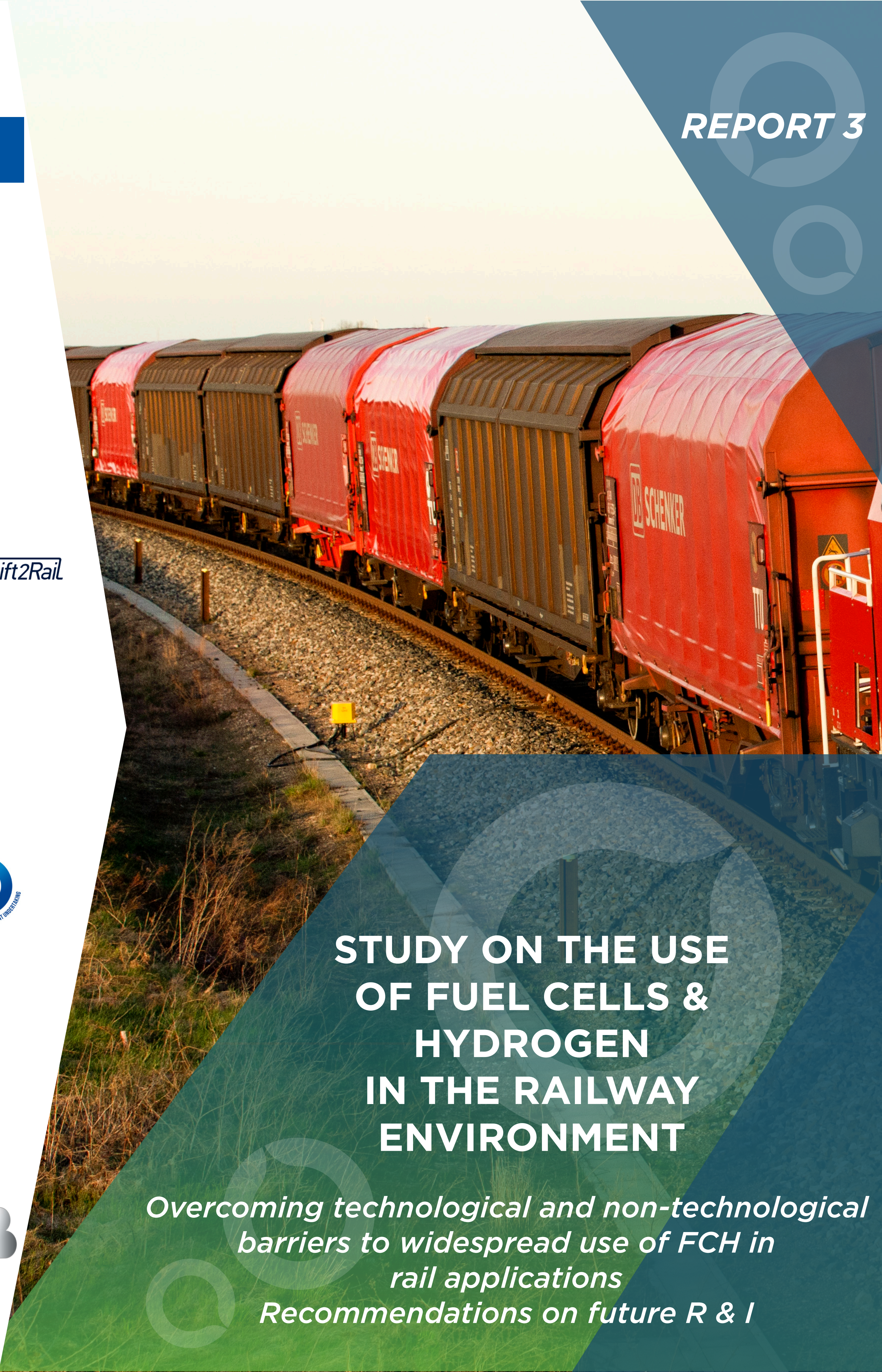
REPORT 3



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

Overcoming technological and non-technological barriers to widespread use of FCH in rail applications

Recommendations on future R & I

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

REPORT 3

Overcoming technological and non-technological barriers to widespread use of FCH in rail applications
Recommendations on future R & I

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)

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF ABBREVIATIONS

FC	Fuel Cells
FCH	Fuel Cells and Hydrogen
FCH2JU	Fuel Cells and Hydrogen Joint Undertaking
H2	Hydrogen
HRS	Hydrogen Refuelling Station
MU	Multiple Units
OEM	Original Equipment Manufacturer
R&I	Research and Innovation
S2R JU	Shift2Rail Joint Undertaking
TCO	Total Cost of Ownership

ABSTRACT

Fuel cell and hydrogen (FCH) technology is a promising option for replacing 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 to the use of FCH technology in different rail applications.

This third report covers Task 4 in Phase 2 of the study and the results from the analysis of overcoming technological and non-technological barriers to widespread use of FCH in rail applications.

The analysis has identified 31 barriers; however, no fundamental show-stoppers exist for FCH technology in rail. The main barriers constitute an optimisation potential that could ease the commercial deployment of the technology. To accelerate the usage of FCH trains and increase the competitiveness of the technology, the barriers can be lifted with future R&I. For steering future R&I needs, the identified barriers have been prioritised and concrete recommendations on future R&I projects are provided. One demonstration project and two technology development projects are recommended in the short term to enable broader commercial adoption of FCH trains.

EXECUTIVE SUMMARY

FCH technology is one of the major zero-emission alternatives for powering transport. FCH transport solutions have been brought to the brink of commercialisation in recent years. Many FCH buses and cars are in operation in Europe, and the hydrogen refuelling infrastructure network is growing steadily. Also, in the railway environment, hydrogen is a suitable environment-friendly energy carrier which can replace diesel where track electrification is not economically feasible. Several trials and pilot projects worldwide have successfully shown the adaptability of the FCH technology to the rail sector across various applications ranging from regional passenger trains, trams and trolley buses to mining locomotives.[1] However, currently only a few projects focus on deploying the FCH technology in the rail environment. The S2R Joint Undertaking and FCH 2 Joint Undertaking 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.

There is a significant potential for the replacement of diesel-powered engines in the three focus applications: Multiple Units, Shunters and Mainline Locomotives. From a business case point of view, the FCH technology has the potential to become cost competitive with incumbent alternatives.[2] Nevertheless, as with all new technologies challenging a proven technology, for successful FCH implementation in rail applications, there are various barriers, technological and non-technological, that need to be addressed. The analysis identified 31 barriers, 21 technological and 10 non-technological. The barriers range from very specific barriers for single rail application (e.g. H2 storage solutions for Mainline Locomotives) to barriers affecting all rail applications (e.g. optimisation potential for fuel cell stack operating hours).

The barriers need to be addressed in a joint effort of all involved parties: the FCH industry, rail OEMs, rail operators and public stakeholders. However, no barriers have been identified that would prevent the FCH technology from being used in the railway environment. In order to provide recommendations on future R&I needs, the barriers have been prioritised, e.g. by geographical relevance or urgency for market introduction. Three barriers have been categorised as high priority, needing to be addressed short term, 15 as medium priority and 13 as low priority.

---

[1] For further details please refer to: Report 1
[2] For further details please refer to: Report 1 and Report 2

The report suggests three specific R&I topics designed to foster faster deployment of the FCH technology in the rail sector. The suggested R&I topics addressing the three high priority barriers should be conducted in the short term:

- Large-scale demonstration of Multiple Unit train fleets
- Development, engineering and prototype operation of Shunters or Mainline Locomotives
- Technology development for optimised hydrogen storage system for FCH rail applications

In the rail sector, there is a focus on reliability and predictability for operations with long lasting impact of investment decisions (e.g. 30 years for trains). Therefore, it will be important to address the identified barriers with dedicated R&I projects in a timely manner. As some barriers affect the implementation of the FCH technology in all transport applications, joint R&I projects should be conducted to ensure synergies.

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, 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, to apply the hydrogen and fuel cell technology successfully in the rail sector preparing a commercial roll-out on a larger scale, several technological and non-technological barriers have still to be overcome. To achieve this goal, targeted research and innovation (R&I) investments from the rail and rail supplier industry will be required. 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 have shown interest in the potential of fuel cell and hydrogen technologies for trains. The S2R Joint Undertaking and FCH 2 Joint Undertaking have commissioned this study to generate a fact base. 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;
- Development, engineering and prototype operation of Shunters or Mainline Locomotives;
- 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. Three rail applications are the focus of the study: Multiple Units, Shunters and Mainline Locomotives.

