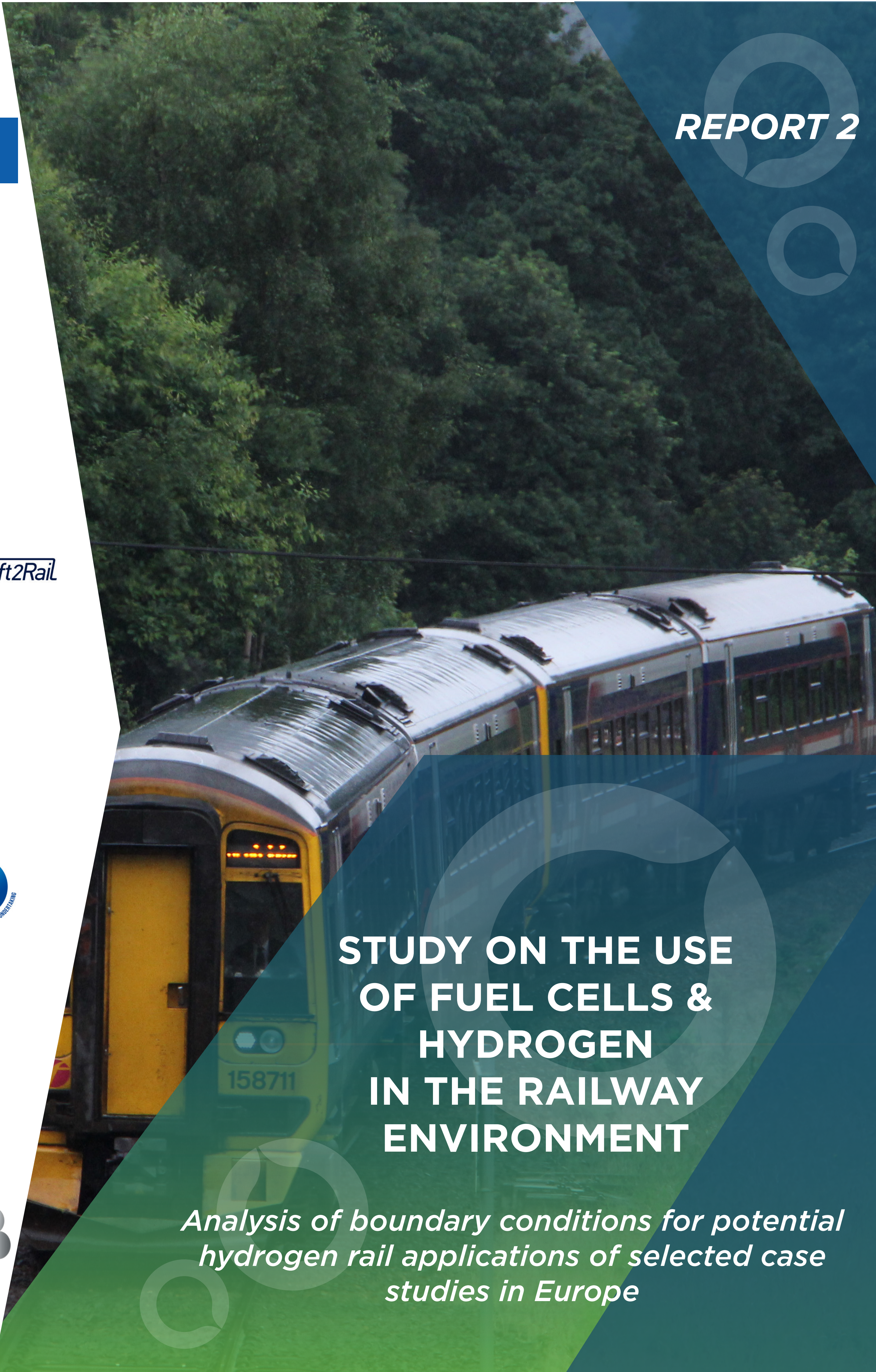
REPORT 2



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

Analysis of boundary conditions for potential hydrogen rail applications of selected case studies in Europe

Shift2Rail

FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Roland Berger

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About this publication

Manuscript completed in April 2019.

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LIST OF ABBREVIATIONS

AB	Advisory Board
Avg	Average
CAPEX	Capital Expenditures
CHC	Cryogenic Hydrogen Compressor
CO2	Carbon Dioxide
FC	Fuel Cells
FCH	Fuel Cells and Hydrogen
FCH2JU	Fuel Cells and Hydrogen Joint Undertaking
H2	Hydrogen
HP	High pressure
HRS	Hydrogen Refuelling Station
IRG	Independent Regulators Group
GH2	Gaseous hydrogen
LH2	Liquid hydrogen
LP	Low pressure
Max.	Maximum
MP	Medium pressure
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	Shift2Rail Joint Undertaking
SMR	Steam Methane Reforming
TAC	Track Access Charges
TCO	Total Cost of Ownership
TSI	Technical Specifications for Interoperability
WACC	Weighted Average Cost of Capital

LIST OF UNITS

%	Percentage	
°C	Degree Celsius	Temperature
bar	Bar	Pressure
EUR	Euro	Currency
h	Hour	Time
kg	Kilogram	Mass
km	Kilometres	Length
km2	Square metre	Area
kmtrain	Train kilometer	Length
kN	Kilonewton	Force
kW	Kilowatt	Power
kWh	Kilowatt hour	Energy
LE	Loading units	Terminal handling capacity
m	Meters	Length
MW	Megawatt	Power
MWh	Megawatt hour	Energy
Nm3	Standard cubic metre	Volume
t	Tonne	Mass
TEU	Twenty-foot Equivalent Unit	Container
TWh	Terawatt hour	Energy

ABSTRACT

In 10 case studies examined, the fuel cell and hydrogen (FCH) technology is economically and environmentally competitive with other powertrain technologies in train applications. The relatively high investments for the train itself and the hydrogen infrastructure can be compensated for by the lower fuel cost and lower maintenance costs. In addition, the FCH technology leads to less local emissions and supports the development of low-carbon electricity generation through the flexible use of electricity for the hydrogen production via on-site electrolysis. Other alternatives such as battery trains or catenary trains also show advantages on highly utilised or relatively short routes.

Recent market studies and the interviews conducted have demonstrated that there are no show-stoppers for the use of hydrogen technology. The costs for the hydrogen infrastructure, batteries, FCH tanks must continue to fall. However, this is not an absolute obstacle to the use of hydrogen trains.

Especially with a holistic view of the energy system of the future, hydrogen trains can make a meaningful contribution to environmental protection and the modernisation of freight and passenger rail transport through their high flexibility and long range

EXECUTIVE SUMMARY

FCH technology can compete with other clean technologies in the railway industry and is a viable clean alternative to diesel powered Multiple Units and locomotives. FCH trains can be designed to meet the same performance specifications as diesel locomotives in use while delivering environmental benefits without making sacrifices in the fields of flexibility, long range and high power ratings.

Based on the in-depth analysis of ten different case studies throughout Europe, including four case studies focusing on Multiple Units, three case studies focusing on Shunters and three case studies focusing on Mainline Locomotives, the following main conclusions can be derived for the use of FCH trains:

- FCH trains make economic sense above all when they are used on longer non-electrified routes of over 100 km.
- FCH trains can be used especially for last mile delivery routes, but also for main routes that have very low utilisation (up to 10 trains per day).
- Low electricity costs of less than 50 EUR/MWh and high utilisation of the infrastructure (hydrogen refuelling station, electrolyser) favour the use of FCH technology.
- FCH trains enable operation with very short downtimes of less than 20 minutes (due to fast refuelling) and are also able to withstand long operating hours of more than 18 hours without refuelling.
- FCH trains are an economically feasible clean alternative to current diesel trains in many cases.
- In some cases, battery-powered trains may appear as a more cost-effective option but come with operational constraints resulting from their highly rout specific tailored battery configurations.

A wide variety of use cases can be covered by precisely adapting the hybridisation (ratio between fuel cell and battery power). This facilitates transporting high loads of up to 5,000 t, maintaining high speeds of up to 180 km/h, and travelling over long distances in excess of 700 km. Nevertheless, while it was noted that many case studies examine specific route conditions, the trains designed to be used on the specified routes must also be eligible for general fleet-wide use by the operator. Therefore, both the hybridisation and the volume of the tanks must be designed with this flexibility in mind.

Case study on Multiple Units in France: The route from Toulouse to Luchon is only partly electrified and characterised by a rather low utilisation in the mountainous region of Luchon with a total length of 140 km. In this case the use of three 4-car bi-mode FCH trains with 200 kg hydrogen tank system, an average power rating of 510 kW and an average hydrogen consumption of 0.36 kg/km were studied. The FCH trains would come with an additional cost of 14% compared to diesel trains. Battery-powered trains are another possible green commercial feasible alternative to FCH trains. Over ten years a total CO2 emission reduction of 1,334 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Multiple Units in Spain: In the eastern Spanish region of Aragon, a fleet of 2 Multiple Units can be retrofitted with FCH bi-mode systems so that the trains can operate beyond the catenary electrification. This will enable an expansion of services and future cross border connectivity without the associated emissions increases. The 2 FCH Multiple Units will have a range of 400 km based on a 175 kg hydrogen tank system, an average power rating of 450 kW and an average consumption of 0.31 kg/km. The FCH trains would come with an additional cost of 35% compared to diesel trains. Over ten years a total CO2 emission reduction of 767 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Multiple Units in Romania: The route from Brasov to Sibiu in the central part of Romania is characterised by a non-electrified single track with a rather low utilisation compared to other main tracks. In this case the use of new 2 car FCH trains with a 135 kg hydrogen tank system, an average power rating of 200 kW and an average consumption of 0.36 kg/km was studied. The FCH trains would come with an additional cost of 37% compared to diesel trains. Over ten years a total CO2 emission reduction of 639 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Multiple Units in the Netherlands: The Northern Netherlands provinces of Friesland and Groningen are working towards regional decarbonisation. Key to achieving this goal is retrofitting existing diesel Multiple Unit trains. The 70 FCH Multiple Units will have a range of 800 km based on a 210 kg hydrogen tank system, an average power rating of 400 kW and an average hydrogen consumption of 0.22 kg/km were studied. The FCH trains would come with an additional cost of 4% compared to diesel trains. Catenary-powered trains are another possible green commercial feasible alternative to FCH trains. Over ten years a total CO2 emission reduction of 56,389 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Shunters in Germany: In Hamburg-Billwerder, FCH Shunters have the potential to replace existing diesel Shunters in service at an intermodal freight terminal. The proximity to a large urban area and the largest inland port in Europe, make this an attractive case for further examination. The 15 FCH Shunters have a daily mileage of 200 km, a 50 kg hydrogen tank system, a maximum power rating of 800 kW and an average hydrogen consumption of 0.39 kg/km were studied. The FCH trains would come with an additional cost of 28% compared to diesel trains. Battery-powered Shunters are another possible green commercial feasible alternative to FCH Shunters. Over ten years a total CO2 emission reduction of 1,969 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Shunters in Latvia: In Riga, heavily polluting diesel Shunter operations in the Skirotava marshalling yard, on the node in the city, and between the several port terminals can be replaced with FCH Shunters. The 15 FCH Shunters have a daily mileage of 100 km, a 170 kg hydrogen tank system, a maximum power rating of 1000 kW and an average hydrogen consumption of 0.49 kg/km were studied. The FCH trains would come with a 2% less cost compared to diesel trains. Over ten years a total CO2 emission reduction of 3,350 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Shunters in Poland: In Gdansk, Poland an existing refinery and rail operator can utilise excess hydrogen from the refinery to power a fleet of 10 FCH Shunters. The co-location and operation of the refinery and marshalling yard allows for an examination of potential synergies and environmental benefits that can be captured. The FCH Shunters have a daily mileage of 25 km, a 50 kg hydrogen storage system, an estimated maximum power rating of 600 kW and an average hydrogen consumption of 0.72 kg/km were studied. The FCH trains would come with an additional cost of 14% compared to diesel trains. Over ten years a total CO2 emission reduction of 339 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Mainline Locomotives in Estonia: Existing Mainline Locomotives used to haul freight between Tallinn and the Russian border in Narva can be retrofitted with FCH components. The FCH locomotives can provide a cost effective and environmentally friendly alternative for moving freight on this popular domestic route. The 2 FCH Mainline Locomotives would have a daily mileage of approximately 500 km, a 980 kg hydrogen storage system, an average power rating of 1,200 kW and an average hydrogen consumption of 0.67 kg/km were studied. The FCH trains would come with an additional cost of 1% compared to diesel trains. Over ten years a total CO2 emission reduction of 2,556 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Mainline Locomotives in Sweden: The route from Kalmar to Linköping is non-electrified and low utilised. Therefore, the possibility of using FCH Mainline Locomotives for both passenger and freight transport on this route would be conceivable. In this case the use of 5 FCH Mainline Locomotives with an average power rating of 900 kW, an on-board storage of 450 kg hydrogen, a daily mileage of 600 km and an average hydrogen consumption of 0.48 kg/km were studied. The FCH trains would come with an additional cost of 16% compared to diesel trains. Over ten years a total CO2 emission reduction of 4,980 t could be achieved by using FCH trains instead of diesel trains on this route.

Case study on Mainline Locomotives in Germany: FCH Mainline Locomotives can be used to carry freight loads from Frankfurt (Oder) in the east of Germany to the Port of Hamburg. In doing so, they can help reduce the heavy congestion on popular mainline route segments and could eventually be used for cross-border operations, eliminating the need for time consuming train switches. The 5 FCH Mainline Locomotives would have a daily mileage of approximately 750 km, a 765 kg hydrogen tank system, an average power rating of 1,350 kW and an average hydrogen consumption of 0.82 kg/km were studied. The FCH trains would come with an additional cost of 30% compared to diesel trains. Catenary-powered Mainline Locomotives are another possible green commercial feasible alternative to FCH Mainline Locomotives. Over ten years a total CO2 emission reduction of 12,874 t could be achieved by using FCH trains instead of diesel trains on this route.

Even though there are no show-stoppers for the fast and broad roll-out of FCH trains, there are still many barriers that must be overcome. On the one hand, these barriers are economic, for example if FCH trains have to be competitive with current diesel technology despite high electricity prices. In some countries the permitting process for hydrogen infrastructure is also more complex than for comparable technologies. On the other hand, there are technological barriers. At the moment, train original equipment manufacturers (OEMs) and FCH component producers still are developing know-how and working experience with standardised, scalable and customisable hybridised powertrain design.

Many different current developments within the energy transition (i.e. volatile power generation, electricity oversupply, etc.) and between different means of transport (i.e. multi-modal approach) will further leverage the benefits for FCH technology and make hydrogen an essential energy source for the future low-emission world. Therefore, focus topics were studied in more detail.

The overall system and its optimisation are important for hydrogen technology in the train sector. Currently, work processes and technology are very strongly oriented towards existing technologies (e.g. diesel technology or catenary). According to a study of different focus topics, it is noticeable that three areas are particularly interesting:

- The multimodal approach, which increases the initial offtake and consumption of hydrogen in order to maximize the utilization of the hydrogen infrastructure
- The technical requirements, which are to be optimized primarily for the route and the intended usecase, but at the same time configure a locomotive type that is flexible enough to be used for similar usecases
- The renewable H2 generation via electrolysis as a source of low-emission hydrogen produced using the volatile generation capacities of renewable energies

Multimodal approach: Based on the France case study, the influence of other hydrogen consumers was analysed within the framework of a multimodal approach. For this purpose, other modes of transport with a hydrogen drive were integrated into the calculation of the TCO, which leads to a reduction of the proportional infrastructure costs. In the investigated case the decrease of hydrogen could be increased from 300 kg to 1.2 t per day, which leads to a reduction of the TCO of the FCH technology in the railway application by 3%. These investigations were also carried out for other cases and generally it can be stated that the consumption of hydrogen in the train application has reached a critical level to be economical. The configurations of refuelling stations used in this report already cover the relatively high consumption of FCH trains and are fully utilised. The multimodal approach does not allow a significant additional load to be achieved; it leads to an expansion of the total capacity, which shows economies of scale. Nevertheless, the broad integration of hydrogen, in the most diverse modes of transport, is certainly a key to systemic success.

Technical requirements: A detailed analysis with route and altitude profiles is necessary to derive the correct technical specifications for FCH trains. Enough flexibility must be maintained, but at the same time the hybridisation and battery/fuel cell systems must be selected in such a way that the trains have both low cost and performance requirements. Operators usually orient themselves on the existing diesel trains, even if the performance profiles are not tailored to requirements. The accurate train configuration is the basis for economic and environmental calculations.

Renewable H2 generation via electrolysis: Fuel cell and hydrogen technologies can help in the transition to a low-emission future, via hydrogen produced by with renewable energy. However, these assets have not been deployed at the scale necessary to power large FCH train fleets. As the cost of hydrogen is closely tied to the cost of electricity, the sourcing and pricing of electricity as well as the asset utilisation levels of power-to-gas plants should be carefully considered when ensuring a renewable H2 value chain.


TGV 1
12
10
TGV 2
12
10

1. A SPECIFIC VIEW OF FCH TECHNOLOGY IN THE RAILWAY SECTOR

The European Union and its Member States have made a clear commitment to lead the way in environmental protection.[1] One of the key pillars of the EU environmental protection scheme is reducing greenhouse gas emissions, other air contaminants and noise.[2] A first step to reduce greenhouse gases is already done. The rail system has been a pioneer in electrification with 80% of its traffic running on electrified lines (representing 60% of the mainline network).[3] 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.

FCH trains have been trialled globally and technology developers have moved beyond the proof-of-concept phase.[4] However, in order to prepare a commercial roll-out on 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 public side. Additional subsidies could potentially be crucial for further technology development due to the 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.

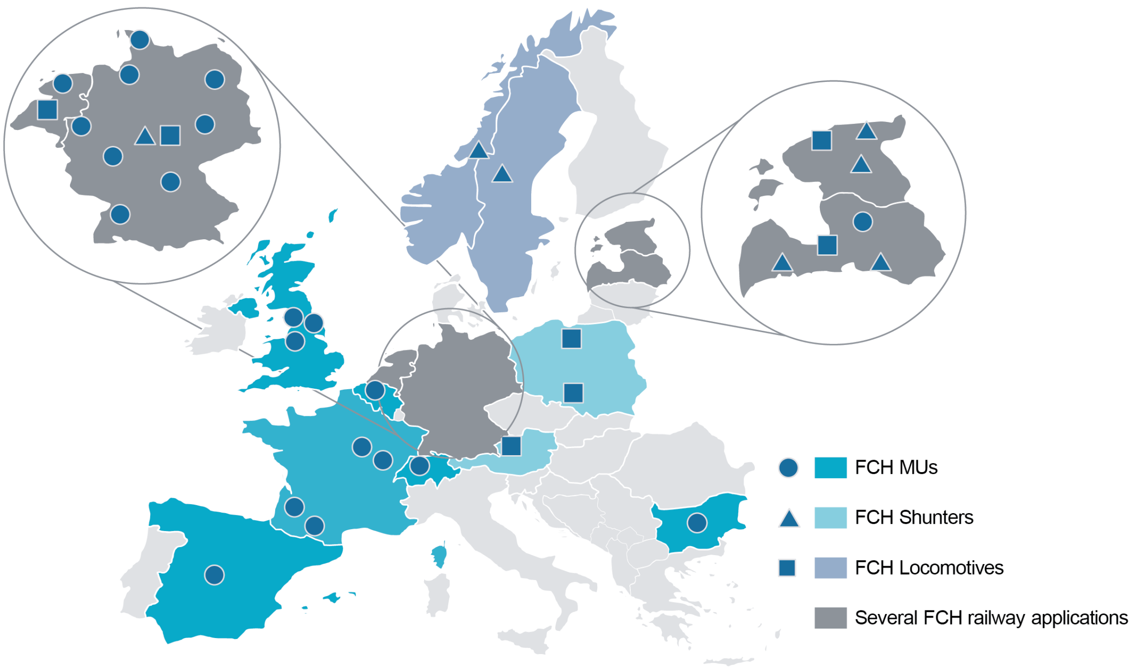

Figure 1: FCH rail case identified in whole Europe

[1]Publications Office of the European Union, 'Environment: A Healthy and Sustainable Environment for Present and Future Generations', Website, 3 November 2014, https://publications.europa.eu/en/publication-detail/-/publication/3456359b-4cb4-4a6e-9586-6b9846931463.
[2]European Union, 'Transport: Connecting Europe's Citizens and Businesses', November 2014, http://europa.eu/!bY34KD.
[3]EUROPEAN COMMISSION, 'Electrification of the Transport System', n.d.
[4]Maciej Andrzejewski, 'The Latest Technical Solutions in Rail Vehicles Drives', vol. 118, 00015, 2017.

In this study ten specific cases with country and route specific assumptions will be analysed in detail. Most available studies look at new technologies or applications from a general perspective.[5] These studies repeatedly point out that specific investigations of individual cases are necessary in order to obtain a more accurate result. The differences between countries, routes and applications will be highlighted. The countries of the European Union have very different framework conditions for FCH train applications. This can be seen, for example, in the different energy prices, the expansion and investment in infrastructure, the degree of electrification of the routes (main and secondary routes) and the legal framework. All these factors influence not only the actual feasibility but also the commercial competitiveness of FCH technology.

Routes also have very different characteristics. The electrified sections and their respective location have an influence on the derived train specifications. It is also essential to examine whether the operations carried out, e.g. at container transhipment terminals, allow no overhead lines at all, what distances have to be covered daily and how the duty cycle of the specific route is defined. The use of hydrogen or other clean solutions can lead to a change in the duty cycle. At the same time, the height profile and the number and length of stops also affect the configuration of the train and thus, indirectly, the costs.

The differences also apply to the differentiation of individual applications such as Mainline Locomotives, Shunters or Multiple Units. Especially here it is interesting to take a look at the different and very specific use cases of the applications. As an example, Shunters can also be used for longer transport of freight wagons if they are located within an industrial infrastructure. This can result in a daily mileage of several hundred kilometres, which is very different from the defined standard Shunter usage profile.

Overall, the report is intended to provide an overview of 10 different train routes in Europe and consider the possibility of incorporating new and clean alternative train technologies. This report cannot claim to derive any overarching statements – rather it serves to illustrate the problem and to present solution variants or examples of procedures as a starting point for a potential future detailed feasibility study.

