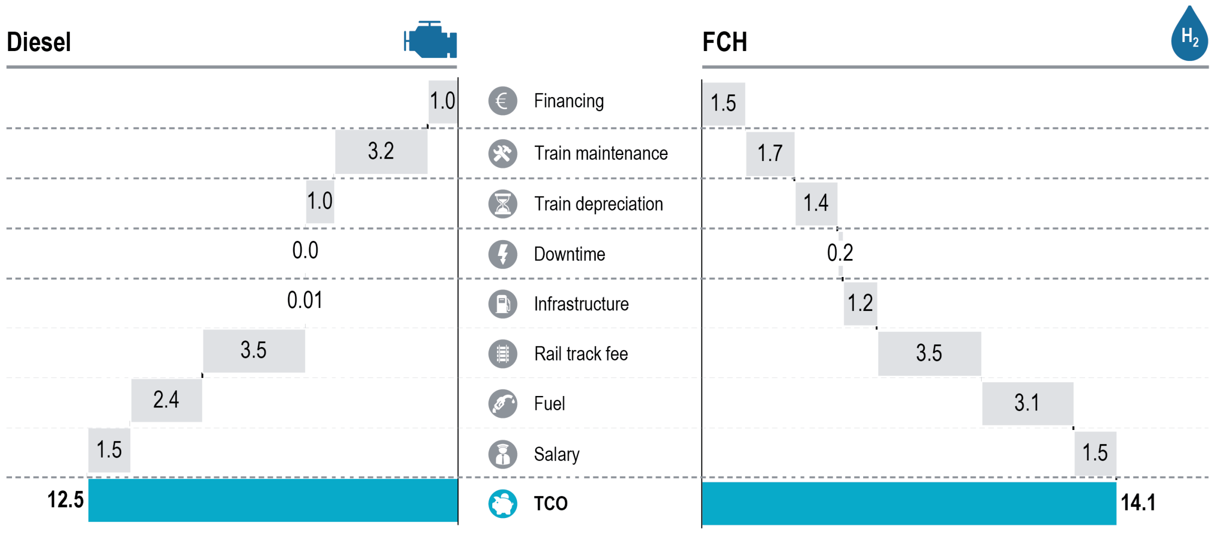


Figure 14: Detailed TCO – Shunter in base case [EUR/km]

Currently, the case is based on desktop study parameters that have been provided by industry stakeholders. These first assumptions need to be validated and ideally benchmarked with similar developments from other train OEMs. In order for the TCO to become competitive, the fuel costs can potentially be reduced if a low-cost hydrogen source is available at a specific location or if low electricity prices can be obtained for on-site production of hydrogen via electrolysis (base case: electricity price at 90 per MWh). The infrastructure cost difference is mainly based on low costs of the required diesel infrastructure and a need to set up new infrastructure for hydrogen production and refuelling.

SUITABILITY OF FCH TECHNOLOGY FOR THE APPLICATION

The FCH technology can become commercially competitive in the use case for Shunters under favourable economic conditions. However, if the assumptions cannot be realised, the cost premium might reach up to EUR 1.6 per kilometre (13%) for a FCH Shunter over a conventional diesel train. Generally, the mode of operation of Shunters at a single depot suggests a favourable case in combination with a single refuelling station supplying a fleet of 10 shunting trains. More clarity is necessary on the operational performance (e.g. hourly consumption) and actual daily operation (e.g. idle times, driving times) of Shunter fleets to confirm the TCO results. A detailed case study and the experience of the performance in practice with a prototype for a specific shunting yard is necessary to verify the first results of a generic business case for FCH Shunters.

3.1.3. MAINLINE LOCOMOTIVES

USE CASE

The use case scenario chosen for the TCO analysis of Mainline Freight Locomotives assumes deployment of 7 FCH trains by a large incumbent. Additional technical parameters for the use case are presented in the illustration below.

Usage profile[1] for TCO model

- > Only **cargo** operations – **Large incumbent** assumed purchasing and operating **7 FCH Mainline Locomotives**
- > **Typical daily mileage of 1,000 km** per train and **5 h to 10 h in operation –** Refuelling overnight at one of four **central depots**
- > **Flat topography** with about **one stop per hour** and **one stop per 100 km**
- > **Average load of 1,600 t** and **availability of 97% (incl. planned maintenance)**

Power rating
2,200 kW
- > Typical power rating[2] ranges from 1,600 to 3,200 kW
- > Dedicated freight locomotives with higher kW (and kN)

Tractive effort
300 kN
- > Typical tractive effort[2] ranges from 200 to 540 kN

Max. capacity
5,000 t

Max. speed
120 km/hour
- > Typical maximum speed[2] ranges from 100 to 160 km/hour
- > Higher speed for passenger/ mixed operations

Hydrogen tank
~1,000 kg
- > Typical tank volume[2] ranges from 3,500 to 7,000 l of diesel

Consumption
~0.9 kg/km

Max. range
~1,100 km
- > Typical range[2),3)] of approximately 500 to 1,100 km
- > Depends e.g. on # of wagons/ coaches, their load, stops and topography

Price
EUR 3.5-5.5 m
- > Typical price[2] ranges from EUR 1.4 to 5.5 m

Lifetime
30 years[4)]

1) Duty cycle data from FINE D3.1 based on EN 50591 2) For diesel locomotives recently purchased in main European markets 3) Based on tank volumes and average considered speed; 0.25 liters of fuel per kilowatt hour 4) Potentially replacement of fuel cells or parts of it necessary after certain period
Source: Expert interviews; Market research; Roland Berger

Figure 15: Use case – FCH Mainline Freight Locomotive

TCO ANALYSIS AND COMPARISON TO INCUMBENT TECHNOLOGY

Compared to a conventional diesel train, the FCH technology shows a higher TCO (14%). The TCO cost premium of a FCH locomotive over a conventional diesel locomotive reaches up to EUR 1.5 per kilometre (6%). The results are based on the assumptions related to the main TCO drivers such as the diesel consumption (3.4 litre of diesel per kilometre), the hydrogen consumption (0.9 kilogram of H2 per kilometre), the electricity price (EUR 90 per MWh), the diesel price (EUR 1.3 per litre of diesel) and FCH Mainline Locomotive purchasing cost (EUR 5.4 m per unit).

The illustration below indicates the detailed TCO in the base case in 2022 in comparison with conventional diesel.

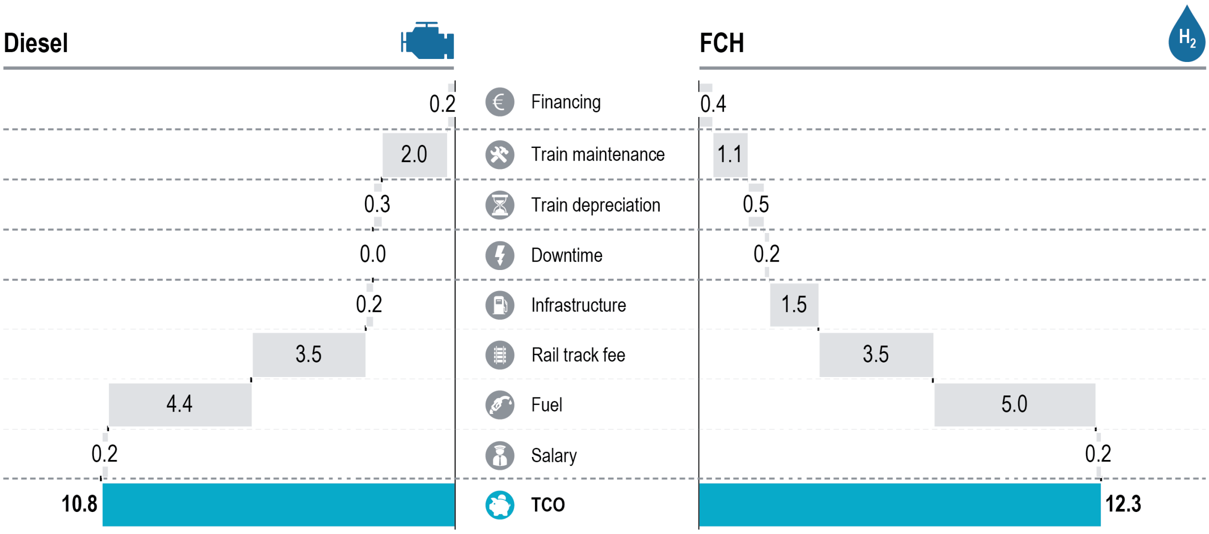


Figure 16: Detailed TCO – Locomotive in base case [EUR/km]