This document is the third report of the study. It analyses technological barriers that need to be addressed through R&I projects and non-technological barriers such as regulations and standards that should be considered before the fuel cell technology can be applied to the rail sector. Results are based on data from the industry stakeholders, industry and research expert interviews as well as extensive desk research. To overcome identified barriers and ensure the successful implementation of the hydrogen and fuel cell technology in the rail sector, recommendations on future activities with a focus on short-term R&I projects and regulatory/standardisation needs are presented. These recommendations take all findings from the project into consideration. The aim is to provide recommendations that could be used to inform potential calls for proposals for future R&I projects of S2R and FCH JUs.

2. BARRIER ANALYSIS AND NEED FOR R & I

Early projects in the field[3] have initiated the path to demonstrate the capability of the FCH technology. Other projects are currently underway, and these new projects will further test the technology in the rail sector.[4] Despite this progress, hydrogen and fuel cell technologies are still not widely regarded as a viable alternative to incumbent technologies. As this section of the report will show, there are no significant show stoppers for the FCH technology and the remaining barriers can be overcome with specific R&I projects and support from governmental and regulatory stakeholders. However, the analysis shows that there are technological and non-technological barriers that need to be addressed to advance the successful deployment of the technology in rail applications. This study demonstrates that there are no substantial drawbacks that would prevent hydrogen and fuel cell technology from being successfully applied in the rail sector, but the technology does face "first step" challenges like any new technology.

To identify the technological and non-technological barriers five main sources were used: (1) analysis of state-of-the-art projects, (2) desk research on current studies and publications in the hydrogen and fuel cell industry with specific focus on rail applications, (3) findings from the case studies and initiatives presented in report 2, (4) data sets from advisory board members based on a data request template and (5) expert interviews with industry stakeholders from the study advisory board. The findings were categorised into technological barriers related to design and engineering of train FCH systems, onboard hydrogen storage and battery systems, FCH train service and maintenance, hydrogen refuelling stations/hydrogen rail infrastructure, and non-technological barriers like safety, legal/regulatory, political, economic/financial, environmental/social/other.

The 31 identified barriers are prioritised as "low", "medium" and "high". The prioritisation is based on six criteria:

Geographical relevance: First, the barrier's relevance for one or multiple countries has been considered. Barriers that exist across Europe were prioritised higher than barriers that only exist in one or a few countries.

Number of FCH train applications concerned: Second, each barrier was reviewed in terms of relevance for multiple train applications. If the barrier is relevant for all or multiple train applications a relatively higher priority was given to the barrier.

---

[3] Such as the Coradia iLint from Alstom in northern Germany.
[4] For example, the Zillertalbahn in Austria.

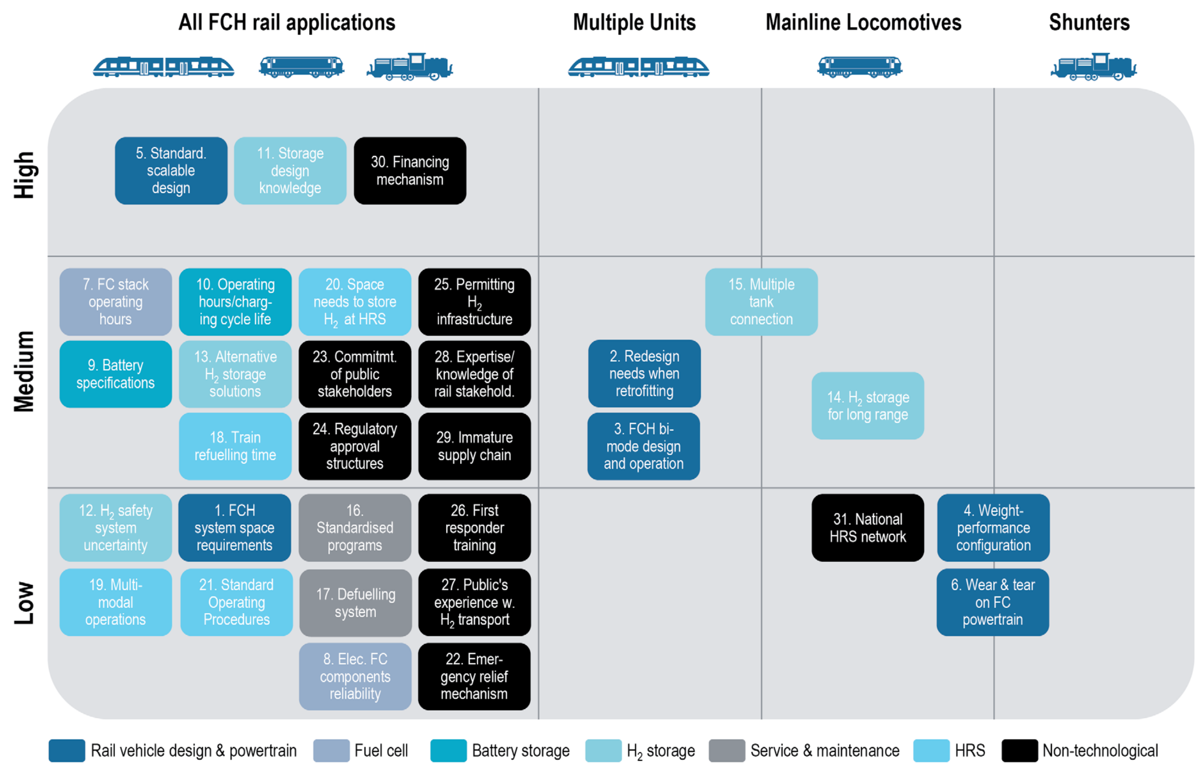
Urgency for market introduction: Third, barriers were assessed and challenged with regard to the impact that each would have on the deployment of FCH trains, and whether each barrier needs to be urgently addressed. If a barrier would entirely prevent or significantly delay the market introduction, a higher priority was given to that barrier.

Availability of technical solutions: Fourth, barriers were assessed based on the broader environment of FCH technologies. If, for example, similar solutions have already been developed for FCH trains by industry stakeholders or within other comparable FCH mobility segments. If the barrier has not yet been addressed in the broader content, then higher priority was assigned.

Technical areas to address: Fifth, a higher priority was given to barriers that have implications for multiple technical areas of FCH trains. Barriers that very specifically focus on limited technical aspects were ranked relatively lower.

Frequency of industry stakeholder response: Sixth, the collected feedback from industry stakeholders was used to steer the prioritisation. If multiple stakeholders mentioned the same barrier it was given a relatively higher priority than if it was only mentioned once.

Generally, there are no considerable European-wide show-stopping barriers preventing FCH trains from being deployed. Most barriers can be considered as optimisation potential that could ease the commercial deployment of FCH trains. The figure below provides an overview of the main barriers. Each barrier is subsequently described in a separate overview. The barriers focus on the application of FCH technology in the railway environment.



Source: Roland Berger

Figure 1: Clustering of barriers per FCH train application and priority for short-term R&I.

2.1. RAIL VEHICLE DESIGN

Existing rail vehicle designs are tailored towards the use of diesel and catenary electric power-trains. Integrating FCH technology in different train applications is expected to cause complications when integrated in existing designs without structural changes of the body. Different weight, volume and installation requirements could potentially reduce the passenger capacity of the train or limit the overall driving performance. Additional challenges arise from retrofitting existing trains before they reach end of life. Another area of development is the market demand for bi-mode trains that can run purely on electricity from the catenary but also integrate FCH technology for the non-electrified parts of the network. These bi-mode designs have not been introduced to the market yet but could become an attractive technical solution for some use cases.

2.1.1. BARRIER 1: SPACE REQUIREMENTS FOR FCH SYSTEM FOR NEW DESIGNS

Category	Rail vehicle design		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Additional space for FCH system needs to be explored in new designs		
Explanation	The space needed by FC and hydrogen storage vessels is approx. 20 30% higher than the space needed for diesel storage. Design adjustments or completely new designs are needed. Design requirements may differ significantly from country to country. Whereas additional space for the FCH system on the roof can be used in Germany, this is not possible in England (headspace is limited). An optimised layout for new rail applications has not been analysed and developed yet.		
Identified R&I needs	• Research on system layout requirements based on individual standards • Development of specific FCH train layouts according to the different market requirements and regulations		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is important in terms of market introduction but less urgent as first solutions exist. It touches a limited number of technical aspects of FCH trains. Furthermore, it has already been addressed for some FCH train applications and has only been mentioned by some stakeholders.		