Furthermore, barriers are presented in the individual case studies. The barriers presented in this report are only exemplary for the case in hand and are intended to give an impression of what core challenges exist. In Report 3, a clear structuring of the common barriers is carried out, their priority is assessed and R&I needs are derived.

During the analysis and in discussion with the stakeholders, overarching topics were identified that are worth to closer investigate. These focus topics enable a holistic view of hydrogen technology and the representation of interfaces to the environment.

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[5] N. P. Brandon and Z. Kurban, 'Clean Energy and the Hydrogen Economy', Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences 375, no. 2098 (28 July 2017), https://doi.org/10.1098/rsta.2016.0400.

2. RATIONALE FOR THE CASE STUDIES SELECTION

Identification and analysis of concrete case studies allows this report to explore the boundaries of FCH rail applications. Technological barriers, regulatory constraints or aspects related to limited economic competitiveness are difficult to identify and explain if only assessment of generic cases is performed. The starting point has been represented by a long list of case studies identified through the joint efforts of the study's Advisory Board (AB) members, supplemented by additional desk research to ensure wide coverage of current and envisaged European FCH rail initiatives.

The analysis revealed a heterogeneous collection of more than 35 case studies throughout 13 European countries. All three rail applications in focus (Multiple Units, Shunters and Mainline Locomotives) are extensively covered by the long list of case studies, with a higher ratio of Multiple Unit cases as a normal consequence of current technology progress. Variances are displayed in terms of potential fleet size or acquisition method (retrofit or newly built), creating a broad selection pool for envisaged shortlisting.

To arrive at the most meaningful selection of shortlisted case studies a prioritisation framework has been developed and used based on several quantitative and qualitative criteria:

- Project ambition and maturity – Expected size of the project and implementation timeline, with preference towards earlier project timeframes and larger volumes.
- Synergies with other modes of transport – Preference for multimodal approach to raise awareness of hydrogen applications and potentially maximise infrastructure utilisation.
- Geographical coverage – Balanced mix of EU member states targeted, coupled with preference towards diversification of countries within each railway application.
- Technological challenges – Preference for projects with special characteristics (e.g. high power rating, hybrid operations), but also balanced acquisition approach, with both retrofitting and newly built targeted.
- Commitment level – Preference for increased overall interest level in developing and implementing FCH rail projects, but also existing political commitment on national or regional level to support further decarbonisation of (rail) transport.
- Coverage by other reports/studies – Preference towards selection of case studies which have not been the subject of other studies and/or research reports in order to focus resources towards unexplored cases.
- Market size – Broad perspective envisaged, with representation desired from both larger and smaller markets.

As an overall selection approach, a balanced selection of case studies has been targeted.

	Location	Application	Country
1	Groningen & Friesland		NL
2	Aragon region		ES
3	Montréjeau – Luchon		FR
4	Brasov – Sibiu		RO
5	Riga node		LV
6	Gdansk		PL
7	Hamburg-Billwerder		DE
8	Frankfurt (Oder) – Hamburg		DE
9	Kalmar – Linköping		SE
10	Tallinn – Narva		EE

Figure 2: Overview of selected case studies

Based on the prioritisation framework mentioned above, 10 case studies have been shortlisted, equally divided among the 3 applications in focus (Multiple Units, Shunters and Mainline Locomotives). The complete list of the case studies is presented below on a high level, along with examples of their special characteristics:

- **Multiple Units –** Three West European case studies in the Netherlands, Spain and France and one case study in Romania were selected. Northern Netherlands provinces display a high level of commitment towards FCH technology, with an existing hydrogen roadmap already available, including clean hydrogen production. The case study in the Spanish region brings challenging climatic conditions with a mountainous route profile. The Montréjeau-Luchon case study from France displays a different technological consideration focusing on a bi-mode rail application, which can use both catenary and FCH technology. The Romanian case study is characterised by a long non-electrified line with low utilisation.
- **Shunters –** Applications were selected from Latvia, Poland and Germany, with East European studies aiming at retrofitting old Shunters, while the German example is looking at newly built rolling stock. Moreover, higher technological requirements (i.e. power rating) are envisaged in Germany. The implementation of FCH Shunters in Riga node highlights potential of hydrogen sourcing from a nearby refinery.
- **Mainline Locomotives –** Applications were selected from Germany, Sweden and Estonia. In Germany a potential cross border line on a highly utilised route is being studied. The Swedish case study will show the full possibilities of Mainline Locomotives used to transport both passengers and goods. The Estonian case study will show an international rail project that links the Baltic countries with Poland and Germany.

3. CASE STUDIES ON HYDROGEN RAIL APPLICATIONS

In this chapter specific routes for Mainline Locomotives, Shunters and Multiple Units are examined in detail. The characteristics of each route are described. After a short introduction the location is specified, followed by background information about the current operation on the route. Route profile and specifications will define the train requirements. In addition, the local climatic profiles are used to improve the estimation of hybridisation (fuel cell, battery capacity split). For this purpose, in colder regions, for example, a higher energy consumption is assumed for the climatisation of the batteries and possibly the hotel power. Based on the derived train configuration, economic and environmental analyses are performed. At the end characteristic barriers for the case study are identified.

The case studies were prepared using expert interviews with stakeholders and extensive desk research. Other industry experts were also interviewed. The economic study is based on the Roland Berger Total Cost of Ownership Model, which compares the costs of different technologies for defined cost items. An explanation of the whole cost items can be found in the Annex.

New technologies typically come to market at a cost premium. 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 monetisation 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 this study. Furthermore, the chapter provides information on the market potential for FCH trains. Since costs are a strong driver of 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.

The Detailed Business Case Tool was developed in the context of this study (Report 1) to illustrate potential TCO development and high level evolution of total costs for roll-out of different sizes of FCH railway fleets and deployment of associated hydrogen refuelling and production infrastructure considering selected specific local framework conditions. As such, the tool provides a good first indication of the effect of different levers on the overall cost development for three different types of FCH railway applications and associated infrastructure (hydrogen refuelling station and hydrogen production):

1. Multiple Unit

2. Shunter

3. Mainline Locomotive

A first input data set contains all cost assumptions for trains, hydrogen refuelling station (HRS) and hydrogen (H2) production facilities. All of the FCH railway applications are in an early stage of development, therefore, current and future costs are difficult to forecast. Also, for HRS and H2 production facilities cost figures can vary significantly depending on specific local requirements. Therefore, assumptions included in the tool or in the cases need to be treated with caution and should be validated individually for each deployment project.

For the specific cases studied in this report, costs are computed based on basic input parameters for each specific train application, country and route. Country-specific data sets were taken into the model (e.g. deployment scheme, feedstock prices, financing costs, weighted average cost of capital (WACC), energy prices, salaries etc.). The basic cost calculation will also rely on the standard cost data that was already outlined in the first report. If additional case-specific data was available, the calculation was customised for subsequent example parameters and assumptions for trains, HRS and hydrogen production facilities. If no additional parameters were known, the calculation was done based on the general cost projections for FCH railway applications and hydrogen infrastructure that were generated during the whole study.

The tool itself does not automatically reflect specific circumstances of individual countries or the parameters of individual local operation set-ups. Therefore, the results generated by this tool are indicative and are no substitute for the development of detailed business cases for individual locations (based on real quotes from potential suppliers) and taking into consideration all individual associated risks and costs (e.g. for prolonged permitting processes, infrastructure configurations differing from the standard assumptions included in the tool, project and stakeholder management etc.). In addition, the tool also takes into account the country-specific electricity mix for the calculation of the environmental impact assessment.

After all parameters for the countries, routes and train applications were defined; the infrastructure and train basic concept design was done and discussed with the stakeholders. These additional configurations of the standard TCO model will allow the calculation of the TCO items of each train application.

An in-depth analysis of the potential technological and non-technological barriers for use of FCH technology in different rail applications was also conducted as a part of the third report, through case analysis and stakeholder input. Beyond the hard facts, the dialogue with stakeholders revealed that, despite defined use cases, a high degree of flexibility of the trains is always required. This means that the operator does not buy a tailor-made solution that is subsequently limited to a certain route. This is especially the case for last mile delivery and passenger trains on secondary routes.

FCH powertrain is the most economical clean solution for many case studies. In general, it could be shown that catenary is always worthwhile for high capacity utilisation of a route and that battery trains are particularly useful for very short daily mileage.

In the generic use case presented in Report 1, the cost differences between diesel and FCH Multiple Units and locomotives were investigated. The generic use case showed an overall high potential for FCH train applications. The specific case studies examined in this report were able to confirm the results of the first report. To estimate the exact TCO differences, specific route parameters must be considered. In the first report, the minimum cost premiums for Multiple Units, Shunter and Mainline Locomotives were calculated. For Multiple Units a TCO premium of 6% was determined. Shunter showed a TCO premium for FCH trains in comparison to diesel trains of 13% and Mainline Locomotives exhibited a TCO premium of 14%.

In the specific case studies of this report, Multiple Unit trains have shown a TCO premium of 20 - 80%, which is higher than the premium calculated in the generic case. This is mainly due to the relatively small number of train units and a low daily mileage. For Shunter have shown similar TCO premiums of 5% - 10%. For Mainline Locomotives lower TCOs premiums of 0% - 20% have been calculated.

3.1 CASE STUDIES ON MULTIPLE UNITS

Multiple Units with a fully electric powertrain have already been deployed and are operating on the main traffic routes in all European countries. They transport people from the main stations to smaller stations. However, diesel-electric Multiple Units are still used today, because remote cities have to be served. One example is the deployment of the trains in the mountains or in rural areas.

Different specifications are defined depending on the route and country. In some countries with a flat route profile and large distances between locations, trains with a higher maximum speed are used, while other routes with a stronger elevation profile place higher demands on the average power than on the maximum speed of the train. Depending on the number of passengers that are foreseen to be transported, between 2 and 4 car units are used. Whether these are equipped with entirely motorised railcars or also have non-motorised cars depends on the operator's strategy.

FCH powertrains for Multiple Units show promising economic and ecological advantages, as the routes are usually connected to a main traffic junction, which has the necessary infrastructure for the on-site production of hydrogen. At the same time, trains usually have to pass through densely populated areas and also stop in scenic areas or mountains, where emissions should be avoided. In addition, some of the population is demanding innovative and environmentally friendly applications. The demand for Multiple Units is high, which is why new models can usually be introduced. Current models have sufficient space for hydrogen technology (fuel cell, cooling system, batteries, and hydrogen storage).

Three factors are important for the success of the introduction of FCH Multiple Units:

1. Right from the start, it is worth thinking about an overall system and, as far as possible, developing many routes from one starting point with hydrogen trains.
2. The trains must be dimensioned beyond the specifications of the actual line so that they are also flexibly available for use on other routes.
3. Hydrogen as a fuel and storage medium for electricity can take advantage of fluctuating energy prices and capitalise on times of low-cost hydrogen production to optimise the overall operating cost.

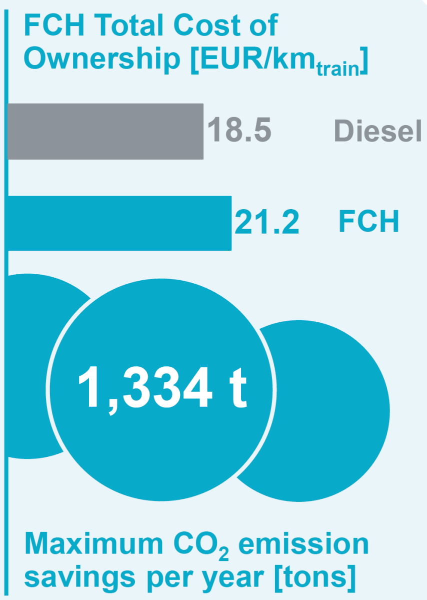
3.1.1. MULTIPLE UNIT CASE: MONTRÉJEAU – LUCHON (FRANCE)

Montréjeau – Luchon, France: Last mile passenger service

The route from Toulouse to Luchon is only partly electrified and characterised by a rather low utilisation in the mountainous region of Luchon.

In this case the use of three 4 car bi-mode FCH trains with 200 kg hydrogen tank system, an average power rating of 510 kW and a maximum tractive effort of 140 kN are studied in more detail. With a maximum FCH-powered range of 500 km, the FCH trains would have a mark-up of 14% compared to diesel trains. In addition, local decision-makers have spoken out against diesel trains and electrification.

Track length	140 km	**Nº of rolling stock**	3 x 4 car trains
H_2 fuel consumption	0.36 kg/km	**Capacity/ load**	230 seats

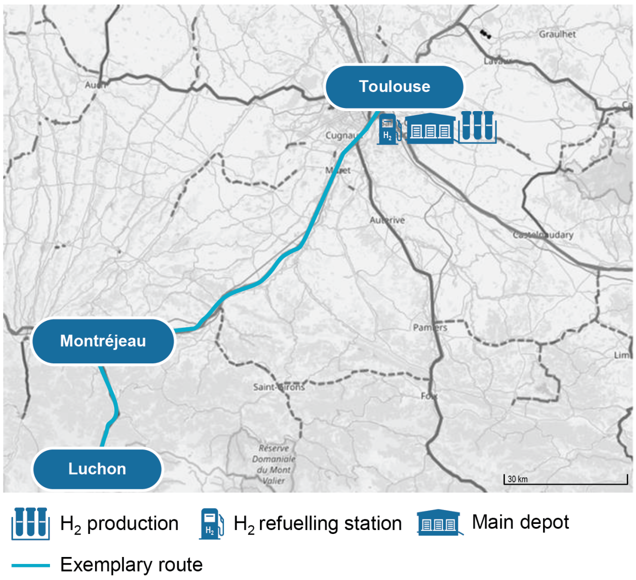


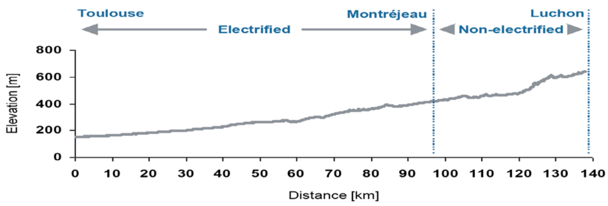
INTRODUCTION

In this case study, an extension of the rail service from Toulouse to Montréjeau and then onwards to Luchon is analysed. It provides an example of how communities in a mountainous area can be effectively re-connected to larger cities with zero-emission rail solutions. Large parts of the track are already electrified and only a shorter part is without electrification.

The European rail network has already reached a high level of electrification.[6] In remote areas, however, electrification is usually not cost effective or, as in this case, the maintenance costs are too high due to the low utilisation of the route. In these areas, diesel trains, which have had no alternative in recent years, are the main type of train used. A closer examination of this case is interesting, as it looks at the potential use of FCH trains in a remote mountain region. The general conditions in France – constant electricity prices due to nuclear power plants with low carbon emissions combined with a developed technology sector in the Toulouse region – make this case well suited for a more detailed investigation. At the same time, the integration of other sectors in the form of a multimodal system can be investigated as a focus topic.

LOCATION





The potential route is located in the south-west of France in the foothills of the French Pyrenees. The route has a total length of 139 km. An existing electrified 103 km service from Toulouse to Montréjeau can be extended on 36 km of formerly electrified track to Luchon.[7] This part is currently without active rail service.

The potential trains shall run on catenary electrification from Toulouse to Montréjeau and then switch to FCH power for the non-electrified distance of 36 km to Luchon.

Starting from Toulouse the trains run on flat terrain with an elevation gain of 285 m in 120 km. After the initial 120 km, the trains climb 109 m in 8 km, the steepest part of the route. This represents a maximum gradient of 1.3%.[8] The climate profile of the potential route includes temperatures of -20 °C to 35 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[9]

[6]Union européenne and Commission européenne, EU Transport in Figures 2017, 2017.
[7]'Haute-Garonne: Les rails sont trop vieux, le TER est supprimé', accessed 14 November 2018, https://www.20minutes.fr/toulouse/1467711-20141024-haute-garonne-rails-trop-vieux-ter-supprime.
[8]ARCGIS', accessed 12 November 2018, https://www.arcgis.com/apps/Profile/index.html.
[9]Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

BACKGROUND OF THE CASE STUDY

In 2015, increasing catenary maintenance costs and underutilisation led the rail operator to discontinue the service to Luchon. Since then, communities along the route have been pushing for restoration of service. For local citizens, trains help reduce road congestion and limit emissions. The train service also stimulates the local economy by enabling visitors and tourists to easily access the mountain resorts, and locals to commute to more distant workplaces in the region.

However, the costs of refurbishing and maintaining the catenary infrastructure were too high for the operator. The community also objects to an alternative service that would be provided by diesel locomotives. In such a case, FCH Multiple Units could provide an attractive, low-emission alternative to diesel Multiple Units with lower costs than refurbishing the catenary electrification.

The potential service could be operated using FCH bi-mode Multiple Units, enabling trains to operate under catenary electrification until Montréjeau and then powered by FCH for the last leg to Luchon. This could provide operators with the necessary flexibility and cost savings while reinstating the service for the local community.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The route that could be serviced with bi-mode trains would entail an additional four stops, of approximately one minute each and one final stop of 15 minutes. An existing fleet of three, 4-car diesel bi-mode Multiple Units carrying approximately 230 passengers could be retrofitted. The retrofit would replace the diesel powertrain with the necessary FCH powertrain components while existing electric components would be maintained.

Key data		Comment
Case specifications		
Deployment:	3 train sets	4-car bi-mode Multiple Units (~230 seats)
Expected daily mileage:	200 km	36 km per route will be driven on non-electrified route segments, which will give a total non-electrified daily mileage of 200 km
Expected days of operation:	365 days	
FCH train specifications		
CAPEX per train set:	EUR 7,320,000	Retrofitting of 4-car units including fuel cell, hydrogen storage system, battery, integration of catenary system for bi-more operations, structural changes of the units, redesign of interior, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.36 kg(H_2)/km	
Maintenance costs:	1.10 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~300 kg(H_2)	350 bar
Production facility:	1x 0.5 MW	On-site facility installation, 350 bar

Table 1: Technical and commercial specifications for Montréjeau – Luchon (France) case

The FCH-powered system includes the fuel cell stack, on-board hydrogen storage and traction batteries. The train would be equipped with a 200 kg hydrogen tank system allowing a maximum range of 500 km with an average consumption of 0.36 kg(H2)/km.

The expected duty cycle for the FCH-powered system is twelve hours of daily operation. The daily FCH mileage of each train could reach up to 200 km – thus, the whole fleet would require up to 245 kg(H2) daily. Under the defined duty cycle, the FCH Multiple Units would need a full refill after 2.5 days. However, it is better to refill the train every day and thus limit the hydrogen refuelling station storage capacity, saving infrastructure costs. Due to the needs and flexibility required by the operator, the trains considered have been optimised for flexibility and interoperability across the broader network. Further TCO savings could be realised if the on-board FCH system is specifically optimised for the route in question.

The related infrastructure includes a hydrogen refuelling station and an on-site hydrogen production facility located at Toulouse Matabiau station. The hydrogen refuelling station is expected to serve all 3 bi-mode Multiple Units and should be designed to have a capacity of 300 kg hydrogen. The infrastructure should allow two trains to be continuously refuelled with an approximate refuelling time of 30 min. The storage capacity should also be twice the daily hydrogen demand (~600 kg) to ensure two full days of train operations. Hydrogen would be produced on-site via a 0.5 MW electrolyser producing ~300 kg of hydrogen a day.

Parameter	Value	Notes
Max. power rating	1,170 kW	
Avg. power rating	510 kW	
Max. tractive effort	140 kN	
Max. capacity	230 seats	(4-car bi-mode unit)
Max. speed	120 km/h	> Typical maximum speed ranges from 100 to 160 km/hour > Over longer distances usually higher speed
Hydrogen tank	~200 kg	> Typical tank volume for a 2-car MU approx. 1,600 l of diesel
Avg. Consumption	~0.36 kg/km	
Max. range	~500 km	> Typical range of approximately 1,000 km > Depends e.g. on passengers on board, stops and topography
Price	EUR 7.3 m	> Retrofitted train
Lifetime	30 years	
Tractive motors	630 kW	
Compressor	88 kW	
Auxiliary and hotel power	441 kW	
Space	21 m³	
Battery capacity	100 kWh	
Fuel cell size	450 kW	
Weight	75 t	

Table 2: Train specifications for Montréjeau – Luchon (France) case

ECONOMICAL ASPECTS

For an FCH-powered train the TCO is 21.2 EUR/km.[10] In this case study, a total estimated investment of EUR 2-3 m for the hydrogen infrastructure would be required. This figure includes 600 kg H2 storage and refuelling infrastructure that has been customised to the site requirements. For this specific infrastructure, the HRS has a cost of EUR 0.7 m and additional costs of EUR 0.3 m. The H2 production infrastructure is based on a standard 0.5 MW electrolyser that has been modified for the case specifications, resulting in an estimated cost of EUR 0.7 m and a compressor skid with an estimated cost of EUR 0.4 m.

The CAPEX for 3 trains, including batteries and FCH components, is EUR 22 m. This results in financing costs of 3.4 EUR/km based on a WACC of 5.7%. The train maintenance costs, including the planned replacement of fuel cells and batteries, amount to 1.1 EUR/km. With an average consumption of 0.36 kg/km and on-site hydrogen production through electrolysis, fuel costs are expected to be 1.58 EUR/km. The electricity price is assumed to be 68.6 EUR/MWh.

Compared to the diesel bi-mode option, the FCH solution has 2.63 EUR/km higher TCO. This difference is mainly driven by higher CAPEX for the FCH-powered train of 0.93 EUR/km, although some of the added cost is offset by lower fuel and maintenance costs. The diesel price is assumed to be 1.0 EUR/l.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. As an alternative to hydrogen generated by an electrolyser, the overall TCO for the FCH-powered train can be reduced by 1.16 EUR/km to 20.01 EUR/km if hydrogen can be sourced for a flat rate of 3.00 EUR/kg. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary-electric units and battery-powered trains are available as alternative solutions. Overall, the TCO for catenary-electric units is 6.35 EUR/km higher than the TCO for the FCH-powered train. A catenary-electric unit would entail higher costs for financing due to higher CAPEX for the catenary electrification. The catenary electrification also leads to significantly increased maintenance costs despite overall lower fuel costs.