SUITABILITY OF FCH TECHNOLOGY FOR THE APPLICATION

The 14% TCO difference is mainly driven by the fuel and infrastructure costs. However, it is important to note that no prototypes have been tested in practice yet which makes the assumptions taken for the use case vaguer. Furthermore, the refuelling infrastructure assumptions could be optimised further if more information on the actual refuelling pattern of Mainline Locomotives had been available for the analysis. Currently, a conservative assumption of two 3,000 kilogram hydrogen stations at each Mainline Hub has been taken. These stations can provide a sufficient amount of fuel for the trains (~6,000 kilogram of H2 daily). Therefore, concept development should be undertaken for different options of trains to better understand the performance requirements (and cost) of the technology and, for example, how hydrogen will be stored on board of the train (e.g. with 350 bar, 700 bar or liquid hydrogen). Based on more detailed concepts the TCO assessment should be revisited to draw detailed conclusions on the suitability of FCH technology for the Mainline Locomotive application.

3.1.4. LEVERS FOR A MORE ATTRACTIVE BUSINESS CASE

In order to illustrate the influence of varying assumptions on the business case, this chapter specifies TCO sensitivities in more detail. The analysis is based on the Multiple Units application as it is the most mature application analysed. In the base case, FCH Multiple Units have a TCO disadvantage compared with diesel-powered trains whereas a competitive advantage exists versus the catenary electrification. This competitive advantage, however, is strongly related to the assumed track length that needs to be electrified.

The sensitivity analysis identifies the percentage change in crucial TCO parameters, which is necessary to reach competitiveness of the FCH Multiple Units with the compared alternative powertrain options. Competitiveness can either be achieved by a decrease in the TCO of the FCH Multiple Unit or by an increase in the TCO of the alternatives. In order to assess the impact of different parameters, individual parameter data points have been optimised while all other parameters were kept constant. Additionally, an optimistic case is determined on the basis that multiple parameters are changed.

The key parameters for the TCO include fuel consumption, energy and fuel price as well as CAPEX for the FCH train. The illustration below presents the overall results of the sensitivity analysis. It includes the key determinants of the business case, required percentage change for each parameter (independently of other parameters) to arrive at a competitive TCO figure and the resulting effect on the TCO of the technologies being compared.

Key levers	Required % change to reach par with diesel	Required absolute change to reach par with diesel
Decrease in hydrogen consumption	- 37.8%	- 0.1 kg H_2/km
Increase in diesel cost	+ 29.8%	+ EUR 0.35 per l
Decrease in electricity price	- 37.8%	- EUR 0.03 per kWh
Decrease in FCH train purchasing cost	- 32.1%	- EUR 1.8 m

Figure 17: Use case – FCH Mainline Freight Locomotive

The hydrogen consumption has a high impact on potential competitiveness of the FCH technology. A reduction in hydrogen consumption by 37.8% would result in the TCO of the FCH Multiple Unit being comparable with diesel. Consumption reduction by every 0.01 kg of hydrogen per kilometre results in a TCO reduction by approximately EUR 0.06 per kilometre. Furthermore, fuel and energy prices are decisive for competitiveness of the FCH technology – however, there are strong regional differences that are taken into account in the case study analysis in Phase 2 of this project. Hence, competitiveness of FCH trains is achievable if the diesel price increases by 29.8%. An increase by 0.02 EUR per litre of diesel results in a TCO increase by roughly EUR 0.04 per kilometre for diesel-powered trains. Furthermore, competitiveness with the diesel technology can be achieved given a 37.8% reduction of electricity cost. A reduction in the electricity price by every EUR 0.01 per kWh results in FCH TCO decrease by up to EUR 0.17 per kilometre. The purchasing cost of a FCH Multiple Unit is another determinant of the TCO – cost competitiveness with diesel is achieved through train CAPEX reduction by 32.1%. Overall, a reduction in the FCH train purchasing cost by every EUR 0.1 m results in a FCH train TCO decrease by around EUR 0.03 per kilometre. Another relevant TCO parameter is the hydrogen infrastructure (i.e. production and refuelling) CAPEX.

The TCO sensitivity on the hydrogen infrastructure cost will strongly depend on fleet size and depot structure – however, in the current base case (EUR 8.7 m for a 3,000 kilogram HRS and EUR 9.6 m for a 3,000 kilogram H2 production facility) this parameter cannot be reduced sufficiently to achieve competitiveness of the FCH train alone. However, cost reduction in this area will contribute positively to reduce the TCO for FCH trains (e.g. a EUR 0.03 per kilometre reduction in the TCO if fully eliminating CAPEX of the HRS). Some of the more favourable conditions (e.g. low electricity prices) could potentially already be achieved today in markets like Norway or Sweden.

Besides the comparison to diesel-powered trains, an analysis comparing with catenary electrification has been undertaken. In the chosen use case, FCH trains are already competitive from a TCO perspective. The main parameters that influence these results are presented in the table below to indicate under which circumstances FCH trains would lose their competitive advantage.

Key levers	Required change to reach par with catenary
Decrease in route length	- 9.5 km
Increase in annual mileage	+ 36,000 km
Decrease in catenary-electrified train purchasing price	- 25.6%

Figure 18: TCO sensitivity analysis – FCH Multiple Unit in base case versus catenary electrification

The competitiveness of the FCH technology in comparison with catenary electrification can be lost with a 9.5 kilometre decrease in the route length from 100 down to 90.5 kilometres. This is due to the high costs of the catenary electrification of about EUR 1.0 m per kilometre. The assumed 100 kilometres route provides for a TCO advantage for the FCH train in the base case. The catenary electrification solution becomes competitive at shorter routes. For every 10 kilometres that do not have to be electrified the catenary-electrified train TCO decreases by EUR 0.3 per kilometre. Thus, the catenary electrification could be the preferred choice for shorter routes of up to 90 kilometres under chosen TCO scenario assumptions.

In order to provide additional insights into the sensitivities of the TCO calculation, the following optimistic case has been analysed. By reducing the electricity price down to EUR 60 per MWh, increasing the diesel price to EUR 1.35 per litre and decreasing hydrogen consumption down to 0.25 kg per kilometre the following results can be achieved (based on 2022 values).