2.1.2. BARRIER 2: STRUCTURAL CHANGES AND REDESIGN WHEN RETROFITTING EXISTING TRAINS

Category	**Rail vehicle design**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓		
Barrier	Potential structural changes and redesign should be considered when retrofitting existing trains		
Explanation	Retrofitting existing rolling stock with FCH systems is an option to replace diesel engines in trains without purchasing a new train while still reducing the emissions of the train before its end of life. Depending on the train type, this could potentially require extensive structural changes to the train body to accommodate the FC systems and could prevent a cost-efficient integration, especially for Multiple Unit trains. A few industry stakeholders indicated the necessity for structural changes for some of their existing train types. Changing Multiple Unit structure to accommodate the weight of hydrogen storage on the roof may be complex and the additional space needed for the FCH system might lead to a complete redesign.		
Identified R&I needs	• Development of engineering designs for already frequently deployed MUs from different OEMs • Demonstration activities to engineer, build and test fleets of different retrofitted trains		
Prioritisation	Medium The barrier is relevant for all of Europe but has mainly been mentioned in the context of Multiple Units (e.g. limited space). It is important in terms of market introduction but less urgent as first solutions are potentially under development already (stakeholder feedback). It concerns multiple technical aspects of FCH trains. However, it has only been mentioned by some stakeholders.		

2.1.3. BARRIER 3: FCH BI-MODE DESIGN AND OPERATION AND INTERACTION BETWEEN CATENARY AND FCH SYSTEM

Category	**Rail vehicle design**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓		
Barrier	Designs for FCH bi-mode operation need to be developed and interaction between catenary and FCH system should be explored		
Explanation	FCH train designs in the Multiple Unit segment often operate with roof-mounted H_2 storage systems. Some future Multiple Unit designs are also being considered for bi-mode operation (i.e. Multiple Unit with FCH and catenary powertrain). Today, there is limited experience with the design of such bi-mode trains (e.g. additional inverters that are needed, etc.). Additionally, uncertainty around the interoperability of catenary and roof-mounted hydrogen storage tanks of Multiple Units are mentioned by industry stakeholders.[5]		
Identified R&I needs	• Development of specific FCH train layouts for bi-mode operation according to the different market requirements and regulations • Support for research activity on additional safety measures necessary if FCH trains with roof-mounted H_2 tanks operate under catenary power lines		
Prioritisation	Medium The barrier is relevant for all of Europe but has mainly been mentioned in the context of Multiple Units. It is urgent for market introduction as concrete opportunities exist for bi-mode operations but are awaiting technical solutions. Furthermore, it concerns multiple technical aspects of FCH trains. It is not addressed yet but has only been mentioned by some stakeholders that are directly concerned.		

[5] Mainline Locomotive and Shunter designs with roof-mounted hydrogen tanks have not been suggested by train OEMs yet.

2.1.4. BARRIER 4: TRAIN PERFORMANCE DUE TO CHANGED RAIL WEIGHT CHARACTERISTICS

Category	**Rail vehicle design**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
		✓	✓
Barrier	Train performance increase needs to be reached due to changed rail weight characteristics		
Explanation	Depending on the train powertrain, the switch to FCH technology might lead to train weight loss. This in turn could impact the vehicle's tractive effort characteristics so that the train may not meet its performance requirements. It might be necessary to add additional weight to the vehicle to ensure sufficient traction. Additional steel plates could be a potential solution option.		
Identified R&I needs	Research and technology development activities on weight-performance correlation especially with regard to tractive effort (e.g. picking specific battery/ fuel cell combinations to achieve right mix of weight, size and performance)		
Prioritisation	Low The barrier is relevant for all of Europe but mainly for the Shunter and Mainline Locomotive segment. It not urgent for market introduction but has to be addressed in any vehicle design. The technical scope is limited with potential solutions available (e.g. adding weight). It has mainly been mentioned by some studies and not by stakeholders.		

2.2. RAIL VEHICLE POWERTRAIN SYSTEM

The FCH rail vehicle powertrain systems are at an early stage of technology development. First products have just entered the market and there is still limited experience with developing rail specific power train configurations. Ideally, standardised configurations could be used for different train platforms that fulfil the requirements of different use cases. Furthermore, there remains a risk of the FCH powertrain being negatively impacted by rail specific operations like the frequent coupling and uncoupling from shunting operations. The respective shock loads on the powertrain need to be understood and technical solutions developed if negative effects are observed.

2.2.1. BARRIER 5: STANDARDISED/SCALABLE, CUSTOMISABLE HYBRIDISED POWERTRAIN DESIGNS

Category	Rail vehicle powertrain system		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with standardised/scalable, customisable hybridised powertrain designs needs to be built		
Explanation	Several train OEMs and FCH component producers indicated limited experience with designing hybridised fuel cell/battery systems for trains. That leads to limited knowledge in how to standardise and scale hybrid powertrain designs for trains. At the moment, a standardised powertrain that can be tailored (and/or scaled) to specific use cases is only available from some train OEMs in the Multiple Unit segment. Therefore, uncertainty exists on how the different powertrain systems will interact and how the dimensioning must be done for other rail applications like Shunters and Mainline Locomotives. Furthermore, uncertainty about the right fuel cell and battery type/size combination and choice necessitates more experience.		
Identified R&I needs	• Engineering studies and prototype development to address sizing, scaling, modularisation of FCH powertrains to different rail applications by industry (e.g. addressing Shunters and Mainline Locomotives) • Analysis of powertrain component transferability from adjacent sectors to be used and applied in the railway environment to profit from economies of scale		
Prioritisation	High The barrier is relevant for all of Europe and all rail applications. It is a factor that needs to be urgently addressed for market introduction, especially for Shunters and Mainline Locomotives. It also concerns multiple technical aspects of FCH trains. It has not yet been addressed sufficiently in some FCH train applications and has only been mentioned by frequently by stakeholders.		

2.2.2. BARRIER 6: WEAR & TEAR ON FCH POWERTRAIN DERIVED FROM RAIL SPECIFIC OPERATIONS

Category	Rail vehicle powertrain system		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
		✓	✓
Barrier	Opportunities to decrease wear & tear on FCH powertrain derived from rail specific operations need to investigated		
Explanation	FCH powertrains for road transport applications are shock and vibration tested to enable a long fuel cell lifetime. For train operation, however, there is a remaining risk that shocks, and vibrations could be harmful to the powertrain system. The risk is, for example, related to the impact from frequent coupling and uncoupling of Shunter trains and Mainline Locomotives.		
Identified R&I needs	• Research and technology development activities on shock and vibration impact on the FCH powertrain system in a rail specific environment (incl. testing of potential alternative installation method as well as buffering, suspension etc.) • Demonstration activities testing the behaviour of FCH powertrains under actual operating conditions (e.g. design of sufficient shock absorbing systems for the fuel cell)		
Prioritisation	Low The barrier is relevant for all of Europe but mainly concerns Shunters and Mainline Locomotives. It is important but not urgent for market introduction as first experience from prototypes exists. The barrier is relevant for multiple technical aspects of FCH trains. Furthermore, it has only been mentioned by some stakeholders.		

2.3. FUEL CELL STACK AND SYSTEM

Fuel cells are at the heart of the FCH train's propulsion system. Their reliability, efficiency and overall performance will be decisive for FCH trains. They are also among the key cost drivers. Increasing the FCH stack operating hours before the fuel cells have to be replaced or undergo significant maintenance is an important lever to reduce the overall cost. Additionally, other heavy-duty FCH applications like public transport buses, long-haul trucks or ships and ferries have equally long operating hours and lifetime. Research and innovation topics that optimise the number of operating hours per fuel cell stack will support the market introduction of not only FCH trains but all heavy-duty FCH applications. Fuel cell for FCH trains will additionally profit from basic research, a maturing supply chain and fuel cell advancement in other sectors.

2.3.1. BARRIER 7: FUEL CELL STACK OPERATING HOURS

Category	Fuel cell stack and system		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Optimisation potential for fuel cell stack operating hours to be explored		
Explanation	The fuel cell stack is at the heart of the fuel cell system and a costly component of the powertrain. In order to minimise the cost of the fuel cell and fuel cell maintenance over the course of the lifetime, the maximum operating hours per fuel cell should be further increased. Today's fuel cell stacks can potentially operate for up to 30,000 hours before maintenance is required. Any increase in operating hours at the same level of stack cost will improve the TCO of the FCH train solutions. Alternatively, the cost of fuel cell maintenance could be reduced.		
Identified R&I needs	Research and technology development activities for conducting test campaigns with enforced degradation to optimise the fuel cell stack for rail specific application		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is important for commercialisation and cost reduction but not urgent as heavy-duty fuel cells with up to 30,000 operating hours exist. Furthermore, it addresses a complex and integral technical aspect of FCH trains. It has not been addressed sufficiently yet and has also been cited by multiple stakeholders and studies.		