For battery-powered trains, the route characteristics and existing catenary electrification on approximately 75% of the route could reduce the required number of recharging stations to one if units are able to charge with catenary electricity. This charging station should be situated in Luchon. If recharging with catenary electricity is not possible, more stations will be needed. The short non-electrified segment limits the battery capacity, leading to lower train costs. The short segment should also not require a change in the train's planned operations (number of stops, departure and arrival times), to facilitate charging in Luchon to 80% prior to returning.

From a purely TCO perspective, the battery-powered train option might be commercially more attractive than an FCH option. However, there are still significant operational constraints and technological barriers concerning batteries in the rail environment that should be outlined in this first case study in order to get an overview of the potential uncertainties. The battery lifetime and life cycle will be impacted by the described route: the steep incline and winter cold weather conditions may limit the batteries' performance. Lower battery performance could lead to the unexpected depletion of battery charge while the train is in service or has a longer stop.

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[10] The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

Additionally, battery-powered trains do not provide the necessary operational and network flexibility that could be a key requirement of a potential operator and could significantly impact planned operation schedules. Due to the remote location of Luchon, the charging station may also require greater CAPEX if the existing grid infrastructure cannot meet the stations' power requirements. Further detailing on battery-powered trains can be found in the Annex. The assumptions for the calculations were equally conservative in all powertrain technology variations and possible uncertainties were taken into account in the respective TCO calculations.

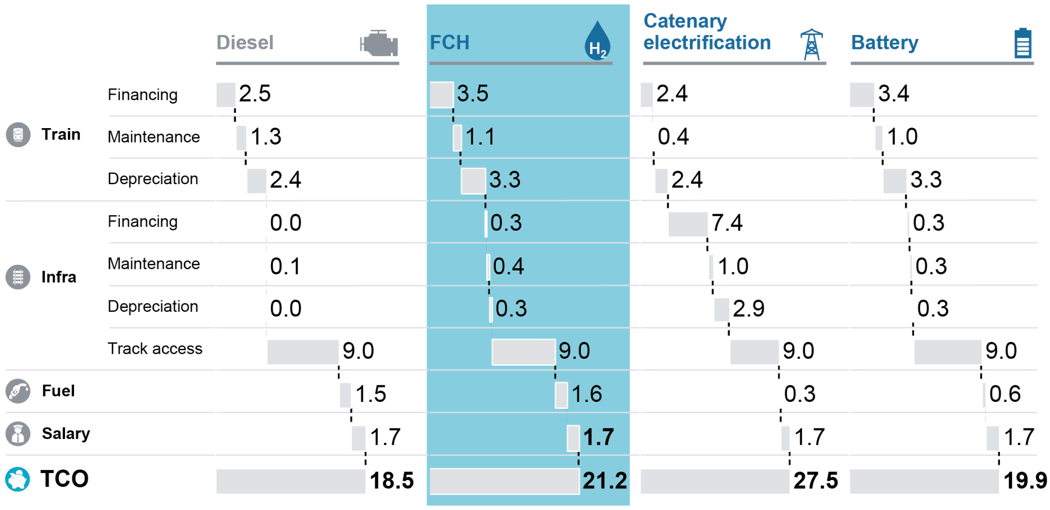

Figure 3: TCO analysis of different technological options for Montréjeau – Luchon (in EUR/km)[11]

ENVIRONMENTAL PERSPECTIVE

Compared to diesel technology, the FCH-powered trains could save up to 1,033 t of carbon dioxide (CO2) emissions in the first year of operation if the French grid electricity mix is assumed. Through 2030 these could generate accumulated savings of 9,586 t CO2, 45 t nitrogen oxides (NOx), and 11 t of organic particles between 2.5 and 10 microns in diameter (PM10). France has a very low-carbon electricity mix, caused by the large share of nuclear electricity production. In 2015 France produced 416.8 TWh with nuclear power plants, 58.7 TWh with hydropower and 21.1 TWh with wind power plants. Conventional high-carbon electricity production amounts to less than 30 TWh including gas combined cycles, cogeneration gas and coal.[12]

In addition, CO2 emission could be reduced by more than 26% when using a completely carbon-free power supply for hydrogen With a car operating an assumed 13,000 km per year and producing 110 g CO2/km, this is equivalent to taking 700 cars off the road per year.[13]

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[11]All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.
[12]Direction de l'économie, de la prospective and et de la transparence, 'BILAN PRÉVISIONNEL de L'équilibre Offre-Demande D'électricité En France', 19 October 2016.
[13]European Federation for Transport and Environment AISBL, 'CO2 EMISSIONS FROM CARS: The Facts', April 2018.

Given the landscape within the mountain valley and the proximity to housing and wilderness areas, an emission free solution with minimal impact on the landscape like FCH trains could reduce the local environmental impact. Additional reductions in local vehicle traffic driven by the introduction of rail service would also lower the local ecological impact.

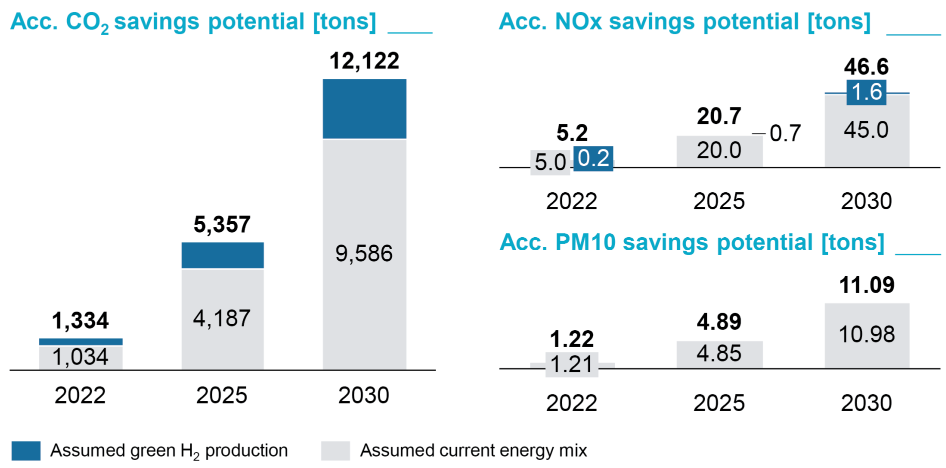


Figure 4: Emission saving potential for Montréjeau – Luchon based on two scenarios (in tons)

1.4 million people live in the Haute-Garonne region. Most of them live directly in the prefecture of Toulouse. The rest of the region is rather rural and about 15,000 people are directly affected by the non-electrified railway route. The majority of people live in single-family houses with up to 3 floors. There are hardly any sources of noise in the immediate vicinity. There are no main roads through the villages. Even though the region is heavily developed for tourism, there is no need to operate the trains at night. However, most of the noise is not caused by the powertrain and the local operator is already taking passive noise protection measures.[14]

It would be conceivable that the use of environmentally friendly trains connecting the prefecture with the countryside would also lead to an additional increase in the use of railway traffic. Similar effects have already been demonstrated on electrified routes. In this case, a new sustainable technology would possibly boost positive perceptions of public transport.[15]

BARRIERS FOR SEAMLESS IMPLEMENTATION

In this case, economic, technological and legal barriers were identified. First, the significant capital expenditures, staff re-training and operational changes required to deploy hydrogen trains will be relatively cost and effort intensive in proportion to the impact generated by the small amount of trains (three) being considered here. Second, a study on the engineering and certification processes required for bi-mode operations will also be needed prior to the trains' deployment. The combination of catenary electric systems and hydrogen storage may exceed existing Explosive Atmosphere (ATEX) compliance requirements, especially in enclosed environments like tunnels and stations.

[14]'Preventing and Reducing Railway Noise to Protect Quality of Life', SNCF Réseau, 1 February 2016, https://www.sncf-reseau.fr/en/about/sustainable-development/environment/noise-reduction.

[15] Saturday Walkers Club, 'The Sparks Effect', Saturday Walkers Club (blog), accessed 4 December 2018, https://railway-history.walkingclub.org.uk/2010/01/sparks-effect.html; Michael Scott Moore, 'Start Slow With Bullet Trains', Pacific Standard, accessed 4 December 2018, https://psmag.com/environment/start-slow-with-bullet-trains-29853.

Finally, the French legislation applicable to gaseous and liquid hydrogen storage is the "ICPE rubrique 4715", which defines different permitting procedures depending on thresholds. In the present case study, the French legislator has already provided simplification, but further obstacles can still be removed. France also has a relatively long 12-month HRS construction permitting phase and very high safety distance for hydrogen storage. This can be seen as a structural barrier and could imply logistical difficulties.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 3: No available designs for FCH bi-mode operation and uncertainty around interaction between catenary and FCH system

Barrier 25: Lack of specific permitting process for rail related hydrogen infrastructure

Barrier 31: Complex build-up of hydrogen refuelling infrastructure across a national rail network

Further details on these barriers can be found in in Report 3 of this project.

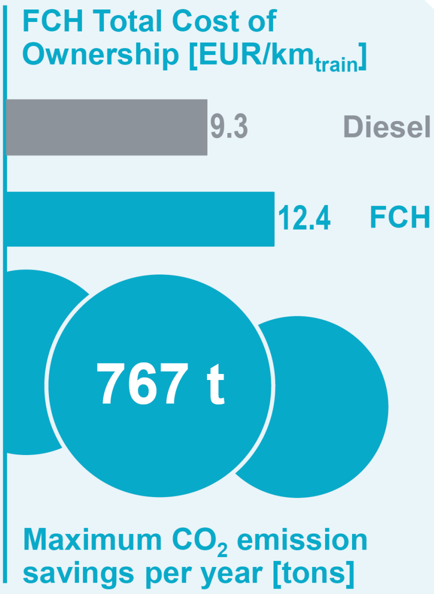
3.1.2. MULTIPLE UNIT CASE: REGION ARAGON (SPAIN)

Aragon, Spain: Powering rail transport with green hydrogen

In the eastern Spanish region of Aragon, a fleet of 2 Multiple Units can be retrofitted with FCH bi-mode systems so that the trains can operate beyond the catenary electrification. This will enable an expansion of services and future cross border connectivity without the associated emissions increases.

The 2 FCH Multiple Units will have a range of 400 km based on a 175 kg hydrogen tank system, an average power rating of 450 kW and a maximum tractive effort of 147 kN. The FCH Multiple Units have a TCO 3.1 EUR/km higher than existing diesel technology.

Track length	165 km	**Nº of rolling stock**	2 x 4 car trains
H_2 fuel consumption	0.31 kg/km	**Capacity/ load**	270 seats

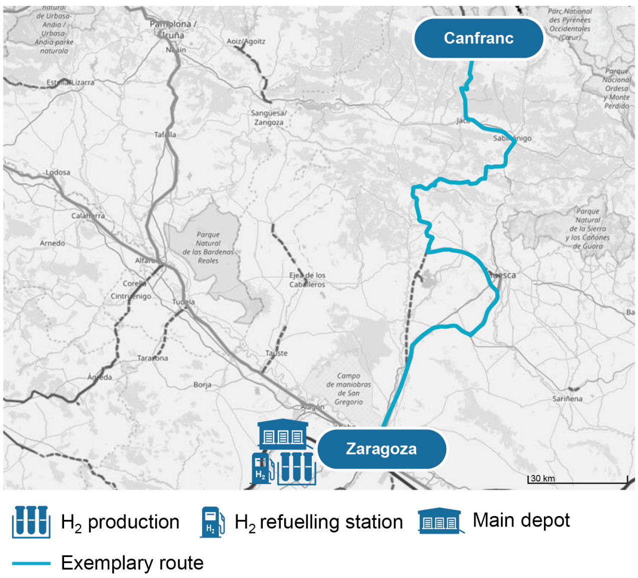


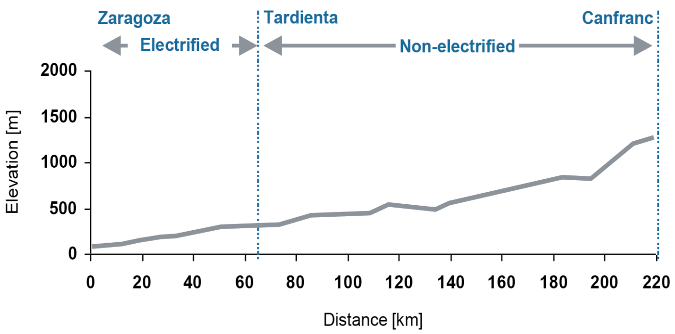
INTRODUCTION

This case study analyses the deployment of FCH bi-mode Multiple Units on a route in the eastern Spanish region of Aragon. This case examines how an operator, striving to reduce the environmental impact of services on routes where service frequency does not justify investment in catenary electrification, can use FCH as an alternative to incumbent diesel technology. The route in question runs from the Spanish city of Zaragoza to the mountain community of Canfranc.

This particular route is a focus for French, Spanish and European Union policymakers seeking to expand cross border transport connections from Zaragoza to Canfranc and on to Pau in France. This case explores how such an expansion of services and interregional and cross border connectivity can be expanded through the use of FCH-powered trains. FCH trains could enable operators and infrastructure managers to quickly realise cross border connections, capture environmental benefits and avoid costly and time-consuming investments in catenary electrification. The Multiple Units should be capable of running on the different voltage systems in France and Spain. Additionally, this case allows for an examination of how a renewable hydrogen production value chain can be established to fuel such a train deployment.

LOCATION





The Aragon region in eastern Spain is the focus of this case. The route being analysed is operated between the main rail station in Zaragoza, and the final stop of the line in Canfranc. The route is approximately 230 km in length, and has a total of 10 stops. Of this 230 km, approximately 28% (65 km) of the route from Zaragoza to Tardienta has catenary electrification. In this case, bi-mode units would be deployed, and the FCH powertrain would be used for approximately 165 km of the route in each direction.

The route in question involves a large variation in climate and geographic conditions. The route starts in Zaragoza at 200 m above sea level and climbs into the Pyrenees with an elevation of 1,200 m. The trains servicing this route would need to operate in the range of temperatures along the route which includes temperatures of -20 °C to 45 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[16]

[16]Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

BACKGROUND OF THE CASE STUDY

Through the Connecting Europe Facility, the European Union, France and Spain have invested EUR 15 m in studying the expansion of rail services from Zaragoza through Canfranc to Pau.[17] This route could enable greater connectivity of Pyrenees towns with stops along the route and ease cross border transport between Pau, Zaragoza and the neighbouring French and Spanish regions. FCH Multiple Units can help speed the realisation of these connectivity goals. Installing a catenary electrification is time consuming and expensive. Furthermore, if the eventual goal is to have seamless rail service where passengers do not have to switch trains in France, FCH Multiple Units can deliver this. Catenary electric units would have to be specially retrofitted to operate on the differentiated catenary voltage systems in Spain and in France.

Additionally, in meeting Spanish national and European emissions reductions, efforts to decarbonise rail transportation will be critical. FCH Multiple Units provide an avenue to develop this service, while limiting the environmental impact and required investment. FCH trains avoid the harmful local emissions that are easily trapped in the mountain valley and would not require a larger disruption of the natural environment of the mountainous area.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

Trains operating along this route will make 10 stops in total, with intermediate stops having an average duration of 1 minute. For this case, two existing 4-car Multiple Units can be modified, with existing diesel engine components being replaced by an FCH system.

The FCH-powered system would include the fuel cell stack, on-board hydrogen storage and an array of traction batteries. The modified trains would each be installed with 175 kg of hydrogen storage capacity, allowing a maximum range of 550 km or a shorter daily mileage and a buffer hydrogen reserve. The train in this case would have an average consumption of 0.31 kg (H2)/km.

Key data		**Comment**
Case specifications		
Deployment:	2 sets	4-car bi-mode Multiple Units (~200-270 seats)
Expected daily mileage:	330 km	450 km per day for train and 330 km for the fuel cell components on the non-electrified route portion
Expected days of operation:	365 days	
FCH train specifications		
CAPEX per train set:	EUR 6,000,000	Retrofitting of 4-car units including fuel cell, hydrogen storage system, battery, integration of catenary system for bi-more operations, structural changes of the units, redesign of interior, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.31 kg(H_2)/km	
Maintenance costs:	0.71 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~240 kg(H_2)	350 bar
Production facility:	1x 0.5 MW	On-site facility installation, 350 bar

Table 3: Technical and commercial specifications for Zaragoza – Canfranc (Spain) case

The service from Zaragoza Delicias to Canfranc takes approximately 4 hours in each direction, and these two trains are expected to have a duty cycle of approximately 10 hours each day. Each train will have a daily mileage of 450 km and will be operating with the FCH system for 330 km of this overall route. Based on the duty cycle, the two trains would therefore require approximately 200 kg(H2) daily. Based on the on-board hydrogen storage capacity that these trains would be equipped with, they would require refuelling approximately each day. If a lower refuelling frequency is sought or if the operator would like to have increased flexibility with these trains, then equipping them with an even greater amount of on-board storage should be considered.

For full FCH train service, an electrolyser and a hydrogen refuelling station will need to be built at the operator's main depot in the southwest of Zaragoza. The hydrogen refuelling station will need to have a daily capacity of 240 kg(H2), in line with the demand from the trains. Since only two trains are being operated on this route and the duty cycle for both is relatively limited, simultaneous refuelling of both vehicles may not be required. For redundancy and maintenance on the electrolyser, the storage capacity of the station should be approximately twice the daily hydrogen demand (~480 kg) to ensure two full days of train operations. The quantity of hydrogen required by the trains will necessitate a 0.5 MW electrolyser producing approximately 240 kg of hydrogen a day. If there are constraints in the supply of electricity (e.g. 18 hours) then a 0.75 MW electrolyser should be considered.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
1,450 kW	147 kN	110 km/h	~350 kg	~550 km	EUR 6.0 m
		> Typical maximum speed ranges from 100 to 160 km/hour > Over longer distances usually higher speed	> Typical tank volume for a 2-car MU approx. 1,600 l of diesel	> Typical range of approximately 1,000 km > Depends e.g. on passengers on board, stops and topography	> Retrofitted train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
450 kW	270 seats (4-car bi-mode unit)		~0.31 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
925 kW	97 kW	463 kW	19 m^3
Battery capacity		**Fuel cell size**	**Weight**
270 kWh		410 kW	75 t

Table 4: Train specifications for Zaragoza – Canfranc (Spain) case

ECONOMICAL ASPECTS

For an FCH-powered train in this case the TCO is 12.4 EUR/km.[18] The infrastructure required to refuel and operate the FCH trains would require an investment of approximately EUR 1.65 m. This includes a 240 kg hydrogen refuelling station has been customised to the site requirements and would cost approximately EUR 0.8 m. Within this figure the equipment would cost approximately EUR 0.64 m and then there are other related development costs of EUR 0.16 m. The hydrogen production infrastructure is based on a 0.5 electrolyser that has been modified for the case specifications, resulting in an investment of EUR 0.85. The electrolyser will cost approximately EUR 0.7 m and the compression skid will cost an estimated EUR 0.14 m.

The investment for the 2 Multiple Unit trains will be EUR 12 m, including the FCH system and its related components like fuel cell stacks, batteries, and on-board hydrogen storage tanks. The financing costs for this will be an estimated 3.57 EUR/km based on a WACC of 10%. The costs for maintaining the two trains, including replacement of FCH related components, amounts to 0.71 EUR/km. The hydrogen consumption for each vehicle will average approximately 0.31 kg/km. Producing the hydrogen on-site via an electrolyser will lead to a fuel cost of 1.50 EUR/km. This is based on an estimated electricity price of 76.0 EUR/MWh. With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

Compared to the diesel bi-mode option, the FCH solution has a 3.10 EUR/km higher TCO. The drivers of this difference are the higher CAPEX for the FCH train, the higher fuel costs and higher infrastructure costs. It must be noted that this is a relatively small deployment of trains with a comparably low mileage. If there were more trains running daily and higher mileage, then these costs would be reduced.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH-powered train can be reduced by 1.20 EUR/km to 11.20 EUR/km if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg. In addition, external sourcing of hydrogen would eliminate the need for on-site production infrastructure. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary-electric and battery trains are also potential solutions that could be considered. The TCO for catenary-electric Multiple Units is approximately 10 EUR/km higher than that of the FCH trains. The large amount of track that would require electrification significantly increases the investment and maintenance costs for the catenary option. The infrastructure financing costs are estimated to be 11 EUR/km higher than the infrastructure financing costs for the FCH train.

[18]The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

The TCO for the battery Multiple Units is estimated to be 1.30 EUR/km more than for the FCH-powered trains. For battery-powered Multiple Units, a battery range of 85 km is assumed. This then means that there are two options for establishing a charging infrastructure. If charging under the initial 65 km of catenary is possible, then two medium sized charging stations would be required, one at the midpoint of the non-electrified route portion and one in Canfranc. If charging via the catenary is not possible, then three smaller charging stations would be required. Regardless, both solutions would require significant changes to the operation of the trains. Longer stop times would have to be factored in on the intermediate stops in order to accommodate the necessary recharging times. Battery systems also limit the flexibility that operators have in using the trains tailored to one specific route. If the operator needed to use these trains on another route or in a slightly differentiated service, then the trains would need to be modified. Further detailing on battery-powered trains can be found in Annex.