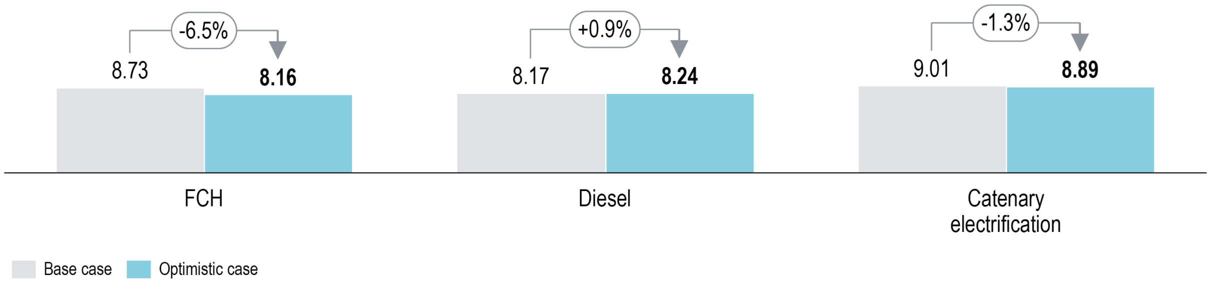


Figure 19: Detailed TCO – Multiple Units in optimistic case [EUR/km]

Based on these parameters the FCH Multiple Unit is the least costly option against all alternatives. It is important to note that these economic conditions can already be achieved today in some locations in Europe, e.g. in Scandinavia, where low cost electricity can be purchased to power the on-site electrolysis

As an additional option to on-site production of hydrogen via electrolysis, the sensitivity from using trucked-in hydrogen has been analysed as an alternative solutions. The illustration below presents the results of the sensitivity modelling on the basis of the hydrogen being purchased externally and delivered by truck to the station.

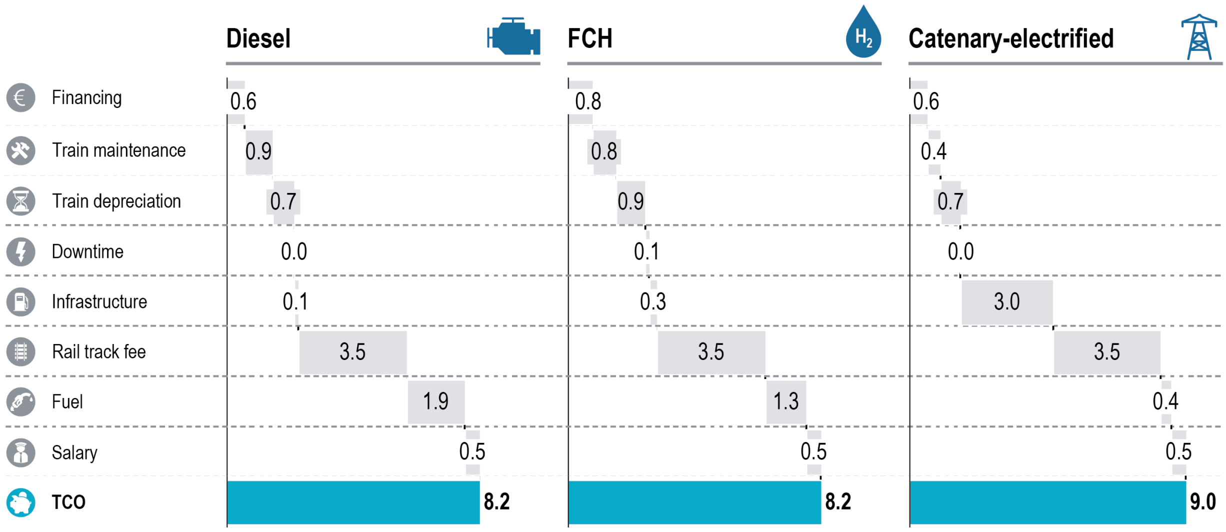


Figure 20: Detailed TCO – Multiple Unit in base case with H2 being purchased externally [EUR/km]

When the results are calculated with a hydrogen price of EUR 5 per kilogram, the FCH Multiple Unit becomes competitive with both alternative technologies. The TCO are at par with a diesel combustion engine and a competitive advantage of EUR 0.83 per kilometre over a catenary-electrified Multiple Unit results. The lower infrastructure costs (as there is no need to set up an on-site H2 production facility) and low fuel costs have positive impact on the TCO results. However, the latter factor significantly depends on the local market conditions and the ability of the rail operators to buy hydrogen from suppliers cheaply.

The TCO of FCH trains has the potential to be reduced considerably with more favourable framework conditions as well as progress in technology and cost development. However, specific local circumstances could lead to a higher TCO for FCH Multiple Units especially when hydrogen or energy in general has to be purchased at a high cost. In these cases the fuel economy of the train and a lower purchasing price of assets can mitigate higher energy sourcing cost. Additionally, favourable framework conditions such as supporting regulations and political support could enable the competitiveness of FCH trains.

In Phase 2 the study will therefore analyse different use cases in detail based on location specific data (e.g. routes, topography, stops along the route, etc.), potentially adjusted technical designs and actual operational requirements.

3.2. MARKET POTENTIAL FOR HYDROGEN TRAINS IN EUROPE

An estimation of the overall market potential[2] for FCH trains in Europe is crucial for providing technology developers and other stakeholders a basis for decision-making. Technology developers obtain an orientation for the interest in the FCH technology in the rail segment which is the basis to take decisions on new product development and investments. For decision makers it provides insights into the relevance of a technology solution for achieving political goals, in particular continued emission reduction in rail transportation (i.e. CO_2, NO_x, particulates).

3.2.1. OVERALL MARKET POTENTIAL IN THE EU – OVERVIEW AND SUMMARY

The market potential for FCH trains in Europe was analysed in a low, base and high scenario. See chapter 3.2.5 for the methodology applied.

In the base scenario, FCH trains are expected to take a combined market share of 20% from diesel-powered trains in all the considered rail application areas, i.e. Multiple Units, Shunters and Mainline Locomotives in 2030. The market uptake for Multiple Units starts as of 2021 with 30 SU. This is in line with the announced market introduction of FCH train products which already received approval for passenger transport in some markets. This development will be followed in the Shunter and Mainline Locomotive segment with delay in year 2023 as the market introduction of FCH train products is not yet announced (interviewed stakeholders suggested a five year development period before market introduction)[3]. Under the assumption that the product development could start immediately, a market uptake with at least two years delay is likely.

In the base scenario, Multiple Units are the largest segment (2022-2024: 200 SU, 2028-2030: 308 SU), followed by Shunters (2022-2024: 5 SU, 2028-2030: 72 SU) and Mainline Locomotives (2022-2024: 4 SU, 2028-2030: 36 SU). This constitutes a market share of 30% for Multiple Units, 12% for Shunters and 8% for Mainline Locomotives of the overall purchasing volume potential in 2030 respectively.

In terms of the emission reduction potential, the accumulated 749 SU in the Multiple Unit segment (2019 – 2030) amount to an annual diesel savings potential of between 81.495.000 and 108.660.000 litres respectively[4] as of 2030. The related CO2 savings would therefore amount to between 229.000 and 305.000 tons of CO_2 annually. Consequently, FCH trains play a considerable role on the way towards an even more sustainable and cleaner railway sector.

---

[2]The market potential is provided in standard units (SU), where each Shunter and Locomotive is counted as a single unit and a Multiple Unit trainset is counted per train car (e.g. 2-car vs. 3-car train sets) in line with the UNIFE World Rail Market Study methodology to make the different Multiple Unit demand from different rail operators in their respective market comparable.

[3]Based on current available market information, it is not expected that established manufacturers plan to introduce an FCH Shunter to the market before 2023. Also, no start-ups appear to be working on products that could be introduced earlier than 2023.

[4]Based on 150.000 km to 200.000 km annual mileage and 1.45 litre diesel consumption per kilometre

All market uptake results are presented accumulatively for three year periods, e.g. 2022-2024, in order to level out annual peaks related to expected single large orders in one year.