2.3.2. BARRIER 8: RELIABILITY OF ELECTRONIC FUEL CELL COMPONENTS IN THE RAIL ENVIRONMENT

Category	Fuel cell stack and system		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Reliability of electronic fuel cell components in the rail environment need to be proven		
Explanation	There are numerous electronic components (e.g. sensors, wires) in fuel cell power systems and only few of them have been tested in a rail context to date. The challenges (e.g. vibration) these components face and thus their reliability in a rail environment are partly unknown. Operation of the first FCH trains could potentially reveal error prone components.		
Identified R&I needs	Research study and testing of FC specific electronic systems operating in a rail environment		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as FCH trains have already been tested in operation. It concerns fuel cell specific components only. However, it has already been addressed for some FCH train applications and has only been mentioned by some stakeholders.		

2.4. BATTERY STORAGE

Batteries are an integral part of any hybridised powertrain. For successful deployment of FCH technology in rail the optimal battery type and size per train has to be identified to fulfil the specific use case. Batteries for heavy duty applications need to have a sufficient cycle life, fast charging characteristics and adequate weight and volume to be integrated in the FCH train's available space. Respective batteries for FCH trains are just being tested and the remaining uncertainty needs to be addressed in dedicated R&I projects.

2.4.1. BARRIER 9: BATTERY SPECIFICATIONS FOR FCH RAIL APPLICATIONS (E.G. CHARGE AND DISCHARGE CYCLES)

Category	Battery storage		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with battery specifications for FCH rail applications (e.g. charge and discharge cycles) need to be extended		
Explanation	There is limited knowledge on how battery specifications and discharge cycles can be optimised for specific FCH rail applications. Specific FCH powertrain battery duty cycles need to be optimised for FCH train specific use profiles (power needs, discharge intervals). Respective testing and trial operations have not been conducted yet. Managing battery discharge cycles in combination with specifications for the battery sizes necessary to perform the duty cycles could vary from day to day, all depending on usage demands and idle time. A major factor in the operating interval is the idle time in the duty cycle and the secondary energy supply during longer downhill rides.		
Identified R&I needs	Research and technology development activities on the design of relevant battery and fuel cell combinations per rail application and use cases		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as it constitutes mainly optimisation potential. However, it is a complex technical aspect that has only been addressed for some FCH train applications. The barrier has also been mentioned by multiple stakeholders.		

2.4.2. BARRIER 10: BATTERY OPERATING HOURS AND CHARGING CYCLE LIFE

Category	**Battery storage**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Battery operating hours and charging cycle life need to be further investigated		
Explanation	Hybridised powertrains for rail applications will often require significantly sized batteries. The large batteries will add significantly to the overall cost of the powertrain. Similar to fuel cells, their replacement should be minimised to save costs. It is important to identify the right battery types for rail applications for the required operating hours and charging cycle life. Furthermore, combinations of different battery types within one FCH train type could be considered to address different use scenarios with a standardised battery configuration.		
Identified R&I needs	Research and technology development activities on the design and selection of relevant batteries for FCH trains per rail application and use case		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as it constitutes an optimisation that could enable further cost reduction. Additionally, it is a complex technical aspect that has only been addressed for some FCH train applications. The barrier has been mentioned by multiple stakeholders.		

2.5. ONBOARD HYDROGEN STORAGE

The amount of hydrogen stored onboard FCH trains will significantly impact the operational performance and independence of the train in the sense of having to be refuelled. While first standards for aspects like the refuelling pressure for Multiple Units (i.e. 350 bars) are emerging, further optimisation potential for the storage system exist. Alternative hydrogen storage options per rail application (e.g. liquid hydrogen), safe integration of hydrogen storage in different designs, optimised refuelling speed and a high level of integration of the storage system within the powertrain system can be further optimised.

2.5.1. BARRIER 11: TECHNICAL KNOWLEDGE ON HOW TO DESIGN USE PROFILE SPECIFIC ONBOARD HYDROGEN STORAGE SYSTEMS

Category	Onboard hydrogen storage		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Technical knowledge on how to design use profile specific onboard hydrogen storage systems needs to be improved		
Explanation	The hydrogen storage capacity would need to be increased not only depending on the operational specifications. An array of hydrogen storage solutions needs to be designed for the different train applications as existing configurations for diesel or electric trains do not provide enough space. Customised and use case specific solutions for onboard hydrogen storage built around the vehicle constraints will be necessary. Indeed, if hydrogen is to be stored on the train in a liquid form, different varieties of high pressure gaseous buffer tanks are needed in order to convert liquid into gas, since the fuel cell will require gas.		
Identified R&I needs	Research and technology development activities for rail specific optimised hydrogen storage designs and supply concepts (array of options for rail applications)		
Prioritisation	High The barrier is relevant for all of Europe and all rail applications. It is urgent for market introduction especially for Shunter and Mainline Locomotives. It is an integral aspect of the technical design of FCH trains. Furthermore, it has not been addressed for all rail applications and can be further optimised for current prototypes. Multiple stakeholders and studies frequently mention this as one of the main barriers facing FCH technology in rail applications.		

2.5.2. BARRIER 12: VEHICLE HYDROGEN SAFETY SYSTEM (E.G. VENTILATION OF ENCLOSED FUEL TANKS)

Category	**Onboard hydrogen storage**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Effective vehicle hydrogen safety system (e.g. ventilation of enclosed fuel tanks) needs to be standardised		
Explanation	Depending on the installation of hydrogen storage tanks, additional safety systems need to be developed and enhanced to account for the specificities of hydrogen. A large amount of hydrogen stored in the tanks can lead to hazards and safety issues such as a requirement for emergency venting. Appropriate separation of fuel tanks from the electric engines and the passengers is required. Additionally, there need to be multiple independently isolatable tanks to avoid the release of large volumes of hydrogen in the event of tank ruptures. Storing compressed hydrogen in closed roof compartments can also limit natural venting in the event of leakage.		
Identified R&I needs	• Research and technology development of rail specific hydrogen safety system • Technology demonstrator of ventilation systems as part of a broader FCH train trial		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as multiple technical designs have been tested. It is also not an issue in current FCH train applications and has only been mentioned by some stakeholders. However, it is also an integral part of any safe technical system design and needs to be addressed appropriately.		

2.5.3. BARRIER 13: ALTERNATIVE HYDROGEN STORAGE SOLUTIONS

Category	Onboard hydrogen storage		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Alternative hydrogen storage solutions need to be developed		
Explanation	The current standard for hydrogen onboard storage in FCH trains is 350 bar. Increasing the pressure to 700 bar would decrease volume requirements (20 - 30%), while a liquid storage tank could reduce tank sizes even further. While this optimises the energy stored on the train it adds to the complexity of technology and energy consumption for additional compression. Also, the infrastructure requirements and the upstream supply of hydrogen have to be considered.		
Identified R&I needs	Research and technology development on alternative onboard hydrogen storage solutions for trains including necessary infrastructure		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is important in terms of market introduction but less urgent as first solutions already exist. It is a complex topic that concerns multiple technical aspects of FCH trains as well as the fuel supply infrastructure. While it has already been addressed in some FCH train applications it has been mentioned by many stakeholders as an area for improvement (e.g. alternatives to 350 bar storage). Industry stakeholders have a divided view on the topic as a better volumetric energy density would be appreciated but the system complexity and costs need to be kept low.		

2.5.4. BARRIER 14: HYDROGEN STORAGE IN MAINLINE LOCOMOTIVES TO ALLOW FOR LONG RANGE

Category	**Onboard hydrogen storage**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
		✓	
Barrier	Solutions for sufficient hydrogen storage in Mainline Locomotives to allow for long range need to be established		
Explanation	Commercial FCH Mainline Locomotives are not on the market yet. Among the key barriers are lack of designs with FCH technology that can fulfil the performance requirements of Mainline Locomotive operation. Redesigning current Mainline Locomotive designs may necessitate significant adjustments to accommodate FCH powertrain related components (fuel cells, batteries and hydrogen tanks). Especially the number of hydrogen tanks for long distance services need to be carefully considered as it is currently not clear where large amounts of hydrogen (>1,000 kg) can be stored. Fuel tender options have been considered but no technology development is underway yet. The fuel tender and connections will need to be designed, tested and receive regulatory approval/pass safety tests.		
Identified R&I needs	• Research and technology development of engineering designs and trials of locomotives with fuel cells with a particular focus on hydrogen storage (e.g. integration of a sufficient amount of hydrogen storage on the train) • Technology demonstrators for innovative Mainline Locomotive fuel storage systems • Demonstration activities of Mainline Locomotive prototypes including required infrastructure for supply of hydrogen (e.g. central fuel tender filling plant)		
Prioritisation	Medium The barrier is relevant for all of Europe but only for Mainline Locomotives. It is an urgent topic for market introduction as no products are available to the market yet. It relates to one specific technical aspect of the train. It is the most frequently cited barrier to the introduction of FCH Mainline Locomotives.		