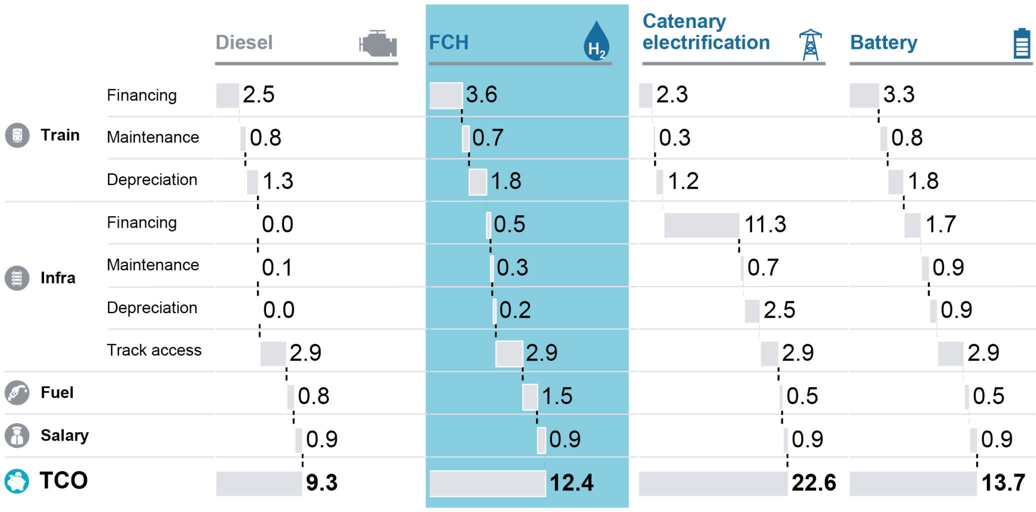


Figure 5: TCO analysis of different technological options for Zaragoza – Canfranc (in EUR/km)[19]

ENVIRONMENTAL PERSPECTIVE

If renewable energy is secured for the hydrogen production, then 767 t of CO2 emissions can be eliminated in the first year, with the potential for upwards of 6,966 t of CO2 savings through 2030. In the first year an additional 5.2 t NOx and 0.72 t PM10 savings can also be realised with potential for 46.4 t NOx and 6.51 t PM10 savings through 2030.

In this case, to achieve emissions reductions, sourcing of renewable power is important. An estimated 40% of Spanish electricity is produced using coal, oil or gas, so renewable energy should be specifically sourced for generation of hydrogen with an electrolyser.[20] In Spain 53% of the electricity comes from nuclear, wind, or hydropower sources. Using any of these as the sole power source could eliminate the carbon emissions generated directly from hydrogen production.

[19]All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.
[20]TInternational Energy Agency, 'Statistics | Spain - Electricity Generation by Fuel (Chart)', accessed 20 November 2018, https://www.iea.org/statistics/

The ecological impact of constructing and maintaining 165 km of catenary electrification is avoided. This is particularly important on the mountainous portions of the route where the rail track is isolated from other infrastructure and challenging to access. Furthermore, if a full rail connection with France is also opened, then regional and cross border road vehicle traffic can also be reduced.

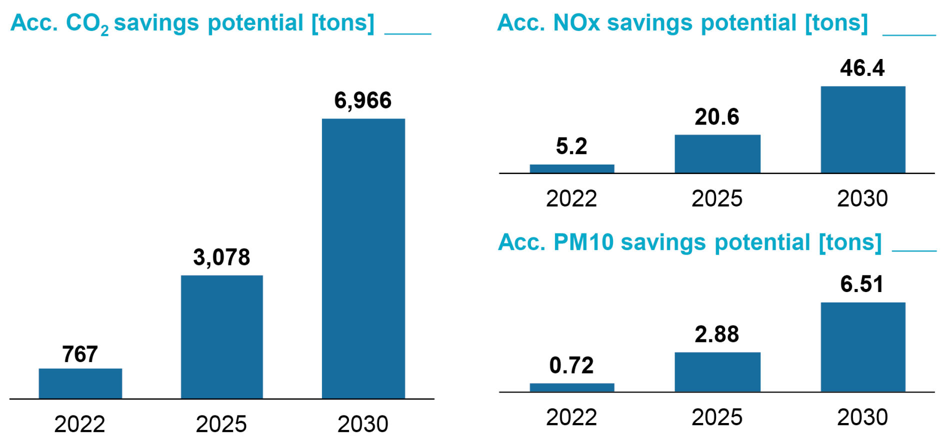


Figure 6: Emission saving potential for Zaragoza – Canfranc based on a green electricity scenario (in tons)

Approximately 1.3 million people live in the Aragon provinces of Huesca and Zaragoza.[21,22] Roughly half of this population lives within the city of Zaragoza itself. The communities located directly along the tracks would be the most impacted by any additional train deployments. FCH trains would help reduce the local emissions of harmful particulate matter and could also help moderately reduce the noise generated from rail operations.

BARRIERS FOR SEAMLESS IMPLEMENTATION

For this case, economic and legal barriers for implementation were analysed. To begin with the low number of trains operating in this case creates a significant economic barrier. This small deployment will have an outsized impact on the overall cost competitiveness of the FCH project. To optimise the investment, a larger deployment should be considered. From a legal perspective, the Spanish hydrogen regulatory structures may also need to evolve.[23] New legislation is needed that more thoroughly outlines hydrogen's role as a fuel. As such, a regulatory authority that will be responsible for certifying hydrogen quality, as is done with other fuels, is needed. The hydrogen refuelling station permitting processes also need to be revised, and significant restrictions categorising hydrogen production as a solely industrial process should be re-examined. Broad legal and regulatory evolution could accommodate the needs of this new technology in the rail environment and simplify the processes for those seeking to build hydrogen infrastructure and make investments.

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[21]Vincente Rodriguez, 'Huesca | Province, Spain', Encyclopedia Britannica, accessed 20 November 2018, https://www.britannica.com/place/Huesca-province-Spain.
[22]Vincente Rodriguez, 'Zaragoza | Province, Spain', Encyclopedia Britannica, accessed 20 November 2018, https://www.britannica.com/place/Zaragoza-province-Spain.
[23]'Database | HyLAW Online Database', accessed 14 November 2018, https://www.hylaw.eu/database#/database/production-of-hydrogen/localised-electrolysis-steam-methane-reforming-and-h2-liquification.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 24: Lack of efficient and appropriate regulatory structures for FCH train approval (safety, environment, and fuel cell system standardisation),

Barrier 25: Lack of specific permitting process for rail related hydrogen infrastructure.

Barrier 30: Insufficient tailored financing mechanisms to support roll-out of FCH trains.

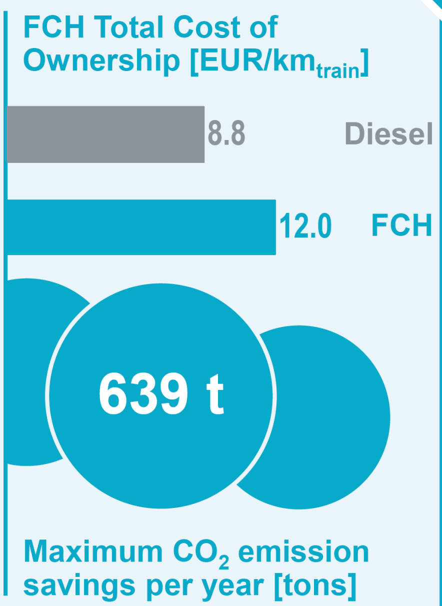
Further details on these barriers can be found in in Report 3.

3.1.3. MULTIPLE UNIT CASE: BRASOV – SIBIU (ROMANIA)

Brasov – Sibiu, Romania: Non-electrified single lines

The route from Brasov to Sibiu in the central part of Romania is characterised by a non-electrified single track with a rather low utilisation compared to other main tracks. In this case the use of new 2 car FCH trains with a 150 kg hydrogen tank system, an average power rating of 200 kW and a maximum tractive effort of 75 kN is studied in more detail. With a maximum FCH-powered range of 375 km, the FCH trains cost 36% more than diesel trains. Romania has one of the oldest rail networks and rolling stocks in Europe. The use of modern hydrogen trains would make it possible to skip the electrification of the rail network and immediately rely on a flexible future technology.

Track length	149 km	**N° of rolling stock**	2 x 2 car trains
H_2 fuel consumption	0.36 kg/km	**Capacity/ load**	150 seats



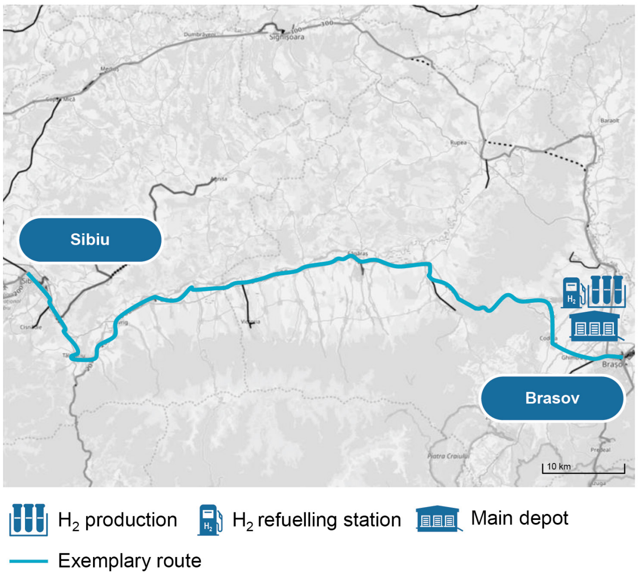
INTRODUCTION

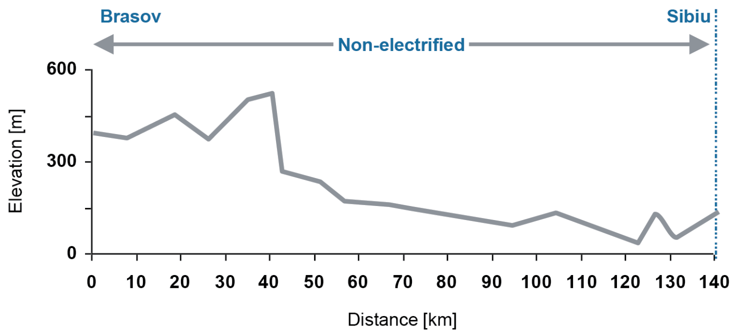
The following case demonstrates how the modernisation of the infrastructure connecting two major and historic Romanian cities, with a new and clean transportation method, could boost tourism and help preserve the natural habitat of the area. The route Brasov – Sibiu was selected based on the strategic location of the two cities in the heart of Romania. Both cities are medium sized, relatively wealthy and are important hubs for tourism.

The area of concern is located in the mountains with ample surrounding wilderness, as well as ski resorts (e.g. Poiana Brasov). The train goes directly into the historical centres of the towns, which are protected historical areas. Moreover, the trains pass through 32 villages/small cities. There seems to be political motivation to make these cities greener. The cities are only just starting to develop a "clean emission" transportation infrastructure, yet they are among the first cities in Romania to do so.[24] Therefore, they are also of heightened interest for the possibility of a multimodal approach to hydrogen utilisation (i.e. buses).

[24] Ranjan K. Bose et al., 'Romania - Imbunatatirea eficientei energetice in Brasov' (The World Bank, 20 December 2013), http://documents.worldbank.org/curated/en/336711468294625067/Romania-Imbunatatirea-eficientei-energetice-in-Brasov.

LOCATION





The following route is 149 km and is mainly constituted of single non-electrified lines. There is only a short portion linking the town of Talmaciu and Sibiu that has double lines; these, however, are also not electrified. The trains running on this route are mostly old, heavily polluting and mostly inefficient diesel locomotives.

The route is part of the "Magistrala CFR 200" and the length of the portion Brasov to Sibiu is as follows: 66.0 km between Brasov and Fagaras. This includes 13 railway stations (Brasov and Fagaras included); 50.63 km between Fagaras and Avrig. This includes 13 railway stations (Fagaras and Avrig included); and 32 km between Avrig and Sibiu. This includes 11 railway stations (Avrig and Sibiu included).

On this route, there is a maximum theoretical speed of 80 km/h (if the infrastructure was in good condition. However, portions with speed limits of 15 km/h can be found). There are also numerous bridges along the route. The trains servicing this route would need to operate in the range of temperatures along the route, ranging from -32 °C to 40 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[25]

[25]Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

BACKGROUND OF THE CASE STUDY

In 2016 Brasov ranked 1st in number of tourism establishments in the top counties in the country. The number of accommodation units has almost doubled in the last decade. Brasov County is in second place in terms of number of tourism accommodations and is currently planning to develop a new airport. The number of tourists who stayed overnight in 2016 increased by 11.7% from 2015. Overnight stays increased by 7.4% in 2016 when compared with 2015. Furthermore, the number of foreign visitors is increasing, being 12.9% higher in 2016 than 2015.[26] The largest number of foreign visitors came from Germany and Israel. Brasov County ranks second in terms of arrivals of tourists, both from Romania and internationally. The route will connect to the city of Sibiu. Sibiu is one of the primary tourism hubs in Romania and has seen a growing number of tourists in past decades, both Romanians and foreigners.

Both Brasov and Sibiu are also among the top cities in Romania leading efforts to reduce greenhouse gas emissions. In 2018, new environmental funding was approved to reduce emission in transport by promoting energy-efficient road transport vehicles with the development of recharging stations for electric vehicles. The total budget of around EUR 29 m was distributed among the various counties, with Sibiu and Brasov receiving among the largest shares.

However, the current situation in rail transportation does not yet reflect these ambitions. The locomotives used on this route are likely to be diesel locomotives of DRG class 97 or Regio Calatori class 57/97 railbus, which is one of the former French SNCF X4500 railbuses. Currently, the total duration of the trip can vary depending on type of service chosen, with a maximum of 4 h and 10 min. The fastest journey makes only one stop in the city of Fagaras (another tourism hotspot), while on the longest journey, the train stops in all the villages and small cities on the route, making a total of 32 stops.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

For this case, two new two-car Multiple Units should be acquired to accommodate the FCH system components. The trains would each be equipped with 135 kg of hydrogen storage capacity. This would give the trains a range of 375 km with an average consumption of 0.36 kg (H2)/km. The service from Brasov to Sibiu takes approximately 4 hours in each direction, and these two trains are expected to have a duty cycle of 9 hours each day. Each train will have a daily mileage of 350 km and will be operating with the FCH system on the whole route. The two trains would therefore require up to 270 kg(H2) daily.

[26] 'Romanian Tourism — Statistical Abstract | National Institute of Statistics', accessed 4 December 2018, http://www.insse.ro/cms/en/content/romanian-tourism-%E2%80%94-statistical-abstract-0.

Key data		Comment
Case specifications		
Deployment:	2 sets	2-car Multiple Units (~150 seats)
Expected daily mileage:	350 km	Single line route, non-electrified
Expected days of operation:	300 days	
FCH train specifications		
CAPEX per train set:	EUR 5,000,000	New trains, standard equipment including train design, train body, fuel cell, hydrogen storage system, battery, design of interior, electronic equipment, hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.36 kg(H_2)/km	
Maintenance costs:	1.20 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~270 kg(H_2)	350 bar
Production facility:	1x 1.0 MW	On-site facility installation, 350 bar

Table 5: Technical and commercial specifications for Brasov – Sibiu, Romania

To optimise storage capacity and infrastructure investments, the trains should be refuelled on a daily basis. For FCH train service, an electrolyser and a hydrogen refuelling station will need to be built at the operators' main depot in Brasov. The hydrogen refuelling station will need to have a daily refuelling capacity of 270 kg(H2), in line with the demand from the trains. Since only two trains are being operated in this case, with stops over a large distance of approximately 150 km, it would be feasible to install one refuelling station in Brasov with a larger storage capacity (~540 kg). The quantity of hydrogen needed will require a 1.0 MW electrolyser.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
800 kW	75 kN	80 km/h	~135 kg	~375 km	EUR 5.0 m
		> Typical maximum speed ranges from 100 to 160 km/hour > Over longer distances usually higher speed	> Typical tank volume for a 2-car MU approx. 1,600 l of diesel	> Typical range of approximately 1,000 km > Depends e.g. on passengers on board, stops and topography	> New-built train

Avg. power rating	Max. capacity	Avg. Consumption	Lifetime
200 kW	150 seats (2-car unit)	~0.36 kg/km	30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
500 kW	39 kW	100 kW	15 m³
Battery capacity		**Fuel cell size**	**Weight**
80 kWh		200 kW	73 t

Table 6: Train specifications for Brasov – Sibiu, Romania

ECONOMICAL ASPECTS

For an FCH-powered train the TCO is 12.0 EUR/km.[27] In this case study, a total estimated investment of EUR 2.5 – 3.0 m for the hydrogen infrastructure would be required. This figure includes 600 kg H2 storage and refuelling infrastructure that has been customised to the site requirements For this specific infrastructure there is an equipment cost of EUR 0.9 m and additional costs of EUR 0.3 m. The hydrogen production side will contain a standard electrolyser of 1.0 MW that has been modified for the case specifications, resulting in an estimated cost of EUR 0.9 m and a compressor skid with an estimated cost of EUR 0.4 m.

The CAPEX for 2 trains, including batteries and FCH components, is EUR 10 m. This results in financing costs of 3.5 EUR/km based on a WACC of 11.1%. The train maintenance costs, including the planned replacement of fuel cells and batteries, amounts to 1.2 EUR/km. With an average consumption of 0.36 kg/km and on-site hydrogen production through electrolysis, fuel costs are expected to be 1.90 EUR/km. The electricity price is assumed to be 81 EUR/MWh.

[27] 'The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered in order to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

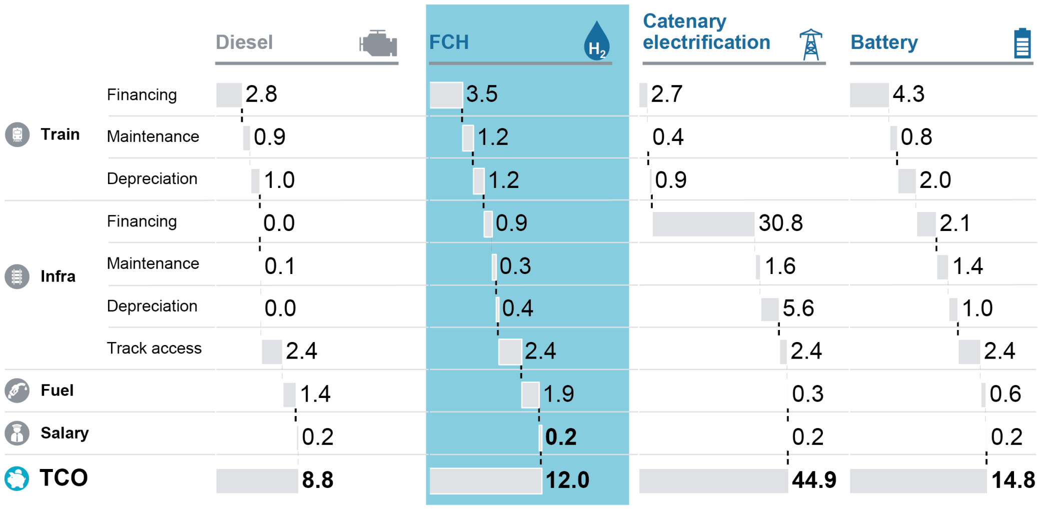


Figure 7: TCO analysis of different technological options for Brasov – Sibiu (in EUR/km)

Compared to the diesel option, the FCH solution has 3.20 EUR/km higher TCO. This difference is mainly driven by the higher CAPEX for the FCH-powered train of 0.69 EUR/km, although some of the added cost is offset by lower maintenance costs. The diesel price is assumed to be 1.2 EUR/l.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. In this case if hydrogen can be sourced for a flat rate of 3.00 EUR/kg then the TCO would be reduced by 1.75 EUR/km to 10.25 EUR/km. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary-electric units and battery-powered trains are available as alternative solutions. Overall, the TCO for catenary-electric units is 33 EUR/km higher than the TCO for the FCH-powered train. A catenary-electric unit would entail higher cost for financing. This is due to higher CAPEX for the catenary electrification. The catenary electrification also leads to significantly increased maintenance costs despite overall lower fuel cost. Particularly in this case with a single-track railway line, the capacity utilisation and use of the line by other trains is very low. The low utilisation leads to a direct or indirect allocation of all costs for electrification to the case shown. Without an integrated electrification or rail infrastructure upgrade concept for Romania, this option makes no economic sense.

For battery-powered trains, the route characteristics and absence of any catenary electrification will require an efficient and innovative charging station design. Therefore, two stations along the route could be planned. One station should be situated in Fagaras and one station should be situated in Avrig. The charging of the trains will take place for only 10 minutes with a longer stop at these stations each way.

Overall, the battery option is still more uneconomical due to the long distances. An adaptation to battery operation would be 2.80 EUR/km more expensive than the comparable hydrogen variant and would also reduce the flexibility of the trains.

ENVIRONMENTAL PERSPECTIVE

Compared to diesel technology, the FCH trains could save up to 639 t of CO2, 5.0 t NOX and 0.58 t PM10 emissions in the first year if green hydrogen production is sourced for production of hydrogen. Through 2030, potentially accumulated savings of 5,807 t CO2, 44.7 t NOx, and 5.31 t PM10 could be achieved.

With the current energy mix, a conventional electrolyser producing hydrogen on-site would increase the CO2 emissions from train services as such renewable energies should be specifically sourced for electrolyser operations. The current energy mix for the generation of electricity in Romania is characterised by a very diverse power plant park. Hydropower plants account for a large share of 31.9%. Lignite accounts for 16.6% of electricity generation, while wind power accounts for 14.2%. Natural gas and heating oil account for 18.3% of electricity generation and hard coal for 5.8%. Nuclear power and solar energy account for approx. 6.5% of total electricity generation.

Looking at where the train stations are located, an estimation of the population living in those areas would total 558,281 people. In the largest regional cities there is the following population distribution: Brasov 275,200, Sibiu 147,245, Fagaras 30,714 and Codlea 21,708. Around 135,836 people are currently living in small cities/villages between those two central towns.

According to the Brasov County Development Strategy 2013-2020-2030, mountains and hills represent almost half of the county's terrain. This extraordinary resource offers one of the most intact wilderness areas in Europe, because the mountain area is mostly still forested. The Fagaras Mountains are the highest mountains in Romania and feature an extensive glacier relief with valleys and lakes.