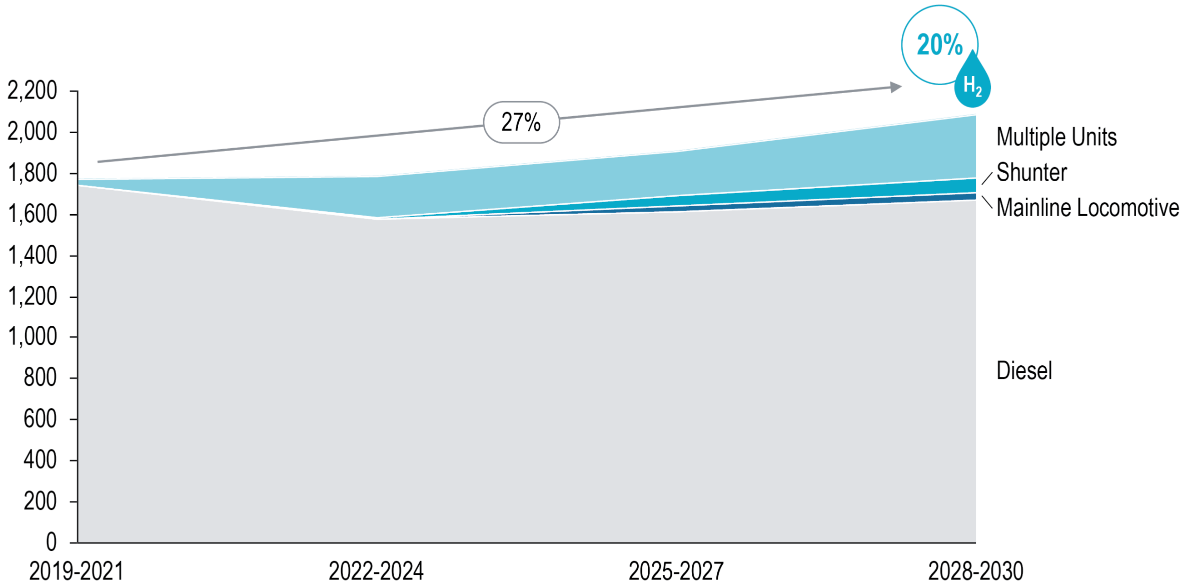


Figure 21: EU market potential FCH trains [base scenario in standard units]

The low and the high scenario provide a perspective on the market development if either FCH trains can or cannot become a competitive solution for diesel-powered trains or if the market conditions develop less or more favourably:

Low scenario: The estimation of the market potential for FCH rail application in the low scenario indicates a market potential of 127 SU 2022 – 2024 which grows by approximately 20% to 546 SU until 2028 – 2030. This comprises a share of 11% of the overall market potential.

High scenario: The estimation of the market potential for FCH rail application in the base scenario indicates a market potential of 313 SU in 2022 – 2024 which grows by approximately 36% to 1,753 SU until 2028 – 2030. This comprises a share of 41% of the overall market potential.

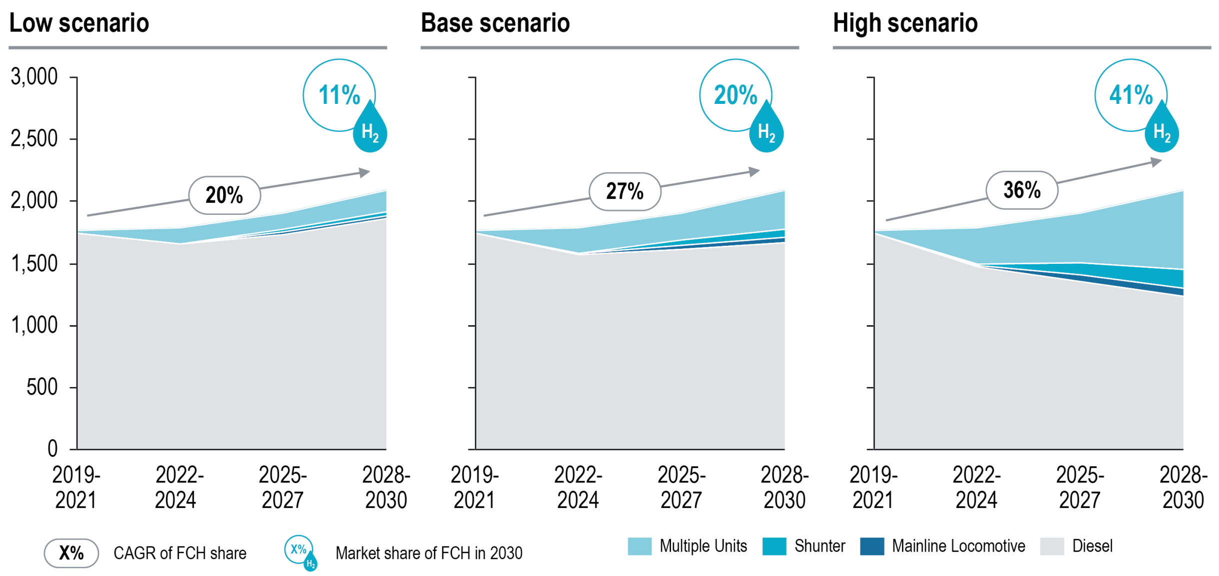


Figure 22: EU market potential for FCH trains – scenario comparison [standard units]

The chart above is based on the underlying SU values per application depicted below:

Low scenario	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	122	129	167	449
Shunters	0	3	25	36	63
Mainline Locomotives	0	2	14	18	34
Diesel	1,740	1,657	1,736	1,866	6,999

Base scenario	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	200	211	308	749
Shunters	0	5	49	72	127
Mainline Locomotives	0	4	28	36	68
Diesel	1,740	1,575	1,615	1,671	6,602

High scenario	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	294	399	640	1,363
Shunters	0	11	98	145	254
Mainline Locomotives	0	8	55	72	136
Diesel	1,740	1,471	1,350	1,231	5,793

Figure 23: EU market potential for FCH trains – detailed volumes [standard units]

3.2.2. MARKET POTENTIAL BY APPLICATION

The section below presents the market potential per application. All presented results reflect the base scenario.

MULTIPLE UNITS

The Multiple Units segment is the most mature segment for FCH technology as prototypes are already operational and approved for passenger services in e.g. Germany. This is why the market potential is higher overall than for the other applications. The market potential is estimated at 200 SU in 2022-2024 which grows to 308 SU until 2028-2030. This comprises a share of 25% and 30% of the overall market volume in this segment respectively.

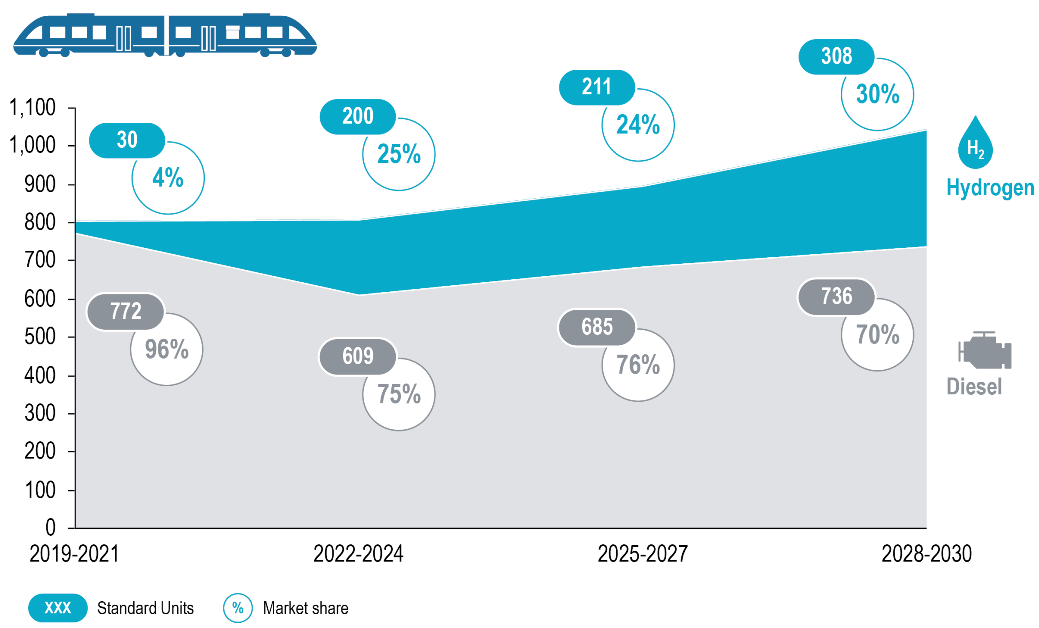


Figure 24: EU market potential FCH Multiple Units [base scenario in standard units]

The market demand is mainly driven by already available product prototypes and publicly communicated targets for market introduction. This became clear in interviews with rail operators and provided a good basis for estimating their potential for replacing existing diesel services in the respective markets. Additionally, limited alternative zero-emission technologies exist which increases the interest from rail operators across Europe. This is also supported by the often citied high costs for catenary electrification on tracks with a low utilisation.