2.5.5. BARRIER 15: CONNECTING MULTIPLE TANK SYSTEMS ACROSS TRAIN CARS

Category	**Onboard hydrogen storage**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	
Barrier	Solutions to connect multiple tank systems across train cars need to be developed		
Explanation	In order to maximise the space for hydrogen storage systems on Multiple Units, the tank systems are installed in multiple separate systems per rail car. This also requires them to be refuelled separately at the refuelling station. Ideally, those systems could be connected but regulation and safety concerns currently prevent such designs. The same would apply to Mainline Locomotives that would carry their fuel in an additional fuel tender behind the locomotive.		
Identified R&I needs	Research and technology development of engineering designs and trials of interconnections of fuel systems across multiple rail cars (e.g. flexible hoses) including roadmap development to updated relevant regulation		
Prioritisation	Medium The barrier is relevant for all of Europe, especially for Multiple Units and Mainline Locomotives. While addressing only one specific technical element, the development of a solution could facilitate significant reduction of operational constraints for train refuelling and system integration across multiple vehicles. The topic has not been addressed yet and is cited by industry stakeholders frequently.		

2.6. TRAIN SERVICE AND MAINTENANCE

Reliability of public transport services with trains is one of the central goals of rail operators. New technologies will have to prove that they can perform according to the specifications without any significant operational downtime. Specific regular service and maintenance procedures alongside fit-for-purpose technical facilities will be an essential prerequisite. In order to increase the rail operators' confidence in the technology, remaining uncertainties regarding service and maintenance of FCH trains should be addressed as part of R&I projects. Existing experience from other transport applications should be leveraged to quickly and efficiently provide an adjusted solution for the rail environment.

2.6.1. BARRIER 16: STANDARDISED FCH RAIL SERVICE AND MAINTENANCE PROGRAMS

Category	Train service & maintenance		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Standardised FCH rail service and maintenance programs need to be conceptualised		
Explanation	All maintenance activities should be conducted in accordance with a standardised and approved service and maintenance manual. These procedures have not been developed yet for a rail specific context.		
Identified R&I needs	Support activity to conduct a study to develop a basis for standardised maintenance procedures for different rail use cases		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as non-standardised service and maintenance programs could be tailored for first projects. Experience from other transport applications can also be leveraged. The barrier has been mentioned by some stakeholders, but mainly by rail operators.		

2.6.2. BARRIER 17: RAIL SPECIFIC HYDROGEN DEFUELLING SYSTEM FOR SERVICE AND MAINTENANCE

Category	**Train service & maintenance**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Rail specific hydrogen defuelling system for service and maintenance need to be developed		
Explanation	In order to perform service and maintenance operations on FCH trains, a hydrogen defuelling/draining system will be needed in each service depot in order to vent the hydrogen safely before maintenance can take place.		
Identified R&I needs	Research and technology development for a safe and reliable hydrogen defuelling system for service and maintenance		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is urgent for market introduction and ultimately to be able to service FCH trains. However, experience from other transport applications can potentially be leveraged. The barrier focuses on one very specific technical element that has been addressed for other transport applications already. The barrier has been mentioned by some stakeholders, mainly the rail operators.		

2.7. REFUELLING INFRASTRUCTURE

The hydrogen refuelling infrastructure is an integral part of efficient and commercially attractive FCH train operation. Filling the FCH trains quickly and safely as well as potentially providing fuel to other modes of transport in a multi-modal approach are areas of potential improvement. Furthermore, large-scale HRS for fleets need to have a significant amount of fuel storage in order to enable a continuous supply of all vehicles at any time. This becomes even more important if it is coupled with on-site production that should be used to produce only from fluctuating renewable energies. While storage solutions from 50 to up to 900 bars exist and are in daily operation already, further improvement to reduce the space requirements of HRS could ease the commercialisation of FCH trains. Similarly, other large consumers of hydrogen like public transport bus fleets could profit from respective improvements. Research and innovation should tackle the topic in general terms as it will support multiple applications at the same time. Alongside technical solutions, work on safety and improved regulation and permitting should be considered as part of such related activities.

2.7.1. BARRIER 18: REFUELLING TIME FOR LARGE AMOUNTS OF HYDROGEN

Category	**Refuelling infrastructure**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Refuelling time for large amounts of hydrogen needs to be optimised		
Explanation	Rail operators would expect FCH trains to be refuelled as quickly as equivalent diesel trains. Current refill time is around 30 min per diesel regional train. Due to the large hydrogen quantity stored (>200 kg), HRS needs to be adapted for fast refuelling time. This would entail nozzle throughput of average >120 g/s or the possibility to refuel the train with two nozzles in parallel. A larger refuelling coupling could also avoid additional investments on the refuelling station side (e.g. fewer dispensers as the HRS could be used more frequently by other trains in the fleet). In addition, a new refuelling protocol for FCH trains could be developed to reduce refuelling times further.		
Identified R&I needs	Research and technology development activity to develop processes and equipment to reduce the refuelling time for hydrogen trains to maximise operational performance		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is important for commercialisation and cost reduction, but not urgent as technically feasible solutions exist. Furthermore, it addresses a complex and integral technical aspect of FCH trains in combination with refuelling infrastructure. It has not been addressed widely yet but has so far only been cited by some stakeholders and studies.		

2.7.2. BARRIER 19: MULTI-MODAL OPERATION OF HRS IN THE RAIL ENVIRONMENT

Category	**Refuelling infrastructure**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with multi-modal operation of HRS in the rail environment need to be extended		
Explanation	The cost of hydrogen supplied to trains can potentially be reduced by sharing the required HRS with other modes of transport like buses, trucks and cars. The first HRS for trains are currently in the design phase and do not consider a multi-modal approach yet. Respective designs have not been developed yet. Constraints from supplying two or multiple modes of transport have not been tested and demonstrated in the rail environment.		
Identified R&I needs	Demonstration activity to show the interoperability of HRS for trains with other modes of transport with a techno-economic analysis of potential synergy effects		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. Multi-modal operation for a HRS is an upside for the business cases across Europe but not urgent for market introduction. It focuses on a specific technical element that has already been developed for other transport applications (e.g. combined HRS serving cars and buses). It has only been mentioned by some stakeholders.		

2.7.3. BARRIER 20: STORAGE OF A SUFFICIENT VOLUME OF HYDROGEN AT THE HRS IN GASEOUS FORM

Category	Refuelling infrastructure		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Space requirements to store a sufficient volume of hydrogen at the HRS in gaseous form need to be investigated		
Explanation	Alternative forms of hydrogen storage at HRS like liquid hydrogen storage should be explored in detail to provide a sufficient amount of hydrogen to the trains. Especially for larger fleets the space required for gaseous storage can become significant and alternative possibilities should be further explored.		
Identified R&I needs	• Research and technology development for alternative ways of large-scale hydrogen storage at HRS (potentially considering the energy consumption of the entire system, e.g. including compression and other operational efficiencies) • Research on an efficient way to easily upscale existing hydrogen storage facilities		
Prioritisation	Medium The barrier is relevant for all of Europe, all rail applications as well as other modes of transport with a large demand for hydrogen. It is important but less urgent for market introduction as the barrier constitutes optimisation potential. It focuses on one specific element of the FCH rail ecosystem but has good potential to improve HRS implementation as it reduces space constraints. It has only been mentioned by some stakeholders.		