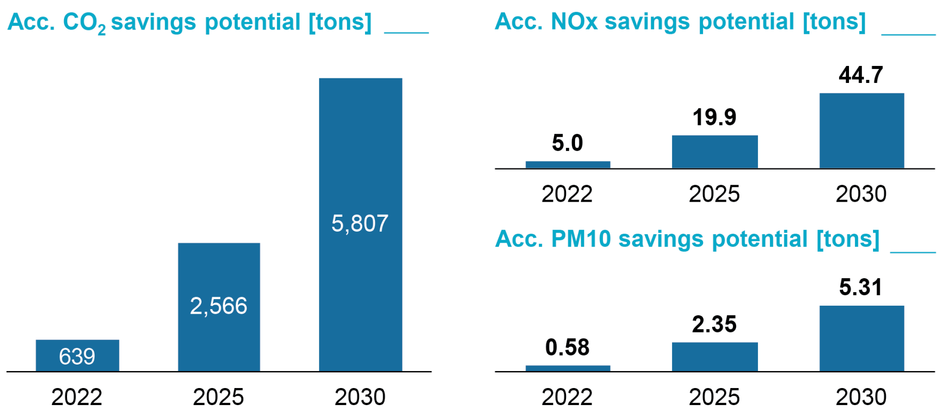


Figure 8: Emission saving potential for Brasov – Sibiu based on green electricity scenario (in tons)

The meadows and pastures in Sibiu with their wild flowers offer a spectacular, colourful landscape during the summer. The meadows are rich in plant species, many of which have disappeared in Central Europe. Also, the fauna is as rich as flora with a large number of mammals, birds, reptiles or insects that are protected both nationally and internationally. A reduction of local emissions would significantly contribute to the protection of this ecosystem.

BARRIERS FOR SEAMLESS IMPLEMENTATION

In Romania, there are mainly commercial and economic barriers that will apply for hydrogen but also for any other new technology. The first barrier is outdated locomotives, limited capability to invest in new trains and the lack of a secondary market for FCH trains which Romanian stakeholders could purchase trains from. The quasi totality of the rail investments made are for the repair and maintenance of the infrastructure with no/few projects for its modernisation. Despite the urge to replace outdated locomotives, only 3 new electrical locomotives where purchased in the last 10 years. A second barrier is the fact that the national railway infrastructure in general is in poor condition, train operating speeds are significantly reduced across the network and train regularity is heavily impacted. The change to FCH trains would need even more investment in infrastructure.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 28: Limited experience and knowledge about FCH technologies among rail stakeholders.

Barrier 30: Insufficient tailored financing mechanisms to support roll-out of FCH trains.

Barrier 31: Complex build-up of hydrogen refuelling infrastructure across a national rail network.

Further details on these barriers can be found in in Report 3.

3.1.4. MULTIPLE UNIT CASE: GRONINGEN AND FRIESLAND (NETHERLANDS)

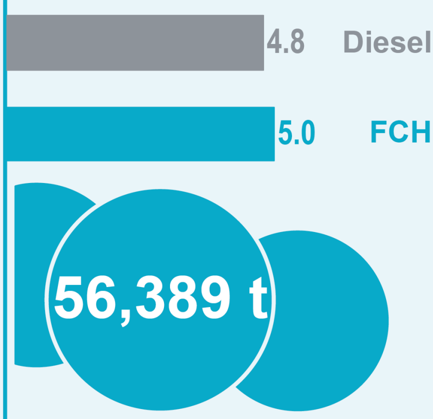
Groningen & Friesland, NL: Regional transport decarbonisation

The Northern Netherlands provinces of Friesland and Groningen are working towards regional decarbonisation. Key to achieving this goal, is retrofitting existing diesel Multiple Unit trains.

The 70 FCH Multiple Units will have a range of 800 km based on a 210 kg hydrogen tank system, an average power rating of 400 kW and a maximum tractive effort of 128 kN. The FCH Multiple Units have a TCO 4% higher than existing diesel technology. With the hydrogen produced with renewable energy, FCH trains could be a cost effective avenue to decarbonising regional train services.

Track length	300 km	**N° of rolling stock**	70 x 3 car trains
H_2 fuel consumption	0.22 kg/km	**Capacity/ load**	230 seats

FCH Total Cost of Ownership [EUR/km_{train}]



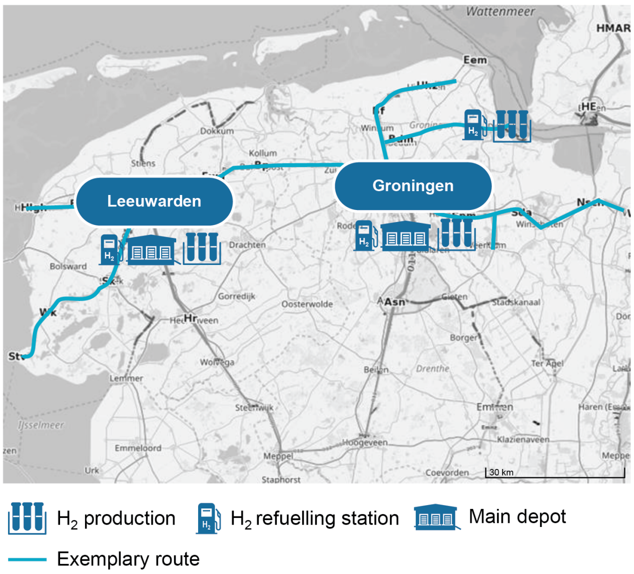
Maximum CO_2 emission savings per year [tons]

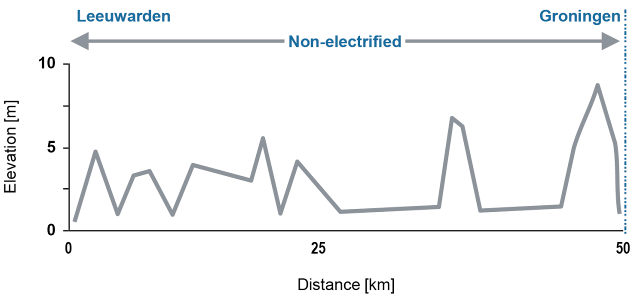
INTRODUCTION

This case study analyses the deployment of zero-emission FCH-powered regional rail service in the provinces of Groningen and Friesland in the Northern Netherlands. These regional governments are striving to eliminate regional carbon emissions by 2030.[28] They hope to tap into the large offshore wind energy potential in the region.[29] For these reasons, this case analyses the development of a renewable hydrogen production value chain, and the potential for FCH Multiple Units to replace the entire fleet of existing diesel Multiple Units operating across the network in Groningen and Friesland.

Decarbonisation on a regional level, in Groningen and Friesland, can be a model for broader national and European decarbonisation efforts. Important lessons can be learned about the process of decarbonising existing transportation systems and the role that FCH can play in transitioning rail transport. Catenary is an existing option, but can be time consuming to construct. This case also delivers insights into cost reductions, economies of scale, and operational efficiencies that can be gained from analysing a large fleet-wide deployment of hydrogen trains.

LOCATION





The network in question is located in the provinces of Groningen and Friesland in the north of the Netherlands. The network contains six different routes and approximately 300 km of track. Only a small fraction of the route has catenary electrification and thus diesel Multiple Units are used currently. The whole route network is analysed. These two cities of Groningen and Leeuwarden represent two large regional population centres and hubs for rail transit. In total the regional network contains about 60 train stops.

As this a coastal area of the Netherlands, there is almost no elevation change and there is an elevation gain of less than 1%. The climate also reflects the northern coastal region and temperatures range from -10 °C to 40 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[30]

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[28] Ad van Wijk, 'The Green Hydrogen Economy in the Northern Netherlands' (The Northern Netherlands Innovation Board), accessed 15 November 2018, http://profadvanwijk.com/wp-content/uploads/2017/04/NIB-BP-EN-DEF-webversie.pdf.

[29] Ibid.

[30] Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

BACKGROUND OF THE CASE STUDY

The Provinces of Groningen and Friesland are both striving to eliminate carbon emissions by 2030. To reach these goals, existing diesel trains will need to be replaced by alternative green technologies powered by renewable electricity. FCH Multiple Units are a cost effective and quick avenue to achieving these goals without the large infrastructure CAPEX associated with installing catenary electrification. Electrification of the 300 km of track on all routes throughout the region would require a rapid and full electrification of all routes before trains can begin to operate.

There are also broader regional plans to expand the production of renewable energy. Groningen and Friesland are located along the North Sea coast in an area with large amounts of onshore and offshore wind energy production potential.[31] This wind energy could be utilised, especially during periods of peak production, to store excess energy as hydrogen for later usage and to generate fuel for the FCH Multiple Units. The hydrogen infrastructure required for rail also has the potential to lay the foundation for a broader regional hydrogen economy if hydrogen is also used in other forms of transportation like buses, municipal fleets, and private vehicles.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The network involves 60 stations for passenger services and the stations Leeuwarden and Groningen are also the main operations depots. The existing Multiple Units are three cars each and carry approximately 170 passengers. To implement the provincial decarbonisation goals, the entire diesel fleet of 70, three-car units, will need to be retrofitted. The diesel powertrain components would be replaced with FCH system components

Key data		Comment
Case specifications		
Deployment: Number of train units operated under the project of this case design	70 sets	3-car Multiple Units (~170 seats)
Expected daily mileage:	1,055 km	
Expected days of operation:	345 days	
FCH train specifications		
CAPEX per train set:	EUR 4,500,000	Retrofit of existing units including redesign costs, fuel cell, hydrogen storage system, battery, structural changes of the units, redesign of interior, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.22 kg(H_2)/km	
Maintenance costs:	0.7 EUR/km	
Infrastructure specifications		
HRS installation schedule (350 bar):	3x ~6,000 kg(H_2)/d	One located in Grongingen, one located Leeuwarden and one in Delfzijl
Production facility:	3x 15 MW	On-site facility installation (350 bar)

Table 7: Technical and commercial specifications for Groningen and Friesland, Netherlands case

[31] van Wijk, 'The Green Hydrogen Economy in the Northern Netherlands'.

For the proposed retrofit, each train would be equipped with a new FCH powertrain system that includes a fuel cell stack, traction batteries, and hydrogen storage tanks. The hydrogen system would include 210 kg of hydrogen storage giving the trains a range of approximately 800 km at an approximate consumption averaging 0.22 kg (H2)/km. This range gives the operator the flexibility to use each train on the entire route network and to serve the longest distances that they could potentially require.

Each train is expected to remain in operation for 18 hours in a standard day. Within these operations the average train in the fleet will have a daily mileage of approximately 1,055 km and an average consumption of 230 kg(H2) daily. Based on this vehicle consumption and the overall fleet size, the demand for hydrogen will be approximately 16.5 t/day. Trains operating at or above this average duty cycle will need to refuel twice per day.

Due to the size of the fleet and the main depots of operation, three hydrogen production facilities with an electrolyser and hydrogen refuelling stations should be constructed. These should be constructed at the operation depots in the main station in Groningen and Leeuwarden, and additionally in Delfzijl. Each HRS will need a daily refilling capacity of approximately 6 t (H2). Due to the fleet size, each filling station will need to have several dispensers, and should be scaled to enable the simultaneous refilling of several Multiple Units. As part of each HRS there should be approximately 12 t (H2).storage, ensuring that two days of refilling capacity is provided during periods of maintenance and production disruption. In Leeuwarden, Groningen and Delfzijl there will also need to be a 15 MW electrolyser producing the approximately 6 t (H2) required for each HRS.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
1,400 kW	128 kN	160 km/h	~210 kg	~800 km	EUR 4.5 m
		> Typical maximum speed ranges from 100 to 160 km/hour > Over longer distances usually higher speed	> Typical tank volume for a 2-car MU approx. 1,600 l of diesel	> Typical range of approximately 1,000 km > Depends e.g. on passengers on board, stops and topography	> Retrofitted train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
400 kW	170 seats (3-car unit)		~0.22 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
1,000 kW	59 kW	300 kW	22 m^3
Battery capacity		**Fuel cell size**	**Weight**
160 kWh		300 kW	110 t

Table 8: Train specifications for Groningen and Friesland, Netherlands case

ECONOMICAL ASPECTS

For an FCH train the TCO is 5.0 EUR/km.[32] In this case study, a total estimated investment of EUR 83 m for the hydrogen infrastructure would be required. This figure includes the three hydrogen refuelling stations of 6 t (H2) and three 12 t (H2) storage systems that have been customised to the site requirements. The hydrogen refuelling station equipment will cost EUR 37 m, and other associated costs will be EUR 3 m. For the hydrogen production, a total investment of EUR 43 m is needed, with the three standard 15 MW electrolysers that have been modified for the case specifications costing EUR 36 m and the compressor skids costing EUR 7 m.

The retrofit CAPEX for the 70 trains, including batteries and FCH components, is EUR 4.5 m per unit and a total of EUR 315 m. The resulting financing costs are 0.40 EUR/km with a WACC of 6%. The maintenance of the fleet, including required replacement of fuel cells and batteries, is 0.80 EUR/km. The FCH fuel costs are expected to be 0.80 EUR/km, with the fleet-wide average consumption 0.22 kg/km and on-site electrolysis. In this case the electricity price is assumed to be 59 EUR/MWh. With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered in order to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

The TCO for the FCH train is only 0.20 EUR/km higher than the TCO for the diesel alternative. This small price premium is largely driven by the higher CAPEX for the FCH trains and associated infrastructure. However, lower fuel and maintenance costs help offset the additional CAPEX over the lifetime of the vehicle.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH train can be reduced by 0.30 EUR/km to 4.70 EUR/km if hydrogen can be directly sourced from industrial or other sources for a flat rate of 3.00 EUR/kg including transport costs. This would eliminate the need for on-site production infrastructure. Furthermore, if hydrogen could be sourced for a flat rate of 5 EUR/km, the overall TCO would be 5.20 EUR/km only 0.20 EUR/km more. However, the emissions associated with such hydrogen if procured from industrial sources may not be in line with the regional government's goals. Nevertheless, the impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary electric and battery Multiple Units are also other alternative solutions. However, batteries would involve a much more significant price premium. In this case, only 4% of the overall network is electrified, therefore a large infrastructure investment is required. The TCO for catenary-electric units and the associated infrastructure developments is 4.50 EUR/km. This is 0.50 EUR/km less than the FCH solution. The higher level of utilisation is the primary driver of this lower cost. However, it must be noted that such a large network of catenary electrification cannot be rolled out as quickly as FCH trains. The entire network or at least significant portions of the electrified route have to be in place before the units can operate. FCH units can begin operation as soon as they are produced, and the refilling infrastructure is in place.

[32] The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

For battery trains, such a large route network and the high daily mileage of the trains in this case, means trains would need to be equipped with large battery capacities and a large network of re-charging stations would need to be established. A total of 50 charging stations would need to be established, with at several in Groningen and Leeuwarden. The battery trains would have a range of approximately 70 km, meaning that trains would have to recharge at least 15 times during a daily duty cycle of 1055 km. This has the potential to significantly disrupt daily operations for the rail operator. Station stop times would have to be recalibrated to accommodate recharging and the operational flexibility of the fleet would be significantly curtailed. The large infrastructure build-up and the extensive operational constraints for battery trains are also not cheaper and actually 0.30 EUR/km more than the FCH solution.

		Diesel	FCH	Catenary electrification	Battery
Train	Financing	0.4	0.4	0.4	0.6
	Maintenance	0.9	0.8	0.4	0.8
	Depreciation	0.4	0.4	0.4	0.6
Infra	Financing	0.0	0.1	0.5	0.2
	Maintenance	0.0	0.1	0.1	0.2
	Depreciation	0.0	0.1	0.2	0.2
	Track access	1.9	1.9	1.9	1.9
Fuel		0.8	0.8	0.2	0.4
Salary		0.4	0.4	0.4	0.4
TCO		**4.8**	**5.0**	**4.5**	**5.3**

Figure 9: TTCO analysis of different technological options for Groningen and Leeuwarden (in EUR/km)[33]

ENVIRONMENTAL PERSPECTIVE

If renewable energy is sourced as envisioned, in comparison with the existing diesel technology, FCH trains could save 56,389 t of CO2 emissions in the first year and 512,376 t of CO2 through 2030. In the first year an additional 603 t NOX and 52 t PM10 savings can be realised. In this case, if environmental benefits are truly sought as publicly stated, then renewable energy has to be sourced for the hydrogen production because the existing blend of grid electricity is too carbon intensive to reduce train service emissions. However, this will also drive regional decarbonisation and could have other secondary effects. The local population could start utilising more public transit, reducing normal passenger car traffic, or as the hydrogen ecosystem develops, locals could also purchase hydrogen powered vehicles. Overall, sourcing renewable energy to operate the electrolyser should be eased by the two provinces' proximity to the North Sea and numerous offshore wind farms.

[33] All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.

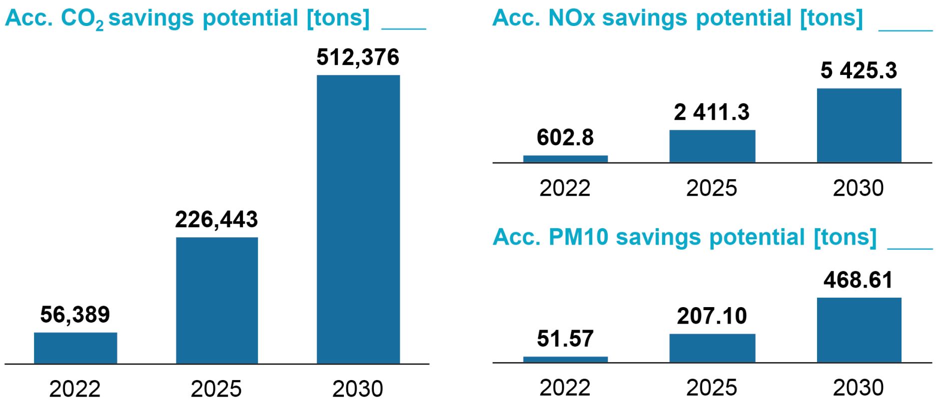


Figure 10: TTCO analysis of different technological options for Groningen and Leeuwarden (in EUR/km)[33]

Beyond overall emissions, local environmental benefits can also be realised. Groningen and Friesland have a population of approximately 1.2 million people. Groningen, with approximately 200,000 people, and Leeuwarden, with approximately 100,000 people, are the large population centres. The provinces are mostly rural, with smaller towns and communities spread widely throughout both.

Particulate matter created by diesel engines is associated with numerous health issues and has recently come under greater scrutiny.[34] Elimination of local particulate matter emissions is an important result of switching to hydrogen. This impact will be largest in Leeuwarden and Groningen, where existing diesel trains make numerous stops at the main depots located in the middle of the city. For these local areas and in particular those residents living close to the track, FCH locomotives will also moderately reduce the amount of noise pollution that the trains generate.

BARRIERS FOR SEAMLESS IMPLEMENTATION

Economic, operational and legal barriers were emphasised in the analysis of barriers in this case. First, economically and operationally, the large scale of the fleet deployment means a large investment is required to retrofit all the trains, install the required hydrogen production and refuelling infrastructure, and make the necessary changes to existing facilities and staff. Most areas of train operations will be impacted by this wholesale change in train power source. Second, regulatory and permitting processes outlined in the Netherland's Wabo and General Environmental Act, also present some barriers for hydrogen production and refuelling stations. Extended permitting procedures taking up to a year, and unclear local interpretation of national standards, can lead to significant uncertainties in the permitting process.

[34] A. Sydbom et al., 'Health Effects of Diesel Exhaust Emissions', European Respiratory Journal 17, no. 4 (1 April 2001): 733.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 16: Lack of standardised FCH rail service and maintenance programs.

Barrier 21: Lack of FCH infrastructure Standard Operating Procedures (SOP).

Barrier 25: Lack of specific permitting process for rail related hydrogen infrastructure.

Barrier 30: Insufficient tailored financing mechanisms to support roll-out of FCH trains.

Further details on these barriers can be found in in Report 3.

3.2. CASE STUDIES ON SHUNTERS

The use of Shunters can vary greatly and is not limited to classical Shunter operations. Through dialogue with various stakeholders, it has become clear that Shunters are also very often used to transport wagons or locomotives between different terminals several kilometres apart. Depending on the load to be moved and the distance to be covered, different performance parameters must be met by the Shunter.

Shunters can be divided into three segments: Shunters with 110 kW, Shunters between 110 kW and 250 kW and Shunters over 250 kW. For the hydrogen applications, very powerful Shunters which have to cover longer distances are the most interesting. For Shunters in the lower power ranges with relatively long idle times, battery applications would likely offer the best clean alternative.

Shunters have a very long lifetime and are usually in use for more than 50 years, although they are occasionally adapted to the actual requirements and equipped with a retrofit including for example a more powerful engine. In the course of retrofitting, the FCH technology can also be installed. Both weight and space requirements for this technology can be integrated into current designs. The hydrogen infrastructure, which can be implemented cost-effectively due to the very centralised form of operation, is particularly favourable.

In the following TCO calculations different technologies for Shunter are investigated. The focus is on the comparison of diesel, FCH and battery technology. A comparison to catenary technology is not performed. This is due to the operational constraints of the shunting operations. Usually freight handling is carried out from above or a complex multiple sorting line layout does not allow electrification.

Three factors are important for the success of the introduction of FCH Shunters:

1. Shunters must be used intensively without long idle time and sometimes for longer distances.
2. A high number of Shunters significantly reduce the common costs for the infrastructure.
3. Strengthening interoperability with other forms of transport (e.g. use of trucks connected via the terminal or Mainline Locomotives that deliver the freight wagons).

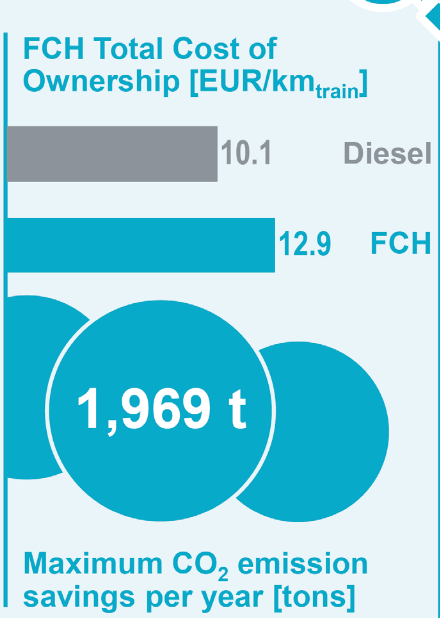
3.2.1. SHUNTER CASE: HAMBURG – BILLWERDER (GERMANY)

Hamburg-Billwerder, Germany: Intermodal terminal FCH shunting

In Hamburg-Billwerder, FCH Shunters have the potential to replace existing diesel Shunters in service at an intermodal freight terminal. The proximity to a large urban area and the largest inland port in Europe, make this an attractive case for further examination.