SHUNTERS

In the Shunter segment the market potential is estimated at five SU in 2022-2024 which grows to 72 SU until 2028-2030. This comprises a share of 1% and 12% of the overall market volume in this segment respectively

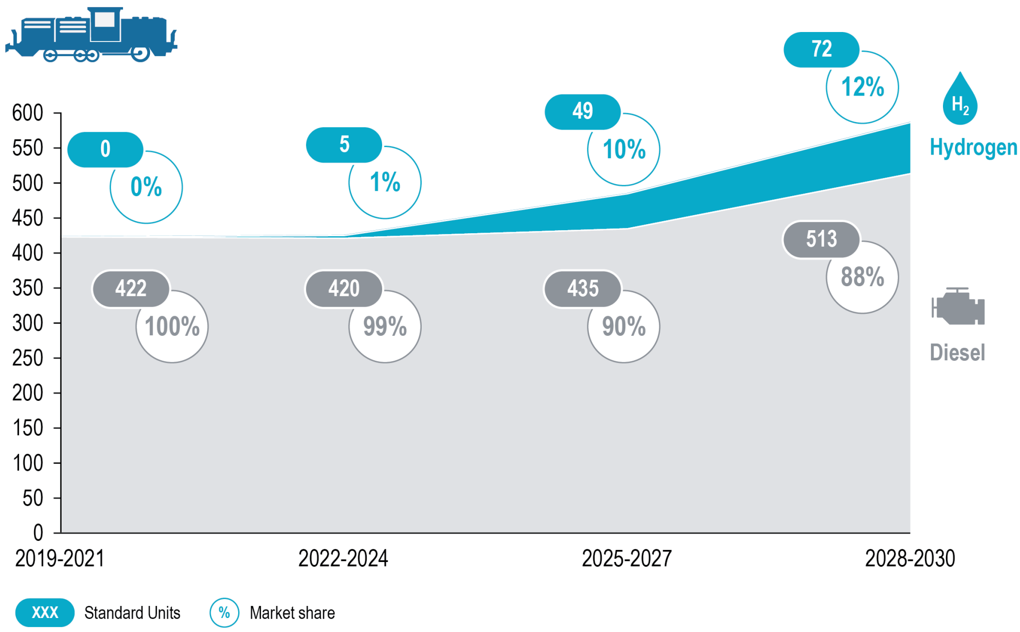


Figure 25: EU market potential FCH Shunters [base scenario in standard units]

The market demand for FCH Shunters is smaller in comparison to Multiple Units, mainly related to the early stage of the technology development as well as a lack of prototype testing and available products in Europe. While some rail operators indicated interest the lack of clear performance specification and evidence that the technology can fulfil the specific operation requirements prompted more conservative expectations on market potential. Also, other alternative technologies based on battery-hybrid and catenary-electrification products are expected to enter the market soon which reduced the interest in FCH Shunters for some rail operators.

MAINLINE LOCOMOTIVES

In the Mainline Locomotive segment the market potential is estimated at four SU in 2022-2024 which grows to 36 SU until 2028-2030. This comprises a share of 1% and 8% of the overall market volume in this segment respectively.