2.7.4. BARRIER 21: FCH INFRASTRUCTURE STANDARD OPERATING PROCEDURES (SOP)

Category	Refuelling infrastructure		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	FCH infrastructure Standard Operating Procedures (SOP) need to be established		
Explanation	SOPs are important for operation and service of HRS and trains across the rail environment. Standardised elements include emergency response procedures (operation of the Emergency Shutdown (ESD) button, emergency contact, evacuation of the station, assistance to emergency personnel), refuelling station start-up procedures (under normal conditions and after ESD activation), fuelling procedure, defuelling procedure (for venting gas from vehicle tanks prior to maintenance). Other elements include safety equipment testing procedures (calibration of fast monitoring equipment, testing of fire and gas detection equipment, station leak check), management of change procedure, incident investigation procedure.		
Identified R&I needs	• Supporting activity to collect best practices and develop guidelines for developing SOP for the operation of HRS in the rail environment • Research and technology development for a safe and reliable hydrogen defuelling system for service and maintenance		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is, however, less urgent for market introduction as non-standardised procedures could be developed. Furthermore, operating procedures can potentially be adapted from other modes of transport. It has only been mentioned by some stakeholders.		

2.8. NON-TECHNOLOGICAL BARRIERS

FCH technology for rail also faces non-technological barriers that have to be addressed in a targeted manner to avoid delays in market uptake. The identified barriers are common for new technologies but should be addressed with dedicated R&I activities within the specific rail context. Among the key drivers are commercial barriers that prevent wider adoption of the technology and a broader lack of experience and knowledge about FCH technologies. Additionally, existing regulatory statutes and processes do not foresee the use of FCH technologies yet, which constitutes a barrier as time-consuming special permitting and approval processes are necessary.

Non-technological barriers can often be addressed by synergising with other modes of transport. For example, the FCH industry has not yet reached a sufficient scale to fully realise the cost reduction potential of its technology. This has a direct impact on the competitiveness of all FCH applications. While global markets for FCH technology are emerging and FCH deployment volumes are growing, more standardisation across FCH applications would be required to better leverage the existing production capacities, allow for the use of similar components across applications and increase the availability of spare parts. Therefore, research and innovation projects that target cross-industry standardisation should be pursued in order to reduce the total cost of ownership for FCH applications by maturing the industry supply chain. Furthermore, some industry stakeholders cited a need to gain more experience with emergency relief mechanisms to ensure safe operation of FCH trains. While rail specific adaptations of these emergency relief mechanisms are necessary, the underlying challenges for other FCH applications will be similar. Therefore, research and innovation should focus on mutually beneficial exchange of know-how and experience to build best practice emergency relief mechanisms across different application segments. Most importantly, the introduction of hydrogen as a new energy source requires great care in terms of safety. First, of course, risks to humans need to be limited to a minimum, but second, the public perception of risk needs to be taken into account. One important element of reducing the risks to humans and increasing the safety levels is proper training of first responders. Independent of FCH applications, first responders like local fire departments need to be trained in the safe handling of hydrogen-powered vehicles when they are involved in emergencies or accidents. Research and innovation in the form of supporting activities should focus on FCH application independent projects that provide targeted first responder training for fuel cell accidents.

2.8.1. BARRIER 22: EMERGENCY RELIEF MECHANISMS OF FCH SYSTEM

Category	Vehicle safety		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with emergency relief mechanisms of FCH system needs to be extended		
Explanation	Ensuring that FCH components can be safely operated in the rail environment requires appropriate emergency relief standards. Emergency relief standards are among several areas where operational testing is still missing. While first FCH trains have been approved for commercial operation, there are no standardised regulations and procedures for approval of FCH trains' emergency relief mechanisms.		
Identified R&I needs	Demonstration project with a work package on emergency response trials		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It is, however, less urgent for market introduction as first FCH trains have successfully obtained approval for operation. The barrier relates to a specific technical topic that has also been resolved for other modes of transport. It has been mentioned by only a few stakeholders.		

2.8.2. BARRIER 23: COMMITMENT OF PUBLIC STAKEHOLDERS FOR FCH RAIL

Category	**Political barrier**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with and commitment of public stakeholders for FCH rail needs to be strengthened		
Explanation	Public stakeholders need to commit to the technology in order to increase confidence in the market and to drive an organised ramp-up of FCH trains. Currently there is a subjective lack of knowledge about the technology from public stakeholders as FCH technology is not in widespread everyday use yet. This delays decision making and seems to be especially relevant for multi-modal applications.		
Identified R&I needs	Supporting activity in the form of hydrogen educational campaigns for public authorities and lawmakers on a local, regional, and national level that are responsible for the railway environment		
Prioritisation	Medium The barrier is a relevant topic for all of Europe and for all rail applications. It is urgent for market introduction, to pave the way for new deployment projects. It is a complex topic that requires a holistic communications approach in order to overcome it. The topic has been frequently mentioned by stakeholders and FCH specific studies.		

2.8.3. BARRIER 24: REGULATORY STRUCTURES FOR FCH TRAINS APPROVAL (SAFETY, ENVIRONMENT, AND FUEL CELL SYSTEM STANDARDISATION)

Category	Legal barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Efficient and appropriate regulatory structures for FCH trains approval (safety, environment, and fuel cell system standardisation) to be extended		
Explanation	FCH trains are a new technology in Europe. The technology is not considered in the currently existing regulatory framework. While first individual type approvals for FCH trains have been achieved, a dedicated regulatory framework still needs to be developed. Neither on a European level nor in many national contexts is this available. Delays in regulatory approval could hamper deployment of trains.		
Identified R&I needs	Supporting activity to do research into different areas where regulations for rolling stock, hydrogen, and hydrogen rail infrastructure on a local, national, and European level will need to be adopted or updated to provide a summary view of the regulatory environment as well as a roadmap to adjust the regulation		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It can potentially be solved on a case by case basis and is therefore not urgent for market introduction. However, it could improve market uptake if resolved. It touches upon multiple technical and safety related topics that must be addressed thoroughly. The regulatory framework for hydrogen and fuel cell technology in Europe is already being updated, and FCH trains could profit from this. Rail stakeholders cite regulation and permitting as one of the key barriers for FCH trains.		

2.8.4. BARRIER 25: PERMITTING PROCESS FOR RAIL RELATED HYDROGEN INFRASTRUCTURE

Category	Legal barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Specific permitting process for rail related hydrogen infrastructure need to be put forward		
Explanation	Permitting processes for hydrogen infrastructure are available in some European countries mainly in the context of road transport. Due to a typically specific rail related set of regulations there is a need either to adapt existing regulations from road transport to the rail environment or to develop new permitting processes for FCH trains.		
Identified R&I needs	Supporting activity to develop best practice guidelines for hydrogen rail infrastructure permitting in collaboration with regulatory bodies		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It can potentially be solved on a case by case basis and is therefore not urgent for market introduction but could improve market uptake if resolved. It touches upon multiple technical and safety related topics that have to be addressed thoroughly. The fuel cells and hydrogen regulatory framework in Europe is already being updated, and FCH train infrastructure could profit from this. Rail stakeholders cite regulation and permitting as one of the key barriers for FCH trains.		

2.8.5. BARRIER 26: FIRST RESPONDER TRAINING FOR FUEL CELL RAIL ACCIDENTS

Category	Legal barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	More first responder training for fuel cell rail accidents necessary		
Explanation	First responders still lack training and experience in responding to rail transport accidents involving hydrogen and fuel cells.		
Identified R&I needs	Supporting activity to standardise procedures and launch structured roll-outs of training programs for FCH rail incident first responders		
Prioritisation	Low The barrier is relevant for all of Europe and all rail applications. It can potentially be addressed for each project and is therefore not urgent for market introduction. Existing first responder training material for FCH accidents will have to be adjusted for the rail environment. The topic was mentioned by a few stakeholders.		

2.8.6. BARRIER 27: HYDROGEN TECHNOLOGIES IN TRANSPORT BY THE PUBLIC

Category	**Social barrier**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience with hydrogen technologies in transport by the public needs to be broadened		
Explanation	Public confidence in and experience with hydrogen trains is limited and popular misconceptions about hydrogen safety are widespread. This could lead to challenges with adoption of the technology. If these concerns are combined with potential train reliability or safety issues they could rapidly erode public trust in the technology.		
Identified R&I needs	• Supporting activity that links up with public relations campaigns and studies of other modes of transport • Demonstration projects with dedicated communication and dissemination of work streams that address public concerns (reliability, safety, efficiency etc.)		
Prioritisation	Low General topic that is not rail specific but relevant for all of Europe and for all rail applications. More hydrogen vehicles (road/rail) in operation and higher media coverage in addition to active communication towards the public should increase public acceptance.		