The 15 FCH Shunters have a daily mileage of 200 km, a 50 kg hydrogen tank system, a maximum power rating of 800 kW and a maximum tractive effort of 236 kN. The FCH Shunter has a TCO that is 27% higher than existing diesel technology.

Track length	10 km	**N° of rolling stock**	15 Shunters
H_2 fuel consumption	0.39 kg/km	**Capacity/ load**	1,200 t



INTRODUCTION

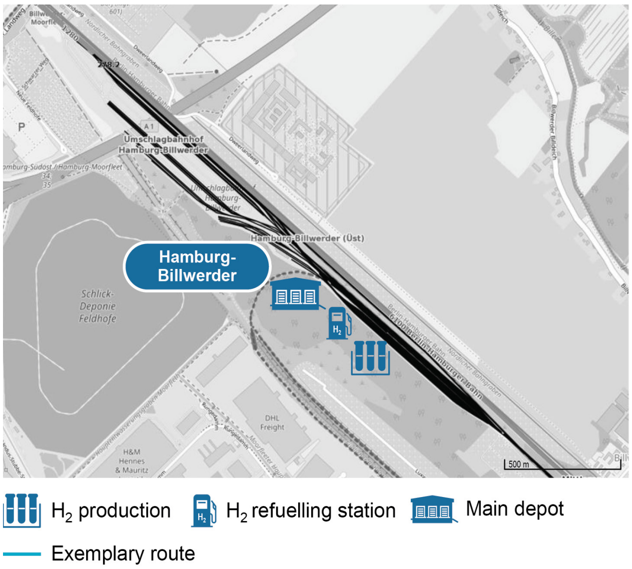
This case studies the operation of Shunters in an area close to a larger city sensitive to both noise and greenhouse gas emissions. The case is characterised by short route transportation with a high number of rolling stock. The size of the intermodal marshalling yard and the number of individual routes promise a high level of attractiveness for clean shunting technologies.

In this case study the potential of FCH applications in the field of shunting locomotives is investigated. There are terminals for loading and unloading of trains and but also large marshalling yards for splitting trains, reordering the wagons and substituting new trains. Another category are terminals used to transfer containers to other means of transport. This connection can be used to transfer freight to road or sea.

In the present case, a modern terminal close to the city is to be investigated. In the area of Hamburg, the largest inland port in Europe, more than 136 m t per year of freight[35] is transhipped daily. This case study was chosen to investigate a smaller site in a larger metropolitan region. The situation is comparable with many of Europe's large terminals, where large volumes of goods are collected in industrial areas, metropolitan areas or port locations.

[34] 'Welcome to the Port of Hamburg', Die offizielle Internetseite des Hamburger Hafens, accessed 15 November 2018, https://www.hafen-hamburg.de/statistiken.

LOCATION



The marshalling yard is located in a relatively sparsely populated urban area and borders the industrial estates on the eastern edge of the port of Hamburg. It has four 720 m long tracks and four 620 m long tracks. A further four tracks with a length of 650 m are under construction.[36] A total network of 26 km can be assumed. The area can be assumed to be flat. The climate conditions in the area include temperature extremes of -20 °C to 40 °C.[37]

The Hamburg Billwerder terminal is connected to rail and road. It has 7 rail gantry cranes and a maximum ground parking capacity of 1,026 TEU. The maximum handling capacity of the terminal is 370,000 LE per year. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[38]

BACKGROUND OF THE CASE STUDY

The Hamburg-Billwerder terminal is the third largest German intermodal terminal with 250,000 LE per year. Built in 1993 it is an important interface for the handling of loading units between road and rail as well as for national and international transfer traffic between freight trains. Through its network-building function, the Hamburg-Billwerder terminal links various transport modes and routes for operators from southern Europe to Scandinavia, in some cases with more than 20 trains per day. With its infrastructure and technical equipment, it is one of the most modern terminals in Europe. Short turnaround times in the facility and fast, reliable handling increase the attractiveness and significance of the terminal in the network. In 2012, a third crane runway was added to the terminal and the handling capacity increased, opening additional growth opportunities for the CT market in the future.

Fast rail connections in all directions are provided by the connection to the Hamburg-Berlin main line and the Hamburg freight railway. Conveniently located in the east of Hamburg, in the direct catchment area of the city's largest transport industry and freight forwarding centre, the terminal also has excellent connections to Hamburg's road network (via Halskestraße and Grusonstraße) and to the A1 motorway.

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[36]'DUSS-Flyer Hamburg 2017 de - Hamburg_flyer-Data.pdf', accessed 15 November 2018, https://www1.deutschebahn.com/resource/blob/714118/6a39dcb91b7fc9879ec92c21ddf368b8/Hamburg_flyer-data.pdf.
[37]'- Klima Hamburg - Klimadiagramme und Klimatabellen für Hamburg', accessed 15 November 2018, https://www.wetter.de/klima/europa/deutschland/hamburg-s101470.html.
[38]Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

A potential of fifteen FCH Shunters is assumed for purchasing in this case study. The FCH-powered system of an FCH Shunter includes a fuel cell stack, an on-board hydrogen storage and traction batteries. The train would be equipped with a 50 kg hydrogen tank system with hydrogen being stored at 350 bar pressure. A maximum range of approximately 120 km with an average consumption of 0.39 kg(H2)/km is required to perform all shunting operations. The train has a maximum load of 1,200 t.

Key data		Comment
Case specifications		
Deployment: Number of train units operated under the project of this case design	15 Shunters	1,200 t towing capacity
Expected daily mileage:	80 km	
Expected days of operation:	365	
FCH train specifications		
CAPEX per train set:	EUR 2,200,000	New built Shunters including design, Shunter body, fuel cell, hydrogen storage system, battery, electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.39 kg(H_2)/km	
Maintenance costs:	1.63 EUR/km	
Infrastructure specifications		
HRS installation schedule (350 bar):	480 kg(H_2)/d	Located on-site
Production facility:	1x 1 MW	On-site facility installation (350 bar)

Table 9: Technical and commercial specifications for Hamburg-Billwerder, Germany case

The expected duty cycle for the FCH system is 12.5 h of daily operation, 4.5 h being idle time assuming 365 days in operation annually for each train. The daily mileage of each train is approximately 85 km. Under the defined duty cycle, the FCH Shunter would need a full refill every day. The maximum expected speed is 45 km/h with an average travelling speed of 8 km/h.

The related infrastructure includes a hydrogen refuelling station and a 1 MW on-site hydrogen production facility located close to the shunting yard. The hydrogen refuelling station is expected to serve all fifteen FCH Shunters and should be designed to have the capacity to refuel 480 kg(H2) per day. The infrastructure should allow an approximate refuelling time of 10 minutes per train. The storage capacity for the HRS should be twice the daily hydrogen demand or refuelling capacity (~960 kg) in order to ensure two full days of train operations.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
800 kW	236 kN	45 km/h	~50 kg	~120 km	EUR 2.2 m
		> Typical maximum speed ranges from 20 to 80 km/hour > Higher maximum speed if used outside of depots or stations	> Typical tank volume ranges from 700 to 6,000 l of diesel	> Typical range of approximately 400 to 1,000 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography	> New-built train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
43 kW	1,200 t		~0.39 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
810 kW	20 kW	8 kW	7 m^3

Battery capacity	Fuel cell size	Weight
180 kWh	100 kW	113 t

Table 10: Train specifications for Hamburg-Billwerder, Germany case

ECONOMICAL ASPECTS

For an FCH Shunter the TCO amounts to 12.9 EUR/km.[39] In this case study, a total estimated investment of EUR 5.5-6.5 m for the hydrogen infrastructure would be required. This figure includes hydrogen storage and refuelling infrastructure of 480 kg H2 that has been customised to site the requirements. For this infrastructure, the HRS has an equipment cost of EUR 1.5 m and additional costs of EUR 0.6 m. The H2 production side will contain a standard electrolyser of 1 MW that has been modified for the case specifications, this results in an estimated cost of EUR 2.1 m and a compressor skid with an estimated cost of EUR 1.5 m.

The CAPEX for 15 Shunters, including batteries and FCH components, is EUR 33 m. This results in financing costs of 1.52 EUR/km based on a WACC of 3.5%. The train maintenance costs, including the planned replacement of fuel cells and batteries, amounts to 1.63 EUR/km. With an average consumption of 0.39 kg/km and on-site hydrogen production through electrolysis, fuel costs are expected to be 2.60 EUR/km. The electricity price is assumed to be 105 EUR/MWh. With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered in order to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

[39]The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH train can be reduced by 2.00 EUR/km to 10.90 EUR/km in total if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg including transportation. This saves on infrastructure investment and fuel costs. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Compared to the diesel bi-mode option, the FCH solution has 2.80 EUR/km higher TCO. This difference is mainly driven by higher CAPEX for the FCH train of 0.48 EUR/km. In addition, the high electricity price in Germany results in a higher fuel cost for an FCH Shunter. The costs are 60% higher than the fuel cost of a diesel Shunter. The diesel price is assumed to be 1.0 EUR/l.

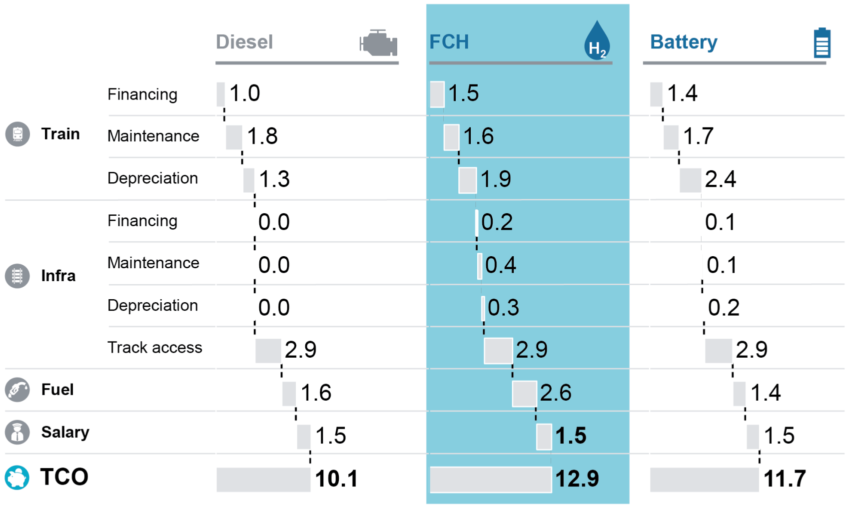


Figure 11: TCO analysis of different technological options for Hamburg-Billwerder (in EUR/km)[40]

The operation of Shunters usually does not allow for a catenary-electric solution. Although the route is partly electrified, battery-powered trains are studied as an alternative solution. The route characteristics and centralised operation of a large number of rolling stock leads to a good ratio between infrastructure and train units. The proximity to the city of Hamburg with its well-developed power grid infrastructure creates the best conditions for cost-effective charging points. The charging station can be installed both in the terminal and in the close-by shunting yard. Also, from an operational perspective, the battery solution is feasible. Rather long idle times will allow charging also in between the shunting operations.

From a purely TCO perspective, the battery-powered train option is commercially more attractive than an FCH option. However, there are still operational constraints and technological barriers concerning batteries in the rail environment. The battery lifetime and life cycle could be impacted by the climate conditions but also long idle times may lead to the batteries discharging.

[40] All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.

ENVIRONMENTAL PERSPECTIVE

Compared to diesel technology, the FCH trains could save up to 1,969 t of CO2 emissions in the first year of operation if green H2 production is assumed based on renewable energies. Through 2030 these could generate accumulated savings of 17,892 t CO2, 93.3 t NOx, and 16.4 t PM10. Due to the high current level of electricity generation from coal as an energy source, the environmental balance would deteriorate due to the use of hydrogen if the existing blend of German electricity is taken. As a result, sourcing renewable energy is important for achieving environmental benefits.

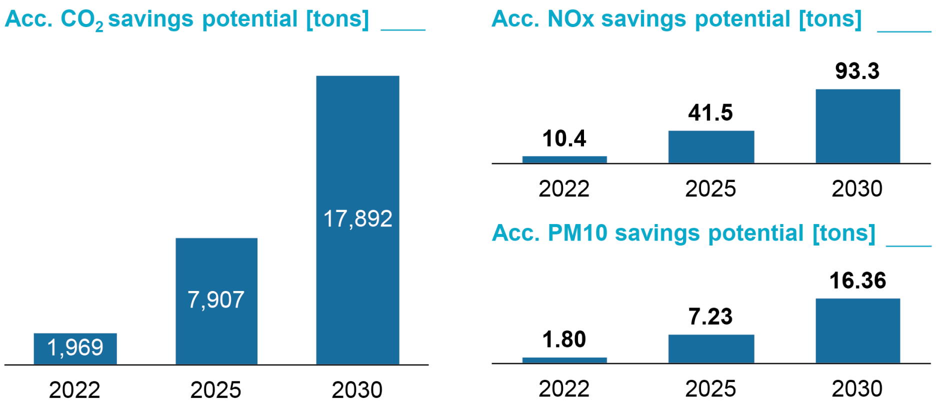


Figure 12: Emission saving potential for Hamburg-Billwerder based on two scenarios (in tons)

Billwerder is a rather small and rural district of Hamburg with an area of 9.5 km2 and a population of 3,784. It has two regional train stations and borders both on the industrial area of the port of Hamburg and on important main traffic routes such as the Hamburg-Berlin railway line and the B1 and B5 federal highways. Billwerder is thus in an excellent economic position but at the same time has to respond to the challenge of noise pollution. The use of clean alternative propulsion systems could reduce noise pollution, although shunting operations also involve noise sources other than locomotives themselves. Hamburg-Billwerder is one of the largest terminals in Germany and operates 24 hours a day.

The terminal is also in the immediate vicinity of Bille, south of the Boberger Niederung nature reserve with its popular sand dunes. The 9.5 km2 are used for agriculture, arable farming, livestock breeding and flower growing. At the same time, a total of 7,000 new apartments are being built on 120 hectares above Billwerder. A modernisation of the Shunters would not only do justice to the industrial location of the shunting yard but potentially also offer possibilities for an expanded H_2 production for use in agricultural vehicles and freight trucks.

BARRIERS FOR SEAMLESS IMPLEMENTATION

The competitiveness of the battery technology for the Shunters considered in this case is a large barrier. Due to the operational specifications and the duty cycle of Shunters, there are often long periods of idle time and short periods of peak power usage for the sorting of loads. Batteries can easily handle the peak power demands and then use the long idle periods for easy charging. Potential battery shunters in this case could come equipped with a pantograph and easily charge using the existing catenary lines that run up to the entrance of the terminal. In such cases where Shunters have lower mileage, and smaller loads, batteries are often very competitive.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 5: Limited experience with standardised/scalable, customisable hybridised powertrain designs;

Barrier 29: Immature FCH rail supply chain;

Further details on these barriers can be found in Report 3.

3.2.2. SHUNTER CASE: RIGA NODE (LATVIA)

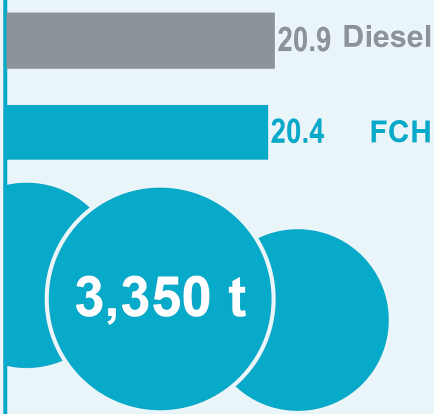
Riga Node, Latvia: Hydrogen fuel cell shunting operations

In Riga, heavily polluting diesel Shunter operations in the Skirotava marshalling yard, on the node in the city, and between the several port terminals can be replaced with FCH Shunters.

The 15 FCH Shunters have a daily mileage of 100 km, a 170 kg hydrogen tank system, a maximum power rating of 1,000 kW and a maximum tractive effort of 290 kN. The FCH Shunter has a TCO that is 3% lower than existing diesel technology. FCH Shunters can also deliver significant environmental benefits, even with rail traffic and operations growing as forecasted with the expansion of Rail Baltica.

Track length	100 km	**Nº of rolling stock**	15 Shunters
H_2 fuel consumption	0.49 kg/km	**Capacity/ load**	3,000 t

FCH Total Cost of Ownership [EUR/km_{train}]



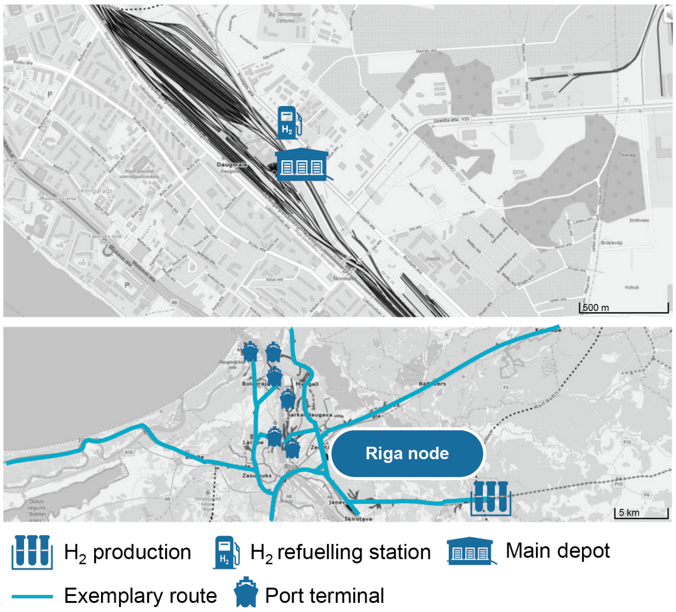
Maximum CO_2 emission savings per year [tons]

INTRODUCTION

This case studies the operation of FCH Shunters in traditional marshalling yard shunting operations and on short distance freight routes between the marshalling yard and port terminals. It explores how FCH Shunters could perform technically and economically in marshalling yard shunting operations and on short haul distances. Within the Riga node a central shunting yard connects six port terminals. The Shunters are used for both shunting operations and transport over the rather long distances between the terminals of up to 20 km.

While electrification is common on regional and mainline routes, within European shunting yards electrification is rare. As a result, diesel-powered Shunters are typically used for marshalling yard sorting operations. In Riga, Shunters perform these tasks and they also transport small rail loads to and from the different port terminals to the marshalling yard for sorting. Standard operations typically involve Shunters idling for long hours of the day awaiting the next task. The deployed Shunters are typically much older than the average rolling stock age, and the shunting yards are often located in urban areas. Because of the existing conditions, it is interesting to investigate the potential for FCH Shunters to deliver environmental, economic, and operational benefits.

LOCATION



The marshalling yard and route/node in question is located within Riga. Located to the southeast of the city centre, the Skirotava marshalling station is the main shunting station and depot of the Latvian operator. The node of operation then includes all lines within Riga, many of which connect this yard with Riga's several port terminals.[41] The node has a total track length of approximately 200 km.

The Skirotava marshalling station has recently undergone a EUR 40 m renovation and the yard has the ability to sort 3,500 wagons in 24 h.[42] This yard will likely be connected to the Rail Baltica intermodal terminal that is being developed to the southeast of Riga.

The overall profile of the Riga node is relatively flat, as it is a coastal region. Within the yard itself any change in height profile is mostly limited to the shunting hump. The climate conditions in area include temperature extremes of -40 °C to 40 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[43]

BACKGROUND OF THE CASE STUDY

With the expansion of the Rail Baltica rail connection from Tallinn through Poland to Germany, upgrades are being made to rail infrastructure and operations in Latvia as rail traffic is expected to increase.[44] Converting existing older diesel shunting locomotives to newer, more efficient and emissions compliant technologies is a priority. Existing shunting operations are located within the city, and Shunters are often idling for several hours per day. This exposes residents to high levels of noise and the existing older Shunters produce NOX and particulate emissions. Potential FCH Shunters could eliminate local emissions produced by shunting operations, guarantee Shunter emissions compliance, and leverage broader regional FCH developments.

A broader development of other forms of FCH-powered transportation is already planned in the region. Recent European Union funding has been awarded for the development of an FCH bus fleet of 200 units in Riga. This creates the opportunity for potential synergies between the rail and public transport operator that could enable cost savings for the operator.

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[41] Latvijas Dzelzceļš, Latvian Railway Opens the Reconstructed Marshalling Hump of Šķirotava Station in Riga, accessed 16 November 2018, https://www.youtube.com/watch?v=HRccdVxiulo.
[42] Latvijas Dzelzceļš.
[43] Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.
[44] 'Rail Baltica', accessed 16 November 2018, http://www.railbaltica.org/.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The Riga node encompasses the main Skirotava marshalling yard in the southeast of the city and then the different routes connecting the six different port terminals on either side of the river. Shunters carry varying different kinds of freight loads to and from these different terminals. For this case fifteen existing diesel Shunters will be retrofitted and existing diesel powertrain components would be replaced by FCH system components.

Key data		Comment
Case specifications		
Deployment:	15 Shunters	
Expected daily mileage:	~200 km	Including shunting operations in Skirotava marshalling yard and short haul freight loads between the marshalling yard and various port terminals
Expected days of operation:	345 days	
FCH train specifications		
CAPEX per train set:	EUR 1,850,000	Retrofitting of 15 existing Shunters including fuel cell, hydrogen storage system, battery, structural changes of the units, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.49 kg(H_2)/km	
Maintenance costs:	1.26 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~850 kg(H_2)	350 bar
Production facility:	1x 2.5 MW	Off-site facility installation, 350 bar

Table 11: Technical and commercial specifications for Riga node (Latvia) case.

The FCH-powered system of an FCH Shunter includes a fuel cell stack, an on-board hydrogen storage and traction batteries. The train would be equipped with a 170 kg hydrogen tank system with hydrogen being stored at 350 bar pressure. A maximum range of approximately 500 km with an average consumption of 0.49 kg(H2)/km is considered to be required to perform all shunting operations.

The expected duty cycle for the FCH-powered system is 18 h of daily operation, 6-7 h being idle time assuming 345 days in operation annually for each train. Under the defined duty cycle, the FCH Shunter would need a full refill after 2-3 days. However, it is better to refill the train every day and limit the hydrogen refuelling station storage capacity. The maximum expected speed is 100 km/h, but the actual average travelling speed is assumed to be 7.5 km/h.