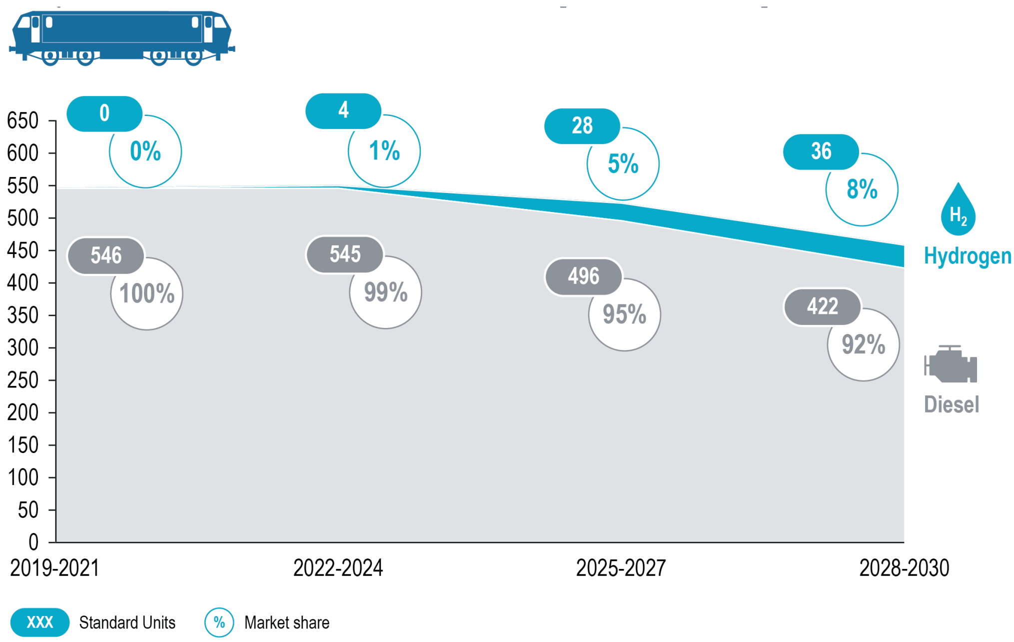


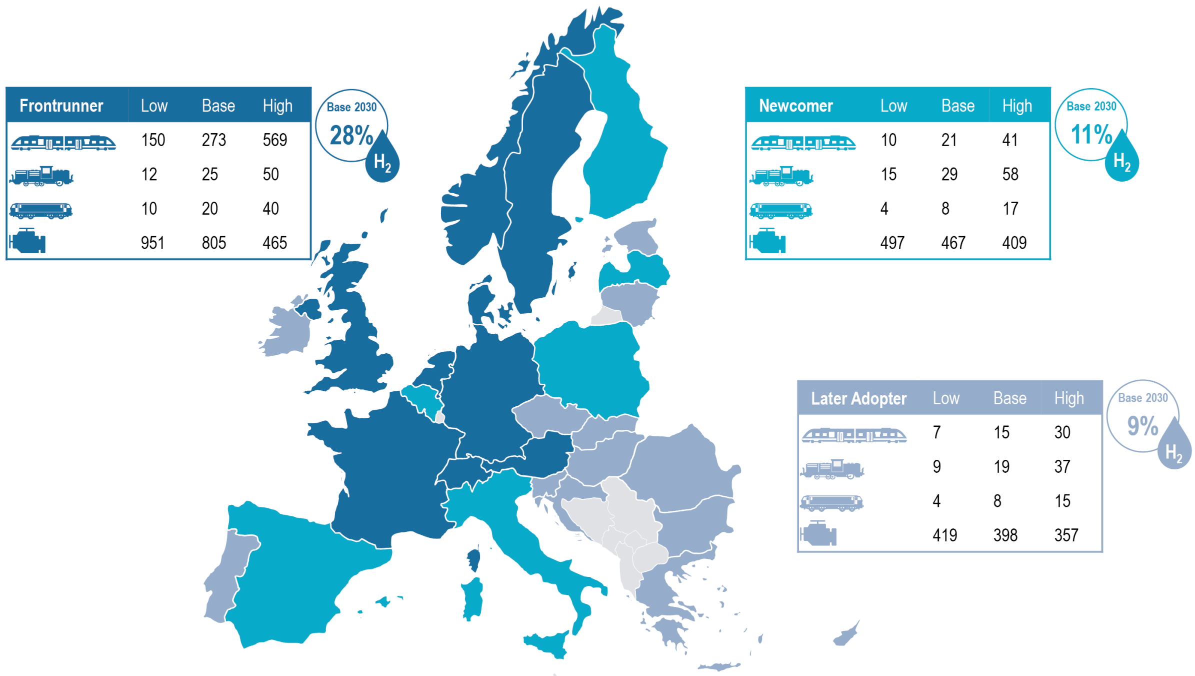
Figure 26: EU market potential FCH Mainline Locomotives [base scenario in standard units]

The market potential for Mainline Locomotives is smaller than for Multiple Units in general and will develop only with delay as no products are in development at the moment. Train OEMs cite the strong competition in the logistics sector as the main reason for lacking development as train logistics companies have to compete at cost against truck-based logistics. Furthermore, rail operators are still sceptical regarding the question whether the FCH technology can meet the performance and range requirements of their services.

3.2.3. MARKET POTENTIAL BY GEOGRAPHY

Besides the application-specific development of the market potential a geographical analysis was conducted. The European countries have been categorised in three main market groups in relation to their potential to deploy FCH trains in the future (see chapter 3.2.5 for more information on the methodology how the market potential was estimated). The three groups are: Frontrunner, Newcomer and Later Adopter markets. The map below provides an overview of these markets. It is important to note that each market group has a different likelihood of replacing diesel-powered trains with FCH trains. The three main input variables for estimating the market potential are (1) actual ongoing and planned FCH train purchases by rail operators, (2) substitution growth based market uptake of similar technologies and (3) an adjusted time line for market uptake based on FCH train product availability.

In addition to the relative market share of FCH trains, the absolute market potential for FCH trains in the respective markets will depend on the projected (diesel) purchasing volumes for these markets. For example, Switzerland has good framework conditions to introduce hydrogen trains but as the network is almost entirely electrified today, a very low number of diesel trains is projected to be purchased in this market and a switch from electrification to FCH is not considered likely at this point.



Frontrunner	Low	Base	High
	150	273	569
	12	25	50
	10	20	40
	951	805	465

Newcomer	Low	Base	High
	10	21	41
	15	29	58
	4	8	17
	497	467	409

Later Adopter	Low	Base	High
	7	15	30
	9	19	37
	4	8	15
	419	398	357

Figure 27: FCH train market categories including base scenario estimations for 2028 – 2030 [standard units]

The market potential for FCH trains in Frontrunner markets is highest (2022-2024: 193 SU, 2028-2030: 318 SU), followed by Newcomer markets (2022-2024: 11 SU, 2028-2030: 58 SU) and Later Adopter markets (2022-2024: 5 SU, 2028-2030: 41 SU). In Frontrunner markets the substitution of diesel trains is mainly driven by the Multiple Units segment where, firstly, high diesel purchasing volumes are projected, i.e., a high substation potential exists. Secondly, multiple rail operators already actively considering the deployment of FCH trains in a segment that is, thirdly, the most mature rail segment for FCH technology, i.e. market uptake can start as of 2021. FCH trains could reach a market share of purchasing volumes of 28% in the base case scenario by 2030. It is assumed that in 2020 273 Multiple Units, 25 Shunter and 20 Mainline Locomotives using FCH technology will be purchased in addition to 805 conventional diesel trains. This amounts to a number of 318 FCH trains out of 1,123 trains in total. In comparison to the Frontrunner markets, the overall volume and the Multiple Units share of projected purchases are lower in the Newcomer markets. These will influence the total amount of purchased FCH trains. The market share of the FCH train purchasing volumes could reach 11% in the base case scenario by 2030. In Later Adopter markets FCH trains could reach a market share of 9% in the base case scenario by 2030.

Based on the assessed framework of different geographical regions, detailed uptake figures per market and per scenario were calculated. The different uptake figures and rates are shown in Figure 28. Details and assumptions are provided chapter 3.2.5 in the Annex.

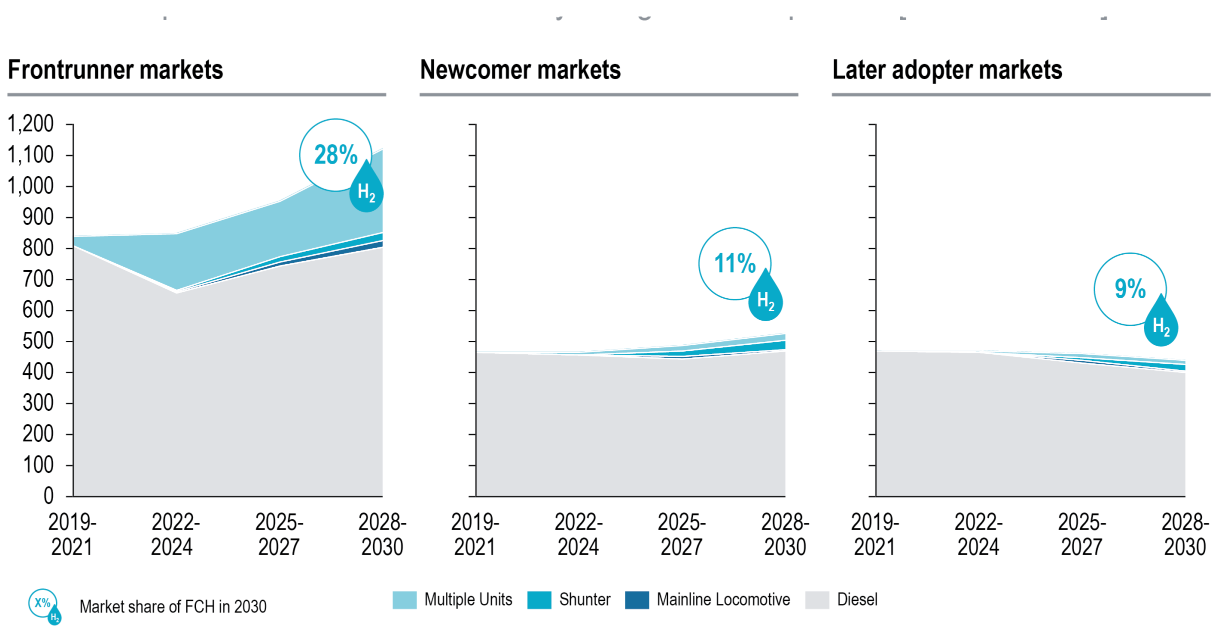


Figure 28: Market potential in Frontrunner, Newcomer and Later Adopter markets [base scenario in standard units]

3.2.4. PERSPECTIVES ON ADDITIONAL MARKET POTENTIAL

The analysis shows a good market potential for FCH trains, especially in the base and high scenario. However, the interviews with industrial stakeholders indicate four areas that directly influence the market potential for FCH trains. These areas need additional clarification in order to specify the market potential further in the next 2-3 years.