2.8.7. BARRIER 28: EXPERIENCE AND KNOWLEDGE ABOUT FCH TECHNOLOGIES AMONG RAIL STAKEHOLDERS

Category	**Social barrier**		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Experience and knowledge about FCH technologies among rail stakeholders needs to be improved		
Explanation	FCH trains are entering the European market. There is still limited operator knowledge and training regarding the operation, maintenance, properties, and safety of FCH trains as well as their performance in different use scenarios. Furthermore, on a management and staff level, the relevant personnel will have to undergo specific training to adjust to and requalify for using the new fuel. Operators must have a thorough knowledge of the unique features of the vehicle – training should include instruction on how to identify emergency situations, how to keep the public safe, and even development of operator specific emergency action plans. Maintenance technicians need to be qualified to work on FCH trains. The training needs to introduce people to the specifics of the new FCH powertrain with a particular focus on working safely with gases. HRS personnel must be trained in the differences between conventional liquid fuel and hydrogen dispensing. Additionally, they require training on the equipment and maintenance procedures used in servicing the fuelling station equipment. Emergency personnel like the local fire department, the police and any other first responders require training on the emergency systems and procedures as well as a general understanding of station operation and locations of key equipment.		
Identified R&I needs	Supporting activity to develop a series of hydrogen rail best practice guides covering staff training, operation, maintenance, safety and general information about hydrogen as a fuel		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is critical for market introduction. Limited rail stakeholder experience could hinder market uptake. Only some rail operators in Europe have developed sufficient knowledge to take the first implementation steps with hydrogen technologies. The technology is still very new, and many rail operators rely on very outdated information. Communication on the topic is complex and still lacks the backing of substantial practical performance evidence for FCH trains. The topic has been cited by FCH rail stakeholders and studies frequently.		

2.8.8. BARRIER 29: SUPPLY CHAIN MATURITY

Category	Economic/financial barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	FCH rail supply chain needs to develop further		
Explanation	The current size of the industry and the lack of vehicles in operation limits the breadth and depth of the supply chain. Having only a limited number of players may cause delays for project execution and service and maintenance. Furthermore, there is currently still limited supply of FCH train products available to the market, which in turn limits the attractiveness for the FCH component suppliers.		
Identified R&I needs	Large-scale demonstration projects with multiple FCH trains to aggregate a critical mass of demand to stimulate the supply chain		
Prioritisation	Medium The barrier is relevant for all of Europe and all rail applications. It is less urgent for market introduction as sufficient supply is available to deliver first prototypes. It is relevant for various elements of the FCH value chain and has been cited by multiple stakeholders as a barrier to the widespread adoption of FCH technology.		

2.8.9. BARRIER 30: DE-RISKING HIGH FINANCIAL REQUIREMENTS

Category	Economic/financial barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
	✓	✓	✓
Barrier	Tailored financing mechanisms to support roll-out of FCH trains need to be set up		
Explanation	In the early market introduction of FCH trains, the new technology is more expensive than incumbent technologies. In order to bridge the gap until the necessary scale for cost reduction is achieved, specific financing possibilities need to be offered. These financing mechanisms would need to be tailored to the national financial capabilities of the different rail operators. They should also mitigate the financial risk of new technology.		
Identified R&I needs	• Requirements to explore innovative financing for any large-scale demonstration project that provides funding for fleets of FCH trains to stimulate the technology • Supporting activity to identify the available financing and funding options for FCH trains and potential gaps. Activity to conceptualise and suggest additional financing and funding tools to implement FCH trains		
Prioritisation	High The barrier is relevant for all of Europe and all rail applications. It is an especially limiting factor at this early stage of technology deployment and very urgent for market introduction. FCH trains have a disadvantage compared to incumbent technologies when they are examined on a purely commercial basis, without factoring in their environmental benefits. No specific financing mechanism is currently available that also takes the value chain complexities into account. Indeed, rail operators frequently cited the high cost and the risks associated with FCH train implementation as the most significant for the technology.		

2.8.10. BARRIER 31: BUILD-UP OF HYDROGEN REFUELLING INFRASTRUCTURE ACROSS A NATIONAL RAIL NETWORK

Category	Economic/financial barrier		
Rail Application	Multiple Units	Mainline Locomotives	Shunters
		✓	
Barrier	Build-up of hydrogen refuelling infrastructure across a national rail network need to be tackled		
Explanation	The hydrogen refuelling infrastructure required to service and operate Mainline Locomotives requires widespread adoption and standardisation within the area of operation, e.g. ideally European wide. This is especially relevant for Mainline Locomotives that operate on international freight routes. In order to be able to operate independent of fixed routes across a network, a standardised refuelling station network potentially has to be built (if no other fuel supply concept is developed). Cooperation is needed between the different players (i.e. institutional, manufacturers and operators) in order to drive the innovations through the same standards.		
Identified R&I needs	Research activity to conceptualise a European FCH Mainline Locomotive infrastructure initiative (e.g. economic viability, standardisation, roll-out planning, financing needs, environmental considerations)		
Prioritisation	Low The barrier is relevant for all of Europe but only for Mainline Locomotives. The topic is not yet urgent for market introduction as first FCH Mainline Locomotive prototypes with adequate hydrogen storage solutions have still not yet been developed. The refuelling concept is also not defined yet. While a limited number of stakeholders showed interest in FCH Mainline Locomotives in general, those who do frequently mentioned fuel supply as a key barrier.		

3. RECOMMENDED R & I PROJECTS

Based on the barrier analysis, three main project topics have been identified as having a high relevance for short-term R&I. The R&I projects have the potential to drive FCH train technology beyond the current state-of-the-art and pave the way for a commercial deployment. The successful implementation of these projects has the potential to safeguard Europe's current leading position with FCH trains.

The R&I project are designed to address a high priority barrier and also include peripheral topics. Low and medium priorities can also be tackled in addition within the same R&I projects. The higher-level project design then incorporates these subordinate topics in work packages or task of the project, which contribute to the solution of the main barrier.

The three suggested R&I projects address the following three areas:

- Large-scale demonstration of FCH Multiple Units to unlock the mass market potential;
- Development of FCH Shunting or Mainline Locomotives to increase technology awareness;
- Optimisation of hydrogen storage systems for increased FCH train performance.