EXISTING GREEN IMAGE OF THE RAIL SEGMENT AND LACK OF AWARENESS FOR THE BUSINESS CASE OF FCH TRAINS

Around 80% of rail transportation in Europe today is already carried out with catenary electrification using increasing shares of renewable electricity for powering the trains. Hence, rail transport is already a comparably clean mode of transport. Therefore, rail operators in multiple markets focus their priority on either increasing the share of renewable electricity in their energy mix and/or increasing catenary electrification in close collaboration with the responsible infrastructure managers and political decision-makers. There needs to be an increasing awareness on the large part of rail operators regarding the business case for FCH trains, especially for the application of regional trains, which is less costly than electrification.

LONG LIFETIME OF DIESEL TRAINS AND SHORT-TERM PURCHASING DECISIONS

New diesel train units have a very long lifetime. Hence, purchasing decisions that will be taken in the next decade will determine the emissions for the next 30 to 40 years. Once these decisions are taken for diesel-powered trains, the emission reduction potential is lost and subsequently no contribution to achieve the EU's 80% emission reduction targets for 2050 materialises. In order to achieve a vast decarbonisation, all possible options in each sector have to be exploited where it can be done in a cost-efficient manner. The TCO analysis of chapter 3.1 suggests, that there is potential for FCH trains to achieve cost-efficient emission reduction if the technology is developed further.

ALTERNATIVES TO FCH TECHNOLOGY

Various options are being considered besides FCH trains, e.g. pure battery-powered trains with point charging, hybridised trains using a combination of batteries and pantograph electrification and diesel-battery combined trains have been mentioned amongst others. Most of these technologies are currently at a similar technology development as FCH trains, i.e. limited or no prototypes are available for actual testing on rail tracks. All train OEMs seem to investigate different concept options at the moment. This results in uncertainty for rail operators to assess whether they would use a specific technology option already today. The operators are awaiting results from performance tests. Experiences from the public bus transport segment have been cited where only insufficient availability figures have been achieved (i.e. 60%). This raises concerns with regards to alternative powertrains in the rail segment, especially if trains are at risk to break down on single track regional networks. While in public transport bus service stand-by buses can continue the service, this was not considered as an option for trains (e.g. large additional CAPEX, blocked rail tracks). Hence, technology tests for all alternatives including FCH solutions are required. With this information available, rail operators would have a higher confidence to project the market potential of alternative powertrain solutions and may signal an even more optimistic market potential (i.e. diesel substitution rates) if the performance can really match diesel-powered trains.

MARKET POTENTIAL FROM EXPORT OPPORTUNITIES TO OTHER GEOGRAPHIES

Further market potential is expected from export opportunities of FCH trains outside of Europe. In order to address these markets, train OEMs currently often work with platform strategies where single traction systems based on specific powertrain technology like FCH are standardised to fit onto regionally differentiated train stets. With this approach, synergies in powertrain development can be leveraged for global deployment. Today these opportunities occur mainly on a project by project level. Project opportunities in North America and South-East Asia have been cited as first potential regions for a developing market for FCH trains. Due to the early stage of the market introduction of first products in Europe, the start of homologation for other international markets has not been indicated yet.

Based on projected diesel train purchase volumes countries like Russia, Japan and India suggest a high substitution potential with FCH trains. For instance, the combined potential for Multiples Units from 2025 to 2027 in these three markets accounts for more than 600 SU. If the local framework conditions for a positive business case can be obtained, significant export market potential exists for train OEMs. When applying similar substitution rates as in the base scenario in Europe (30%), up to 200 SU could be purchased as FCH Multiple Units. This potential could provide a good opportunity for European OEMs as no market introduction from other international OEMs has been announced yet. Considering the lead time for the homologation of FCH trains towards the local technical standards and regulation, an uptake of market demand after 2025 is likely.

The above suggests that the actual potential for FCH solutions could be even higher. rail operators and train OEMs are just at the beginning of exploring alternative options. Due to the nature of the rail market with different operational requirements per country and per specific case (e.g. topography, frequency of service and stops, level of electrification and catenary electrification technology), the actual competitiveness of different technologies has to be assessed on a case by case basis in detail. Therefore, this study intends to investigate specific use cases in multiple case studies in a second phase with a focus on the use of FCH train technology. This is necessary to pinpoint the relevant drivers for decision making and showing opportunities (e.g. specific emission reduction potential), competitiveness of alternatives (e.g. catenary electrification) and potential hurdles (e.g. energy costs, required train performance) to derive learnings for the additional Research & Innovation (R&I) activities necessary to exploit the full emission reduction potential to achieve the EU 2050 targets.

3.2.5. METHODOLOGY FOR THE MARKET POTENTIAL ASSESSMENT

BASELINE MARKET VOLUME

In order to assess the market potential for FCH trains in the three analysed segments Multiple Units, Shunters and Mainline Locomotives, the annual projected diesel purchases were analysed first, before assessing a substitution volume with FCH trains.

The purchasing volumes have been derived from existing UNIFE World Rail Market Study projections and were extrapolated until 2030. The UNIFE study bases the underlying market development for diesel trains on the historic development of the overall rolling stock market in Europe. Furthermore, this is combined with the diesel fleet age and industry-validated market growth rates that provide the basis to assess the projected diesel train purchases.

Geographically, the analysis focused on current EU-28 countries (status 07/2018) and also considers Switzerland and Norway. The market volume is provided in standard units (SU) in line with the UNIFE methodology. Shunters and Locomotives are each counted as a single unit and a Multiple Unit trainset is counted per train car (e.g. two for 2-car trainsets, three for 3-car trainsets, etc.) to make the various Multiple Unit products and demand from different rail operators comparable.

It is important to note that the overall market demand for rolling stock was assumed to stay in line with the UNIFE projections for the analysis with and without FCH trains as no additional market demand is expected from introducing FCH technologies.

MARKET POTENTIAL FOR FCH RAIL APPLICATIONS

With the baseline market volume for diesel purchases by application as a starting point, the market potential for FCH trains has been analysed for three scenarios (low/base/high) that were developed in three steps based on the following methodology:

- **Step 1:**

As a start the countries where categorized based on a multi-dimensional assessment framework to differentiate their potential to adapt FCH technology. The assessment considered existing and planned FCH train activities, stakeholder and budget support for zero-emission technologies, the level of ongoing national hydrogen activities in other commercial areas and political emission reduction targets in transport. By using this framework, the countries were divided into three groups: Frontrunner (e.g. France, Germany, UK), Newcomer (e.g. Italy, Spain) and Later Adopter (e.g. Czech Republic, Ireland, Portugal) markets. Frontrunner markets are characterised by ongoing FCH rail projects, defined budget and available stakeholder support, extensive existing experience with FCH technology in adjacent sectors (e.g. FCH buses) and visible political support to phase out diesel technology in transport. Newcomer markets plan FCH rail projects, have smaller budgets or less stakeholder support and can draw some experience from existing FCH projects in adjacent market segments. They have general political support for emission reduction. Later Adopters have no or limited experience with FCH technology and currently focus their emission reduction agenda on other sectors. For instance, they focus on renewable electricity generation instead of reducing emissions in the rail segment.

- **Step 2:**

For each country, different substitution rates for diesel train purchases (sales potential) have been derived. These are based on actual industry projections and past and current public tenders for FCH trains. Furthermore, substitution rates based on industry and rail expert interviews as well as similar substitution rates of alternative powertrains in adjacent transportation segments (e.g. the car market) were applied. In addition to higher or lower diesel substitution rates per country group, a later start of the market uptake has been assumed for Newcomer (one year later than Frontrunner markets) and Later Adopter markets (two years later than Frontrunner markets).

- **Step 3:**

Finally, the market potential was analysed in a low, base and high substitution scenario. The low scenario assumes a lack of TCO competitiveness against alternatives, limited public budget and support as well as low fossil fuel prices. The medium scenario assumes TCO at par, maintained current public budgets and support as well as stable fossil fuel prices. For example, the TCO analysis for Multiple Units of chapter 3.1.1 suggests that the TCO can be at par if the diesel price is at EUR 1.22 per litre and the electricity price is EUR 60 per MWh without further cost reduction for FCH train and FCH refuelling infrastructure (based on assumptions for 2018). In the high scenario, the FCH train TCO is lower than for its alternatives and diesel prices would increase to reduce competitiveness of diesel-powered trains even further. A stricter regulatory framework that would enforce a switch to diesel alternatives has not been considered for the scenarios.

The results of the analysis described above are presented in chapters 3.2.1 to 3.2.4. and are in line with the market expectation of multiple rail operators across Europe for the three market groups.

ANNEX 1: LITERATURE LIST AND EXISTING STUDIES

Name of the study	Publisher	Geographical focus	Published in (year)
1. Fuel cells market – forecasts from 2018 to 2023	Knowledge Sourcing Intelligence LLP	Worldwide	2018
2. Global fuel cells industry	n/a	Worldwide	2018
3. Hydrogen fuel cell vehicle market – Global opportunity analysis and industry forecast, 2017-2023	Allied Market Research	Worldwide	2018
4. Regional express rail program Hydrail feasibility study report	Metrolinx	Canada	2018
5. Comparison of daily operation strategies for a fuel cell/battery tram	Tsinghua University, Beijing	Worldwide	2017
6. Energy performance of a fuel cell hybrid system for rail vehicle propulsion	University of Calabria, Italy	Italy	2017

7. Evaluation of fuel cell train mass increase depending on conditions of line alignments	IEEE	Worldwide	2017
8. Hydrogen scaling up – A sustainable pathway for the global energy transition	Hydrogen Council	Worldwide	2017
9. Shell hydrogen study – Energy of the future?	Shell Deutschland Oil GmbH, Wuppertal Institut	Worldwide	2017
10. Analysis of alternative modes of operation for non-electrified lines	SINTEF	Norway	2016
11. FCEMU project – Phase 1 report – Issue 1	University of Birmingham, Hitachi Rail, Fuel Cell Systems Limited	UK	2016
12. Fuel cell technologies – Market report 2016	US Department of Energy	Worldwide	2016
13. Wasserstoff-Infrastruktur für die Schiene – Studie – Ergebnisbericht / Hydrogen railway infrastructure – Study – Results report	Federal Ministry of Transport and Digital Infrastructure (BMVI), NOW GmbH	Germany	2016
14. Future of Rail 2050	ARUP	Worldwide	2014
15. System integration of China's first proton exchange membrane fuel cell locomotive	International Journal of Hydrogen Energy	China	2014

16. Well-to-wheel analysis for electric, diesel and hydrogen traction for railways	Elsevier	Worldwide	2012
17. Rail transportation by hydrogen vs. electrification – Case study for Ontario Canada, I: Propulsion and storage	International Journal of Hydrogen Energy	Canada	2010
18. Rail transportation by hydrogen vs. electrification – Case study for Ontario, Canada, II: Energy supply and distribution	International Journal of Hydrogen Energy	Canada	2010
19. Review and assessment of hydrogen propelled railway vehicles	IET	Worldwide	2010
20. Fuel cells could power a streetcar revival	IEEE Spectrum	USA	2009
21. Hydrogen Fuel Cell trial (T722)	Rail Safety & Standards Board	UK	2009
22. Review of potential rail vehicle fuels and 'energy carriers'(T721)	Rail Safety & Standards Board	UK	2008
23. Feasibility study into the use of hydrogen fuel: Final report (T531 Report)	Rail Safety & Standards Board	UK	2005

ANNEX 2: MARKET POTENTIAL – DETAILED VOLUMES

FRONTRUNNER, NEWCOMER AND LATER ADOPTER MARKETS [STANDARD UNITS]

Low Scenario					
Frontrunner					
	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	114	113	150	406
Shunters	0	3	9	12	24
Mainline Locomotives	0	2	7	10	19
Diesel	809	730	823	951	3,312
Newcomer					
	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	5	9	10	24
Shunters	0	0	10	15	25
Mainline Locomotives	0	0	4	4	8
Diesel	463	460	466	497	1,886
Later Adopter					
	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	3	8	7	18
Shunters	0	0	5	9	14
Mainline Locomotives	0	0	3	4	7
Diesel	468	467	447	419	1,801

Base Scenario

Frontrunner

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	184	178	273	664
Shunters	0	5	19	25	49
Mainline Locomotives	0	4	14	20	38
Diesel	809	655	741	805	3,011

Newcomer

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	11	17	21	49
Shunters	0	0	21	29	50
Mainline Locomotives	0	0	8	8	16
Diesel	463	455	443	467	1,828

Later Adopter

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	5	16	15	36
Shunters	0	0	10	19	28
Mainline Locomotives	0	0	6	8	13
Diesel	468	465	431	398	1,762

High Scenario

Frontrunner

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	30	261	333	569	1,193
Shunters	0	11	37	50	97
Mainline Locomotives	0	8	28	40	76
Diesel	809	568	554	465	2,396

Newcomer

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	22	35	41	98
Shunters	0	0	42	58	100
Mainline Locomotives	0	0	15	17	32
Diesel	463	444	396	409	1,713

Later Adopter

	2019-2021	2022-2024	2025-2027	2028-2030	Total
Multiple Units	0	11	32	30	73
Shunters	0	0	19	37	56
Mainline Locomotives	0	0	12	15	27
Diesel	468	459	400	357	1,684

Document Overview

"Study on the use of fuel cells & hydrogen in the railway environment"

The study is commissioned by the Shift2Rail Joint Undertaking and the Fuel Cells and Hydrogen 2 Joint Undertaking. It consists of three reports and a Final Study:

Final Study: *"Study on the use of fuel cells & hydrogen in the railway environment"*

The Final Study summarizes the main conclusions, results and recommendations from Report 1, 2 and 3. It provides a market overview and show the significant market potential of FCH trains in Europe and shows how the three analysed applications Multiple Units, Shunters and Mainline Locomotives perform in different case studies. It concludes with recommendations on short-term R&I needs derived from the analysis of technological and non-technological barriers that prevent a successful market entry of FCH technology in the rail sector. Please click here for the full report.

Report 1: *"State of the art & Business case and market potential"*

Report 2: *"Analysis of boundary conditions for potential hydrogen rail applications of selected case studies in Europe"*

The report evaluates the economic potential of fuel cell and hydrogen technologies in the EU rail sector based on ten case studies covering the three focus applications Multiple Units, Shunters and Mainline Locomotives, in nine European countries. The analysis demonstrates that the FCH technology can be economically and environmentally competitive with other powertrain technologies in the rail sector. Additionally, a set of focus topics is provided to introduce key success factors for a successful implementation of the FCH technology in the rail industry.

Report 3: *"Overcoming technological and non-technological barriers to widespread use of FCH in rail applications – Recommendations on future R&I"*

The report analyses technological and non-technological barriers that hinder the mass market introduction of the FCH technology in the rail sector. 31 barriers (21 technological and 10 non-technological) are identified, described in detail and prioritised according to their impact on and importance for FCH technology application in the rail sector. The report provides recommendations on three R&I projects to address the identified barriers and realise further optimisation.

All reports are available in electronic format on the FCH JU and Shift2Rail JU websites.

Access to reports via FCH JU

bit.ly/HydrogenTrainFCH

Access to reports via S2R JU

bit.ly/HydrogenTrainS2R