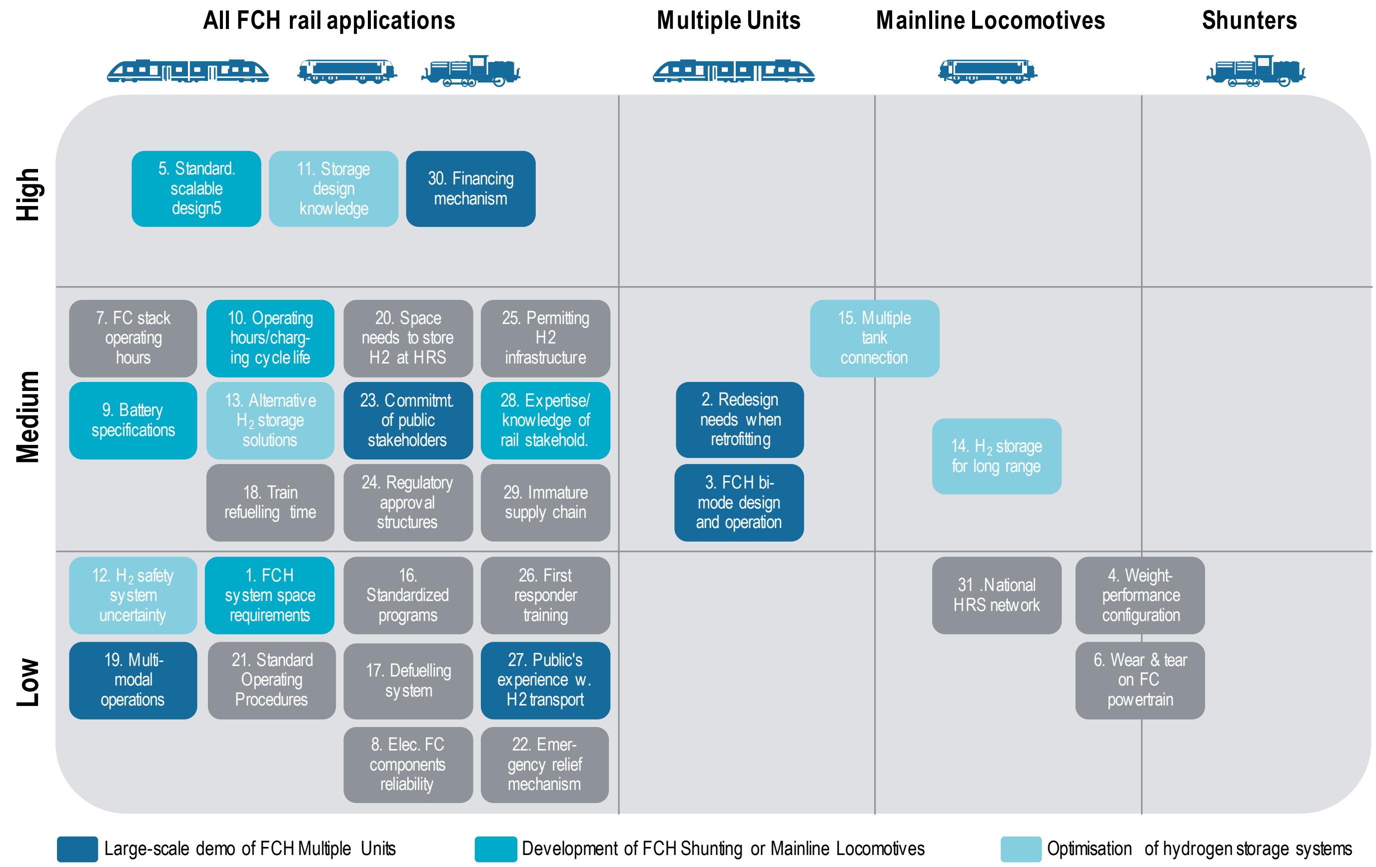


Figure 2: Overview of barriers to be addressed with R&I projects.

3.1. LARGE-SCALE DEMONSTRATION OF MULTIPLE UNIT TRAIN FLEETS

Main barrier to be addressed

Barrier 30: De-risking high financial requirements

Introduction to the high-level project scope

FCH train deployment requires tailored financing mechanisms that take into account, among other things, the long train lifetime and the specific project set-ups (e.g. partly public tenders for train services; different responsibilities for train assets, railway lines and refuelling infrastructure). At the current stage of the market, the FCH technology still comes at a cost premium that needs to be mitigated. A large-scale demonstration project of FCH Multiple Unit train fleets has the potential to provide the first sufficient funding for an initial deployment of a larger train fleet (e.g. more than 15 trains with a single refuelling station). The large fleet size is recommended in order to showcase the FCH train use case at scale. A smaller fleet would face challenges with underutilised refuelling infrastructure and relatively higher project development and management cost.

In contrast to a research study, this project will fulfil two main purposes: first, it will provide operational and commercial experience with the trains' performance. This provides a better understanding of the risks and the remaining cost gaps associated with operating the FCH trains. Second, based on the main risks of the operation and a potential cost gap identified in the project, a set of tailored financing mechanisms should be developed that specifically addresses the FCH train environment. Part of this analysis should focus on applying existing financing mechanism for trains, but also entirely new tailored financing mechanisms should be suggested.

Other barriers that could be addressed within the same project

- **Barrier 2:** Structural changes and redesign when retrofitting existing trains;
- **Barrier 3:** FCH bi-mode design and operation and interaction between catenary and FCH system;
- **Barrier 19:** Multi-modal operation of HRS in the rail environment;
- **Barrier 23:** Commitment of public stakeholders for FCH rail;
- **Barrier 27:** Hydrogen technologies in transport by the public.

Estimated total project cost[6]

EUR 80 – 100 m

---

[6] Assuming an investment in 10 – 15 Multiple Units at EUR 5 – 6 m each, hydrogen refuelling infrastructure in the order of EUR 15 – 20 Mio and additional budget for project management and supporting research, development and engineering work.

3.2. DEVELOPMENT, ENGINEERING AND PROTOTYPE OPERATION OF SHUNTERS OR MAINLINE LOCOMOTIVES

Main barrier to be addressed

Barrier 5: Standardised/scalable, customisable hybridised powertrain designs.

Introduction to the high-level project scope

Today, there is still limited experience and knowledge about FCH technologies among rail stakeholders, especially outside the Advisory Board of this study and for rail applications where no FCH product is available. This was revealed by the market potential analysis for FCH trains in Europe. While FCH Multiple Units were well known to most interviewees, limited knowledge on FCH Shunters and Mainline Locomotives was available. Some cited that they are missing concrete reference products to assess whether FCH train solutions are suited for their specific operational requirements. Therefore, an integrated project with concept development, engineering and prototype fleet operation for either Shunters or Mainline Locomotives is suggested. The project should either be centred on the development and implementation of 5 new FCH Shunters or Mainline Locomotives or should seek to convert/retrofit up to 10 Shunters or Mainline Locomotives to FCH technology. The prototype location should ideally be at a heavily frequented Shunting Yard or Mainline route with ideally one or two large HRS to realise economies of scale.

The project fulfils multiple purposes: First, the project will close the existing product gap and introduce state-of-the-art FCH Shunters or Mainline Locomotives to increase the awareness of rail stakeholders. Second, the project and specifically the prototype operation will allow necessary experience to be built up with FCH trains in general but also specifically on their potential for the Shunting or Mainline Locomotive use cases. Third, the performance of FCH technology can be tested against other incumbent (e.g. diesel) and zero-emission (e.g. battery) alternatives to verify the results of the total cost of ownership comparison in practice.

Other barriers that could be addressed within the same project

- **Barrier 1:** Space requirements for FCH system for new designs;
- **Barrier 28:** Experience and knowledge about FCH technologies among rail stakeholders;
- **Barrier 10:** Battery operating hours and charging cycle life;
- **Barrier 9:** Battery specifications for FCH rail applications (e.g. charge and discharge cycles).

Estimated total project cost[7]

EUR 80 – 100 m

---

[7] Assuming build-up of 2 – 3 prototype trains at 3 – 5 Mio each with accompanying temporary refuelling, research, development, engineering and project management.

3.3. TECHNOLOGY DEVELOPMENT FOR OPTIMISED HYDROGEN STORAGE SYSTEMS

Main barrier to be addressed

Barrier 11: Technical knowledge on how to design use profile specific onboard hydrogen storage systems

Introduction to the high-level project scope

Hydrogen as an energy source is in principle suited to providing FCH trains with very high fuel autonomy without refuelling. However, this is constrained by the number of hydrogen tanks that can be fitted on an FCH train from a weight and volume perspective. The refuelling operations ideally need to be as simple as with diesel to realise the full operational benefits of hydrogen. While first FCH trains have been put into operation, multiple barriers regarding the storage of hydrogen on FCH trains have been cited by FCH train studies and industry stakeholders. The hydrogen storage barriers often constitute a system optimisation problem. Other hydrogen storage barriers are application specific and require further detailed analysis to select and implement the best available option. Therefore, an integrated technology development project for optimised hydrogen storage systems for use in FCH rail applications is needed. This should analyse potential knowledge gaps and suggest concrete solutions for Multiple Units, Shunters and Mainline Locomotives. Problems regarding the right filling pressure, ideal tank location, connection of multiple tank systems across rail cars and retrofitting considerations can be analysed.

The suggested project fulfils the following purposes: First, it will provide an overview of the existing hydrogen storage solutions for FCH trains as well as their advantages and constraints. Second, it will give an indication of the most viable hydrogen storage option within rail application, including new engineering concepts to integrate more energy in the available space and have cross-railcar connections of hydrogen storage systems. Furthermore, the optimal supply pressure/physical state should be evaluated in relation to the hydrogen supply infrastructure (e.g. HRS energy consumption, liquid hydrogen supply chain). Prototype development and integration in operational FCH trains should be an integral part of the project in order to provide tangible results and to increase the visibility of the technology. Third, the feasibility of alternative storage technology which are at a lower TRL stage should be investigated to better understand their potential to alleviate potential remaining barriers for specific FCH train applications like Mainline Locomotives.

Other barriers that could be addressed within the same project

- **Barrier 12:** Vehicle hydrogen safety system (e.g. ventilation of enclosed fuel tanks);
- **Barrier 13:** Alternative hydrogen storage solutions;
- **Barrier 14:** Hydrogen storage in Mainline Locomotives to allow for long range;
- **Barrier 15:** Connecting multiple tank systems across train cars.

Estimated total project cost[8]

EUR 80 – 100 m

---

[8] Expert estimation.

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.

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

The report provides and overview of past studies or technological trials on the implementation of fuel cell and hydrogen technologies in the railway sector. 22 trials and demonstrations in 14 countries across Europe, Asia, North America, the Middle East, Africa and the Caribbean since 2005 are identified and analysed. Furthermore, the report shed light on the Business cases FCH rail applications and assesses the market potential to replace diesel-powered trains in Europe until 2030. The analysis for the three focus applications Multiple Units, Shunters and Mainline Locomotives concludes a significant potential to decarbonize the remainder of the rail sector

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"*

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