The related infrastructure includes a hydrogen refuelling station at Skirotava marshalling yard and an off-site hydrogen production facility located outside the city. The hydrogen refuelling station is expected to serve all fifteen FCH Shunters and should be designed to have the capacity to refuel 850 kg(H2) per day. The infrastructure should allow an approximate refuelling time of 20 minutes per train. The storage capacity for the HRS should be twice the daily hydrogen demand or refuelling capacity (~1,700 kg) in order to ensure two full days of train operations. Hydrogen would be produced off-site via electrolysis at a level of ~850 kg(H2) per day at a price of approximately 5 EUR/kg including distribution costs associated with the tube trailer and truck transportation.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
1,000 kW	290 kN	100 km/h	~170 kg	~500 km	EUR 1.9 m
		> Typical maximum speed ranges from 20 to 80 km/hour > Higher maximum speed if used outside of depots or stations	> Typical tank volume ranges from 700 to 6,000 l of diesel	> Typical range of approximately 400 to 1,000 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography	> Retrofitted train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
200 kW	3,000 t		~0.49 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
510 kW	50 kW	5 kW	20 m^3
Battery capacity		**Fuel cell size**	**Weight**
420 kWh		255 kW	122 t

Table 12: Train specifications for Riga node (Latvia) case

ECONOMICAL ASPECTS

For an FCH Shunter in this case the TCO is 20.4 EUR/km.[45] In this case study, a total estimated investment of around EUR 8.2 m for the hydrogen infrastructure would be required. This figure includes a 850 kg H2 hydrogen refuelling station and associated 1.6 t of hydrogen storage have been customised to the site requirements and will cost approximately EUR 2.7 m. The equipment will cost approximately EUR 2.23 m and the other associated costs will be approximately EUR 430,000. For the off-site hydrogen production, an investment of EUR 5.54 m is required.[46] For off-site production, a standard 2.5 MW electrolyser has been modified for the case specifications and will cost EUR 2.5 m, the storage at the station will cost EUR 400,000, the filling station for tube trailer transport will cost EUR 850,000 and there is an additional cost of approximately EUR 1.7 m (land, developing cost, environmental study, etc.).

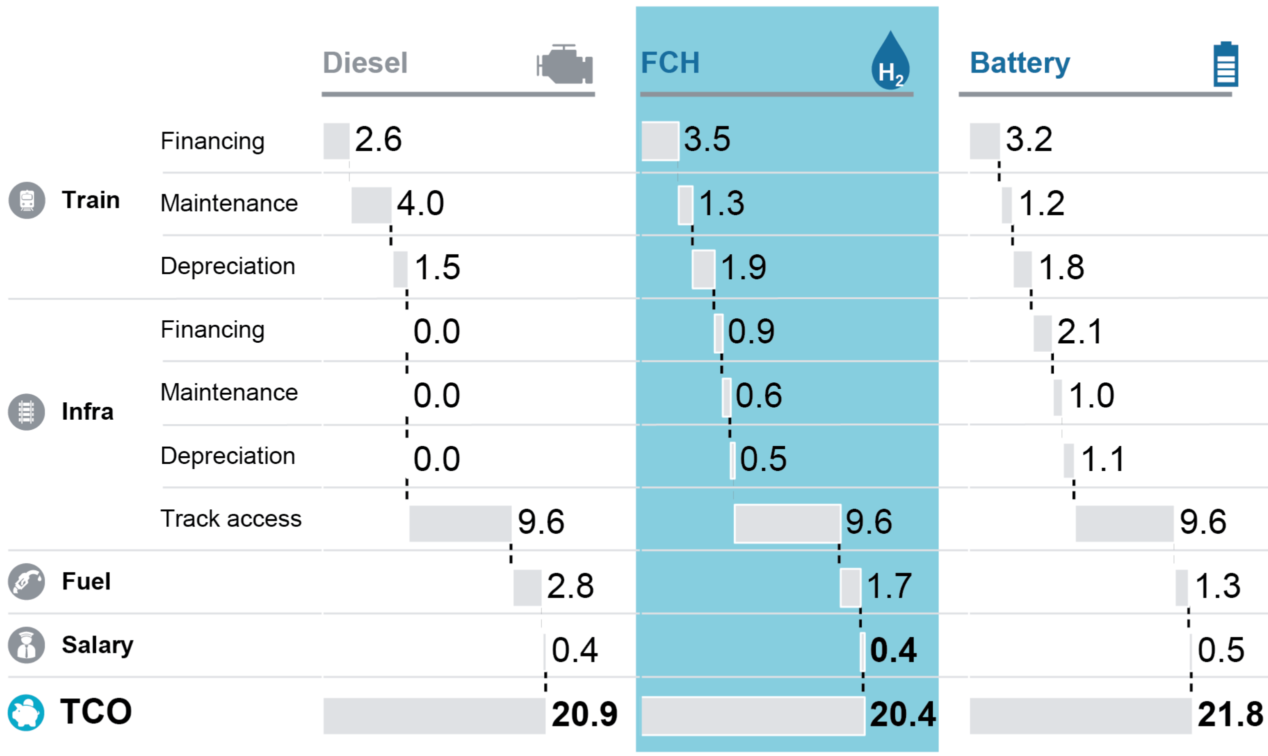


Figure 13: TCO analysis of different technological options for Riga node (in EUR/km).[47]

The CAPEX for 15 trains, including batteries and FCH components, is approximately EUR 28 m. This results in train financing costs of 3.5 EUR/km based on a WACC of 9.30%. The train maintenance costs including replacement of fuel cells and batteries amounts of 1.3 EUR/km. With an average consumption of 0.49 kg(H2)/km and an off-site hydrogen production via electrolysis, fuel costs are assumed to be 3.4 EUR/kg(H2) with an electricity price of 45 EUR/MWh.

[45] The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex.
[46] This figure is not included in the cost associated with acquiring land for the off-site hydrogen production.
[47] All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.

Compared to a diesel Shunter, the FCH solution has 0.5 EUR/km lower TCO. FCH trains have higher infrastructure financing, maintenance, and depreciation costs of 2.0 EUR/km and higher train financing costs. However, the maintenance costs for the FCH train are 2.7 EUR/km cheaper than the diesel maintenance costs and the fuel cost will be reduced by 1.1 EUR/km with the FCH technology, assuming a diesel price of 1.21 EUR/l.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH train can be reduced by 1.63 EUR/km to 18.7 EUR/km total if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg including transportation. This allows for some savings on fuel and hydrogen production infrastructure costs. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Battery-powered Shunters are available as an alternative clean solution. Overall, the TCO for battery-powered Shunters is 21.8 EUR/km, approximately 1.4 EUR/km more than the FCH option. The performance of battery systems in the railway environment still carries significant uncertainty concerning battery lifetime and operational flexibility. Given that the shunting yard and node are not electrified, 9 charging stations costing EUR 18 m (pantographs) are required in the home depot and on the route due to the approximately 40 km range enabled by the batteries. Depending on the number of loads, the weight of cargo and daily duty cycles, upwards of 3 charging cycles would be required across the 100 km daily mileage of the train. This could become a significant constraint for the operator if the charging cycles disrupt the trains' operations.

ENVIRONMENTAL PERSPECTIVE

Compared to diesel technology, the FCH Shunters could save up to 1,128 t of CO2 emissions in their first year if Latvian grid electricity is assumed. Through 2030 these could generate accumulated savings of 11,675 t CO2, 129 t NOx and 28 t PM10. Latvian grid electricity is primarily generated from hydro and thermal powerplants. This existing blend of electricity limits the carbon reduction potential. If renewable energy from wind production or solely hydropower is sourced though, then CO2 reductions can be increased to 3,350 t in the first year and over 30,000 t through 2030. Additionally, hydrogen production with renewable energy could also double the reduction in PM10 emissions.

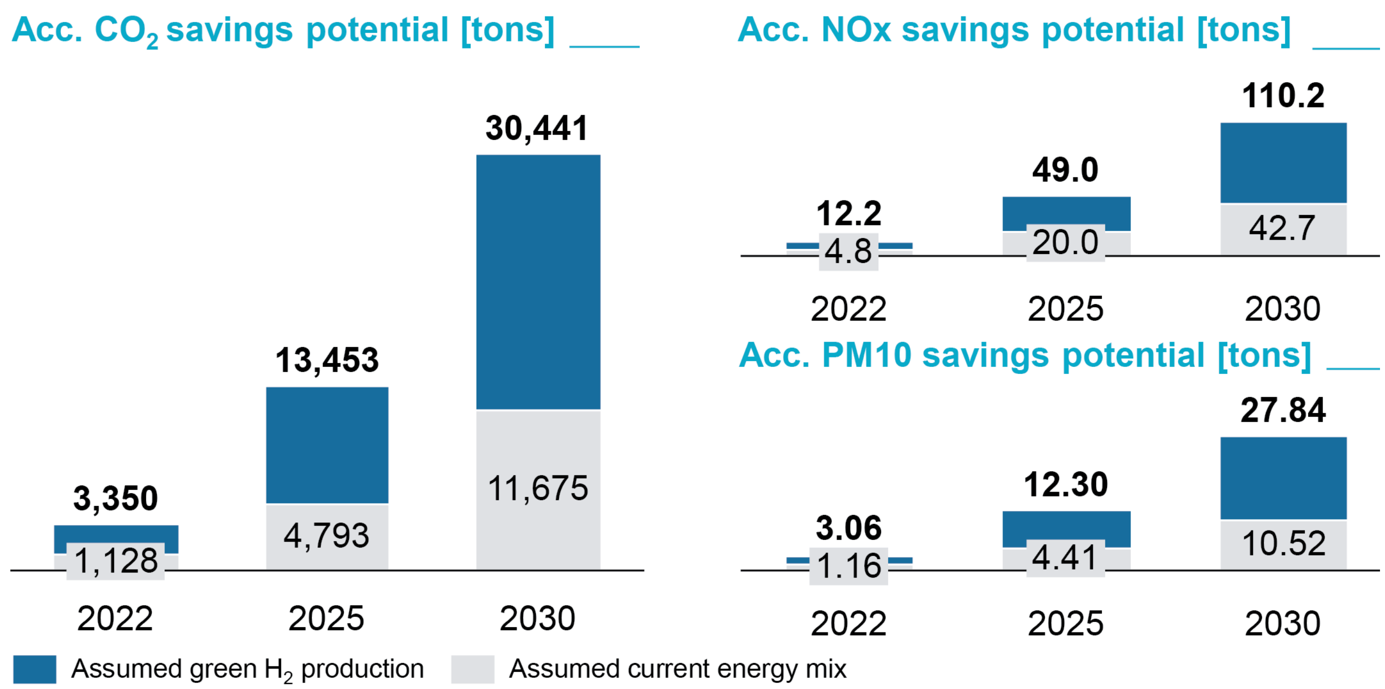


Figure 14: Emission saving potential for Riga node based on two scenarios (in tons).

The Shunters in this case are operating in an urban environment. Riga has a population of approximately 640,000 people. With the existing fleet of Shunters, the diesel engines are idling in the shunting yard for long hours of the day and operating heavily on routes between the 6 different port terminals scattered throughout the city. These operations create significant local emissions, noise, and particulate emissions. FCH alternatives, depending inevitably on electricity source, could reduce this local impact. FCH Shunters would not produce the large amount of tailpipe emissions while idling in the shunting yard and on operations within the city. However, if electricity is sourced from the large thermal electricity plant to the east of Riga, then these emissions will be produced only 5 km away from the marshalling yard. Therefore, sourcing of renewable energy is very important in realising environmental benefits.

BARRIERS FOR SEAMLESS IMPLEMENTATION

First, the technological requirements needed for operating FCH Shunters should be explored prior to making a full-scale investment as there are no FCH Shunters in full operation across Europe yet. The operator should explore the impact of repeated coupling and uncoupling cycles (e.g. shocks and vibration) on FCH components and the overall durability of the fuel cell and electronic components Additionally, the electronic interdependencies between battery capacity and fuel cell power required for shunting operations need further exploration. The amount of idling that the Shunter performs throughout the day and whether or not the Shunter can be switched on and off easily between loads will have a large impact on the charging and discharging strategy for the internal battery. The operator here should carefully consider the needs of their operation when choosing the specific battery and fuel cell types.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 4: Reduced train performance due to changed rail weight characteristics;

Barrier 6: Increased wear & tear on FC powertrain derived from rail specific operations;

Barrier 8: Unproven reliability of electronic fuel cell components in the rail environment;

Barrier 9: Limited experience with battery specifications for FCH rail applications (e.g. charge and discharge cycle).

Further details on these barriers can be found in in Report 3.

3.2.3. SHUNTER CASE: GDANSK (POLAND)

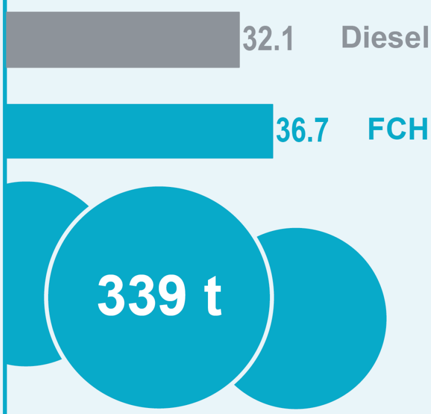
Gdansk, Poland: Utilising refinery hydrogen for rail transport

In Gdansk, Poland an existing refinery and rail operator can utilise excess hydrogen from the refinery to power a fleet of 10 FCH Shunters. The co-location and operation of the refinery and marshalling yard allows for an examination of potential synergies and environmental benefits that can be captured.

The FCH Shunters have a daily mileage of 25 km, a 50 kg hydrogen storage system, an estimated maximum power rating of 600 kW and a maximum tractive effort of 220 kN. The FCH Shunter has a TCO that is approximately 14% higher than the existing diesel technology.

Track length	35 km	**N° of rolling stock**	10 Shunters
H_2 fuel consumption	0.72 kg/km	**Capacity/ load**	3,000 t

FCH Total Cost of Ownership [EUR/km_{train}]



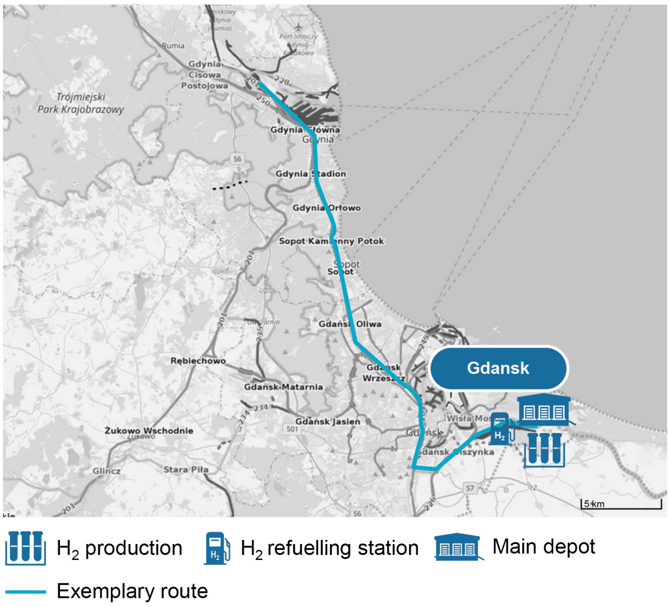
Maximum CO_2 emission savings per year [tons]

INTRODUCTION

This case examines the deployment of FCH Shunters in Gdansk, Poland. In particular, this case looks at how existing industrial hydrogen sources can be combined with a deployment of FCH Shunters in order to provide cost effective and environmentally friendly fuel for rail operations. Refineries and other industrial plants often use hydrogen as a process gas or produce it as a by-product. Many of these industrial plants often use rail transport and are often located close to freight rail hubs. Under the right conditions there is a potential for hydrogen to be used as a fuel for FCH trains.

In this case the co-location of the shunting yard with the Gdansk refinery allows for a close examination of potential synergies between the Shunters and industrial hydrogen. Grey hydrogen provides moderate emissions reductions when compared with diesel engines and could provide a cost-effective source of hydrogen for fuel cell powered transportation, while the cost of sourcing renewable energy becomes more competitive. This case examines the key factors and costs associated with deploying and fuelling FCH Shunters in conjunction with a refinery.

LOCATION



The northern Polish city of Gdansk is the focus of this case. The marshalling yard is located to the east of the city centre, and directly adjacent to the refinery. The marshalling yard is primarily used for unloading, filling, sorting and dispatching the petrochemical tank wagons used within the refinery.

Additional operations are sometimes also conducted on lines between the marshalling yard, the port in Gdansk and potentially even the port in Gdynia, a neighbouring town approximately 35 km away.

The overall route profile is relatively flat. Within the Gdansk marshalling yard there is a limited incline and the route between Gdansk and Gdynia shows an elevation gain of approximately 50 m. The climate conditions in the area include temperatures ranging from -25 °C to 40 °C and daily icing conditions. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[48]

[48]Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

BACKGROUND OF THE CASE STUDY

In this case, there is potential to create synergies between the hydrogen used in industrial processes and hydrogen that would be needed for FCH rail transport. Refinery operators or industrial users of hydrogen often have excess that they end up using for calorific heating or simply release and burn off. With proper purification, this hydrogen could be used in fuel cells for transport purposes internally or externally through hydrogen sales. This creates potential operator cost savings or additional income sources for industrial producers. For rail operators, usage of hydrogen produced through such industrial processes can be a cheap and more environmentally friendly alternative to diesel.

However, for such an arrangement there needs to be close alignment between the potential rail consumers of hydrogen, and the industrial producers. In this case the refinery operator has received European Union CEF Blending funding for hydrogen purification infrastructure and has plans to sell hydrogen to bus operators.[49] However, the refinery operator also operates a freight rail and shunting service, creating avenues for hydrogen use in rail operations as well.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The Shunters considered in this case conduct operations in the marshalling yard, on lines to and from the different terminals of the Gdansk and Gdynia ports, and on the loading yard inside the refinery. These Shunters are almost exclusively carrying tank wagons filled with oil and chemicals required for the refining processes, and petrochemicals that are produced by the refinery. This case has considered the retrofitting of 10 diesel Shunters, which will have diesel powertrain components replaced with an FCH system.

The FCH system considered includes a fuel cell stack, on-board hydrogen storage and traction batteries. The Shunters would be equipped with an on-board hydrogen storage capacity of 50 kg of hydrogen, allowing a maximum range of approximately 70 km with an average consumption of 0.72 kg (H2)/km. The trains that would be considered should have an approximate load capacity of 3,000 t.

Key data		Comment
Case specifications		
Deployment:	10 Shunters	3,000 t capacity
Expected daily mileage:	25 km	Over 20 hours of operations daily, but due to long idle periods the Shunters' daily mileage is only 25 km
Expected days of operation:	350 days	
FCH train specifications		
CAPEX per train set:	EUR 2,000,000	Retrofitting of each Shunter including fuel cell, hydrogen storage system, battery, structural changes of the units, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.72 kg(H_2)/km	
Maintenance costs:	8.80 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~180 kg(H_2)	350 bar

Table 13: Technical and commercial specifications for Gdansk (Poland) case.

[49]European Commission, 'CEF Transport Blending: Selected Projects: Blending Call (Second Cut-off Date)', 10 January 2018.

Typical Shunter operations include long periods where the trains are idling, and short periods and distances of operation. As a result, the daily duty cycle of the train is 20 hours, but the daily mileage of the train is approximately 25 km. Based on these daily operations, the entire fleet would require an estimated 180 kg(H2) daily. Based on this duty cycle and the estimated tank size of 50 kg, then the Shunters would need to refuel approximately every two days. However, the operator in this case can decide whether the on-board storage tank can be further optimised. If the required maximum range is reduced, then the on-board storage tank can be reduced. This would then mean more frequent refuelling as well.

The hydrogen infrastructure required for this case includes a hydrogen refuelling station located within the marshalling yard. This hydrogen refuelling station should be able to serve the entire fleet of Shunters and should have a capacity of 180 kg(H2). This refuelling station should be accompanied with on-site hydrogen storage that is approximately twice the daily hydrogen demand, or approximately 360 kg. This enables continuous operations in the event hydrogen production is interrupted. Additional details on the industrial production and purification of hydrogen can be found in the focus topic accompanying this case.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
600 kW	220 kN	70 km/h	~50 kg	~70 km	EUR 2.0 m
		> Typical maximum speed ranges from 20 to 80 km/hour > Higher maximum speed if used outside of depots or stations	> Typical tank volume ranges from 700 to 6,000 l of diesel	> Typical range of approximately 400 to 1,000 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography	> Retrofitted train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
35 kW	3,000 t		~0.72 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
750 kW	37 kW	8 kW	9 m^3
Battery capacity		**Fuel cell size**	**Weight**
320 kWh		190 kW	70 t

Table 14: Train specifications for Gdansk (Poland) case.

ECONOMICAL ASPECTS

The FCH Shunters considered in this case would have a TCO of 36.7 EUR/km.[50] This figure includes the establishment of the 180 kg H2 refuelling infrastructure which has been customised to the site requirements and would require an investment of approximately EUR 800,000. This is including the 360 kg of customised hydrogen storage that would accompany the refuelling station. The equipment would cost approximately EUR 560,000, excluding EUR 220,000 of additional costs.

The CAPEX for the retrofitting of the 10 trains, including batteries, fuel cell stacks, and on-board hydrogen storage will be an estimated EUR 20 m. The resulting financing cost for the trains is 12.6 EUR/km, based on a WACC of 8.7%. The maintenance costs for the train, including the eventual replacement of fuel cells and batteries, comes to 8.8 EUR/km. The train will have an estimated consumption of 0.72 kg/km, and the hydrogen will be purchased from the on-site refinery owned by the train operator. Fuel costs are estimated to be 2.1 EUR/km.

In comparison with existing diesel technology, the FCH Shunter would have a 4.6 EUR/km higher TCO. Driving this difference are the higher costs for the train, higher fuel costs, and the associated investment in the hydrogen refuelling station. Some moderate savings on train maintenance offset some of these costs. Low hydrogen prices are key for the operations of the FCH Shunters and the overall TCO.

To analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included based on the sourcing of hydrogen from the industrial source. For example, if an actual price of 5.50 EUR/kg is assumed, then the overall TCO increases by 1.80 EUR/km, leading to a total TCO of 38.53 EUR/km for an FCH Shunter. The impact of the estimated flat rate indicates the potential TCO impact of the hydrogen price.

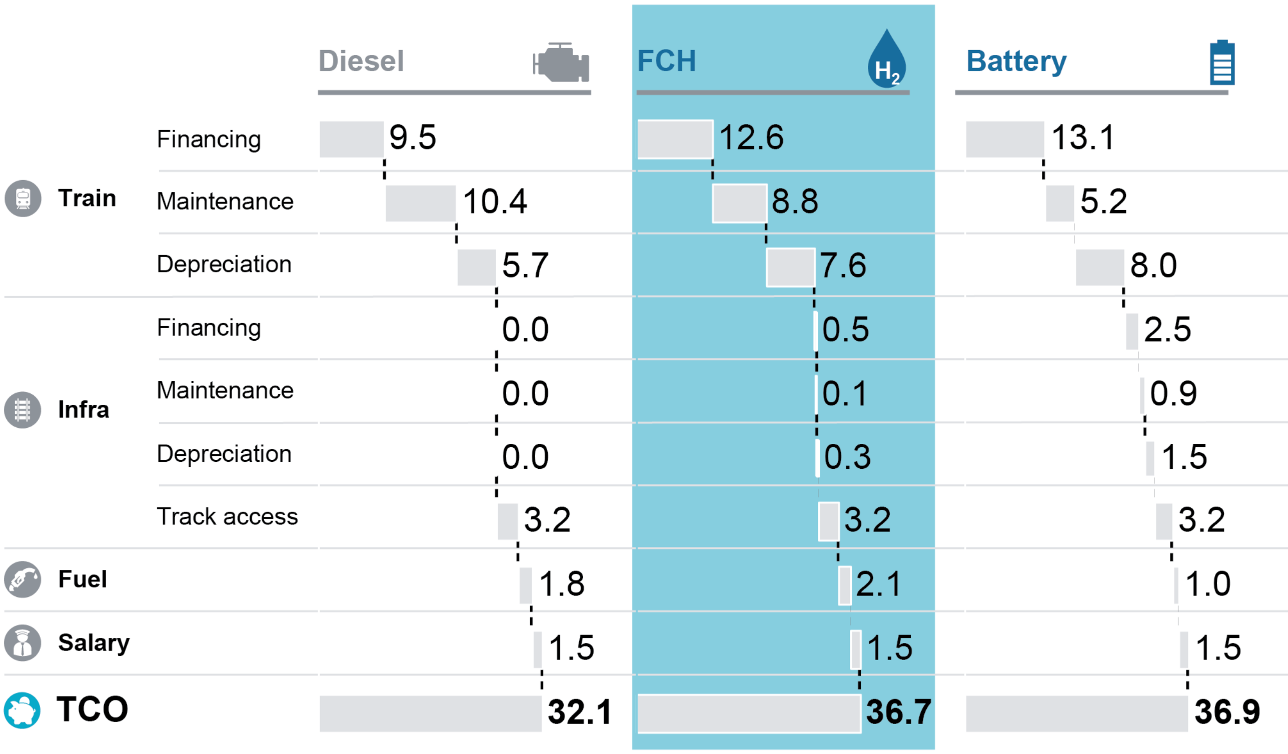


Figure 15: TCO analysis of different technological options for Gdansk (in EUR/km).[51]

[50]The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex.
[51] All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.

For another alternative technology, battery-powered Shunters, the TCO is 0.20 EUR/km more than the FCH solution. Based on the number of trains that would need recharging, two charging stations would need to be established within the marshalling yard. Battery-operated Shunters would have a range of approximately 25 km per day, enough to only require charging once per day. Battery-powered trains do not take advantage of the excess hydrogen that is being produced by the adjoining refinery. The battery-powered trains would require the operator to purchase additional grid electricity for recharging the Shunters.

ENVIRONMENTAL PERSPECTIVE

The FCH Shunters studied in this case could save up to 339 t of CO2 emissions in their first year and approximately 3,079 t CO2 through 2030. An additional 18.6 t of NOX and 2.82 t of PM10 can also be eliminated through 2030 if FCH Shunters replace diesel Shunters. Utilising an existing hydrogen supply from the refinery eliminates both the necessity for diesel to power the engines and the associated emissions that come with them. Nevertheless, it must be considered that the current hydrogen is not suitable for immediate use in fuel cells. Energy must also be used to process the hydrogen, although this energy consumption is rather low in contrast to the energy consumed by the production of hydrogen with electrolysis. The production of the hydrogen is not emission free, but specific to each individual plant and the way the industrial hydrogen is produced. As such the exact emissions are not calculated here. However, the hydrogen would be produced even in the absence of FCH trains, at the minimum using hydrogen here would allow for the emissions generated by the diesel Shunters to be eliminated.

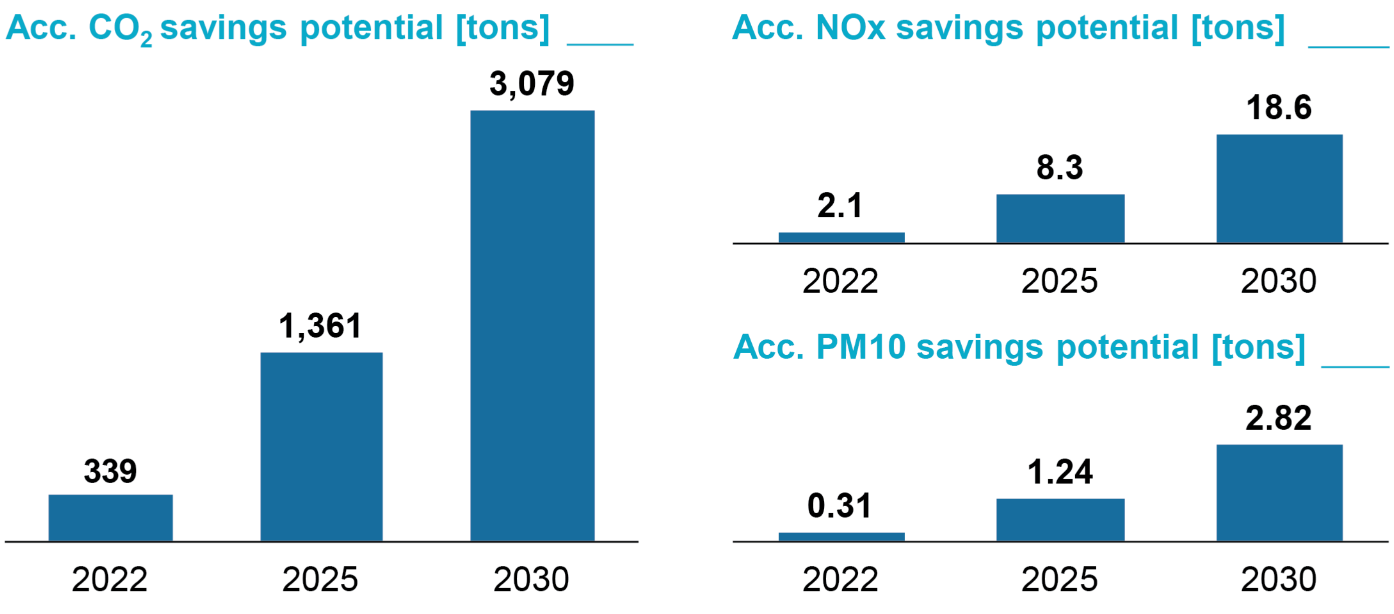


Figure 16: Emission saving potential for Gdansk (in tons).

Gdansk is a city of almost 600,000 people. Many of the daily shunting operations, particularly those operations to and from the port, involve close proximity to the urban population in Gdansk. FCH Shunters will eliminate some of the noise and the harmful emissions that result from long hours of shunting operations.

Considerable potential for reducing noise pollution lies in the high idle time of classic diesel Shunters, which are typically operated continuously. This results in constant noise emissions. These noise emissions can be significantly reduced by using FCH Shunters, which also reduces the emissions during empty runs between the different terminals.

BARRIERS FOR SEAMLESS IMPLEMENTATION

In this case in particular, economic and legal barriers were examined. Economically, the cost of hydrogen sold by industrial producers is critical for the overall FCH Shunter TCO. Industrial producers and users of hydrogen hoping to sell excess hydrogen to rail operators should be cognisant of these cost constraints. Rail operators could choose to invest in on-site production via an electrolyser if it proves to be cheaper than purchasing industrial hydrogen. Additionally, the competitiveness of the FCH Shunters could improve as the cost of the rolling stock becomes more competitive. The comparative cost of FCH powertrain components could prove to be a significant barrier until greater economies of scale in FCH production are achieved. In terms of regulatory issues, the co-location of the marshalling yard and the refinery allows developers to avoid many of the traditional legal barriers that the establishment of hydrogen infrastructure would normally encounter. However, national regulations neglect to provide proper standards and certification processes for hydrogen used as a fuel.[52] This applies to certifying hydrogen origin, quality, and measurement, where there is also not an appointed body for overseeing these processes.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 24: Lack of efficient and appropriate regulatory structures for FCH train approval

Barrier 29: Immature FCH rail supply chain

Barrier 30: Insufficient tailored financing mechanisms to support roll-out of FCH trains

Further details on these barriers can be found in in Report 3.

[52] 'Database | HyLAW Online Database'.

3.3. CASE STUDIES ON MAINLINE LOCOMOTIVES

Mainline Locomotives are used for the transport of passengers and freight. Most of these locomotives operate on major routes. Due to the high level of electrification in Western Europe, many Mainline Locomotives operate with catenary-powered electric engines. However, in international freight trains, diesel locomotives are still used due to the different systems in operation. Another field of application for diesel locomotives is the last mile delivery for freight. This is often combined with the use of Shunters, which take over the final distribution of the freight. In Central Europe, some major routes are already congested and the flexibility of non-electrified locomotives can be advantageous – also with regard to the Rail Track Access fee, which can be reduced with the flexibility of trains.

Mainline Locomotives are mostly characterised by very high maximum and average power ratings. The high weight and the sometimes very demanding routes require a high constant power output. The speed is usually restricted by the freight wagons, which also produce the highest noise emissions.

The use of hydrogen makes particular sense in this field of train applications, as the performance parameters of the existing Mainline Locomotives can be achieved with FCH technology, the operational capability across national borders is maintained, and the flexibility of route guidance is significantly increased compared to electrification. The enormous CAPEX for electrification are unjustifiable, especially in the case of main lines with low utilisation. Infrastructure for the hydrogen trains would only have to be installed at main hubs where there are sufficient framework conditions for the production of hydrogen.

Most Mainline Locomotives are operated over a long period of time and after a certain time a retrofit takes place. This retrofit can be used to convert the powertrain. However, the compact design of the Mainline Locomotives together with the high power requirement does not allow the hydrogen storage to be accommodated. This would have to be transported by an additional tender wagon.

In the following TCO calculation of each case study, the focus is on the technical feasible technology options diesel, FCH and catenary. Due to operational constraints (e.g. long distance and the absence of charging infrastructure) batteries will not be compared.

Three factors are important for the successful introduction of FCH Mainline Locomotives:

1. Since Mainline Locomotives are not only used on a single route, the framework conditions must be created to ensure that refuelling stations can be used even across national borders;

2. The external storage of hydrogen (tender) brings advantages and disadvantages. Thus, the tenders can be held in stock and can always be adapted to the necessary range of the current order, but the operation may have to be modified;

3. The use of hydrogen technologies is particularly interesting on cross-border routes and an international standard must be created.

3.3.1. MAINLINE LOCOMOTIVES CASE: TALLINN – NARVA (ESTONIA)

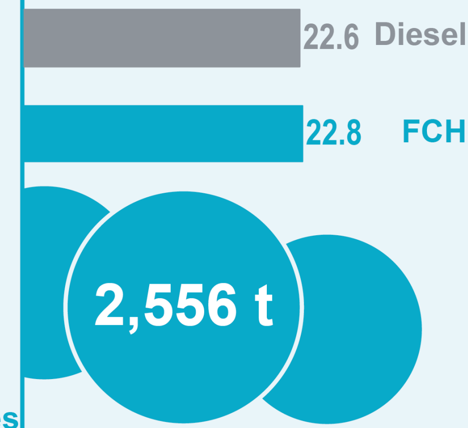
Tallinn – Narva, Estonia: Short-haul FCH freight services

Existing Mainline Locomotives used to haul freight between Tallinn and the Russian border in Narva can be retrofitted with FCH components. The FCH locomotives can provide a cost effective and environmentally friendly alternative for moving freight on this popular domestic route.

The 2 FCH Mainline Locomotives would have a daily mileage of approximately 500 km, a 980 kg hydrogen storage system, an average power rating of 1,200 kW and a maximum tractive effort of 405 kN. The FCH option is 0.20 EUR/km or less than 1% more than the incumbent diesel technology.

Track length	210 km	**N° of rolling stock**	15 Locomotives
H_2 fuel consumption	0.67 kg/km	**Capacity/ load**	5,000 t

FCH Total Cost of Ownership [EUR/km$_{train}$]



Maximum CO_2 emission savings per year [tons]

INTRODUCTION

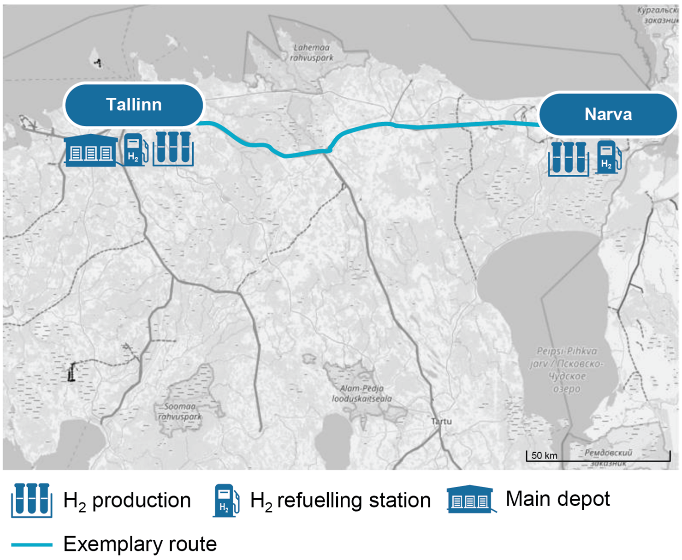
In Estonia, FCH Mainline Locomotives provide an avenue for railway operators to modernise rolling stock, while simultaneously ensuring future compliance with environmental regulations. This is particularly important in Estonia, where rolling stock is older and purchased second hand, and where electrification is low. Existing rail services use second hand diesel locomotives designed to operate on wide-gauge Estonian railways.

The route in question is important because it connects, Tallinn, the capital, with Narva, where rail traffic and freight cross the border with Russia. The Rail Baltica project plans to increase rail interconnectivity in the Baltics, Poland, and Germany.[53] This calls for the development of a dedicated standard gauge rail route running from Tallinn through Latvia, Lithuania, Poland and on to ports on the North Sea. This route from Tallinn to Narva has the potential to become an important route, feeding cargo on to the rest of Europe, via Rail Baltica.

Finally, in the early stages of deployment FCH Mainline Locomotive operations will be constrained by the network of hydrogen refuelling stations and supports. This is especially true in operational contexts where Mainline Locomotives do not operate the same fixed routes. However, a smaller country like Estonia where Mainline Locomotives operate on a specific selection of routes of shorter distances, provides a good context for potential early deployment of hydrogen locomotives. These conditions make this case interesting for further analysis.

[53] 'Rail Baltica', accessed 4 December 2018, http://rail-baltica.com/pub/?id=2.

LOCATION



The route in question operates from Tallinn to Narva and is approximately 210 km in length. This route carries both passenger and freight traffic. The route has double tracks, but only 25% of the route is electrified. This is the 50 km portion of the route between Tallinn and Aegviidu. The route involves a colder climate, with mild temperature conditions ranging from 40 °C to 35 °C.

Much of the traffic is international in nature, carrying either freight or passengers from Tallinn to Russia, and cities like St. Petersburg in particular.

Tallinn, as such, is the economic and political heart of Estonia. The route has a slight incline up until roughly the midpoint of the route. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[54]

BACKGROUND OF THE CASE STUDY

Following the collapse of the Soviet Union, Estonia regained its independence, and separated its national rail system and operator from the rest of the Baltic states and Russia. In the late 1990s this state railway was privatised. Today, the national freight rail operator has evolved from the company that was formed through this privatisation process. This national operator is responsible for operating the freight rail services on this route from Tallinn to Narva. Most of the traffic carried on this route is freight in transit to or from Russia. A significant portion of this freight is oil related products produced in Russia.[55]

In Estonia, large portions of the rail infrastructure need refurbishment. These investments are needed to increase freight traffic and economic activity, and to encourage an increase in rail passenger traffic. However, these investments need to be made strategically in order to maximise budget utilisation and impact. On the route in consideration there is only catenary electrification on 25% of the route. Electrification of the final 150 km would cost well over EUR 100 m. Also, when it comes to freight locomotives, most of the rolling stock is older diesel locomotives that have been purchased second hand. Ensuring compliance with increasingly stringent European Union diesel emission standards will likely require investment in new technologies in the coming years.

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[54] Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.
[55] Sakari Salo and Ilkka Hova, 'Estonian Railways Today', Today's Railways, accessed 22 November 2018, http://www.rrdc.com/article_05_2003_evr_todays_rwys.pdf.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The FCH Mainline Locomotives considered in this case would operate on the 210 km route between the operations hub in Tallinn and the transfer yard in Narva. From Narva cargo is then transferred onwards to Russia. This case considers the retrofitting of 2 Mainline Locomotives for operation along this route.

For this case, the locomotives will require all the necessary subcomponents for an FCH powertrain, including fuel cell stacks, compressed hydrogen storage, and a traction battery. The train should have an on-board tank system capable of storing 980 kg of hydrogen at 350 bar pressure. Based on this storage the maximum range is 1,000 km, with an average consumption of 0.67 kg(H2)/km. The train can carry up to 5,000 t.

Key data		Comment
Case specifications		
Deployment:	2 units	Mainline Locomotives
Expected daily mileage:	500 km	On the non-electrified route
Expected days of operation:	330 days	
FCH train specifications		
CAPEX per train set:	EUR 3,900,000	Retrofitting of existing locomotive including fuel cell, hydrogen storage system, battery, structural changes of the units, replacement of electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.67 kg(H_2)/km	
Maintenance costs:	1.13 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~700 kg(H_2)	350 bar
Production facility:	1x 1.5 MW	On-site facility installation, 350 bar

Table 15: Technical and commercial specifications for Tallinn – Narva (Estonia) case.

The duty cycle for the locomotives considered on this route is 13 h. The distance of the route considered here is relatively short compared to the standard profile of Mainline Locomotives. However, the locomotives on this route should be able to complete at least three trips between Tallinn and Narva each day. The daily mileage for each locomotive is 500 km. Based on the size of the on-board storage and the daily mileage, the locomotives would need to refill every other day of operations.

The total hydrogen demanded by the two locomotives is 670 kg/day. For this case, the fleet would require one hydrogen refuelling station and one electrolyser producing hydrogen located in Tallinn. The hydrogen refuelling station should have the capacity to refuel approximately 700 kg(H2)/day. The trains will need to be refuelled in under an hour, preferably in half an hour. For operational contingency, the refuelling station should also have a 1,400 kg(H2) storage capacity, or twice the typical daily demand. The on-site electrolyser should also have a production capacity of 700 kg(H2)/day.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
2,800 kW	405 kN	120 km/h > Typical maximum speed ranges from 100 to 160 km/hour > Higher speed for passenger/ mixed operations	~980 kg > Typical tank volume ranges from 3,500 to 7,000 l of diesel	~1,000 km > Typical range of approximately 500 to 1,100 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography	EUR 3.9 m > Retrofitted train
Avg. poer rating 1,200 kW	**Max. capacity** 5,000 t		**Avg. Consumption** ~0.67 kg/km		**Lifetime** 30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
2,800 kW	226 kW	28 kW	102 m^3
Battery capacity		**Fuel cell size**	**Weight**
1,000 kWh		1,150 kW	106 t

Table 16: Train specifications for Tallinn – Narva (Estonia) case.

ECONOMICAL ASPECTS

The FCH Mainline Locomotives considered in this case have a TCO of 22.8 EUR/km.[56] The hydrogen infrastructure necessary for the deployment of these trains would require an investment of EUR 6 m. This figure includes the 700 kg H2 refuelling station and associated storage which have been customised to the site requirements and will have an equipment cost of EUR 2.2 m and additional associated costs of EUR 800,000. The hydrogen production will require a standard 1.5 MW electrolyser that has been modified for the case specifications. This results in an electrolyser investment of EUR 2.05 m, and a compressor skid costing EUR 735,000, for a total investment of EUR 2.8 m.

The investment for the required retrofitting of the two trains in consideration is EUR 7.8 m. The financing cost for these two vehicles is 0.92 EUR/km based on a WACC of 6.4%. The associated maintenance cost for the trains is 1.13 EUR/km, including the replacement of FCH related components. Fuel costs are 2.60 EUR/km, based on electrolysis and an electricity price of 61 EUR/MWh. With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered in order to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

56 The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex.

The FCH option is 0.20 EUR/km more than the incumbent diesel technology. This is largely driven by the higher financing costs for the trains and infrastructure. However, lower fuel prices resulting from the electricity price help offset this. Diesel price in this case is assumed to be 1.33 EUR/l. The lower maintenance costs associated with the lack of moving parts in an FCH powertrain also helps to drive the competitiveness of the FCH train.

To analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH locomotive can be reduced by 1.80 EUR/km to 21.00 EUR/km total if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg including transportation. This would create large savings in hydrogen production infrastructure costs. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary electrification is another alternative environmentally friendly option, but would cost 24.40 EUR/km, approximately 1.60 EUR/km more than the FCH option. This is largely driven by the high amount of infrastructure investment required to build the catenary system. This cost is reflected in the TCO of approximately 4.50 EUR/km. In this case, the overall low amount of existing electrification means that a very large investment would be needed, in addition to a long infrastructure development timeline.

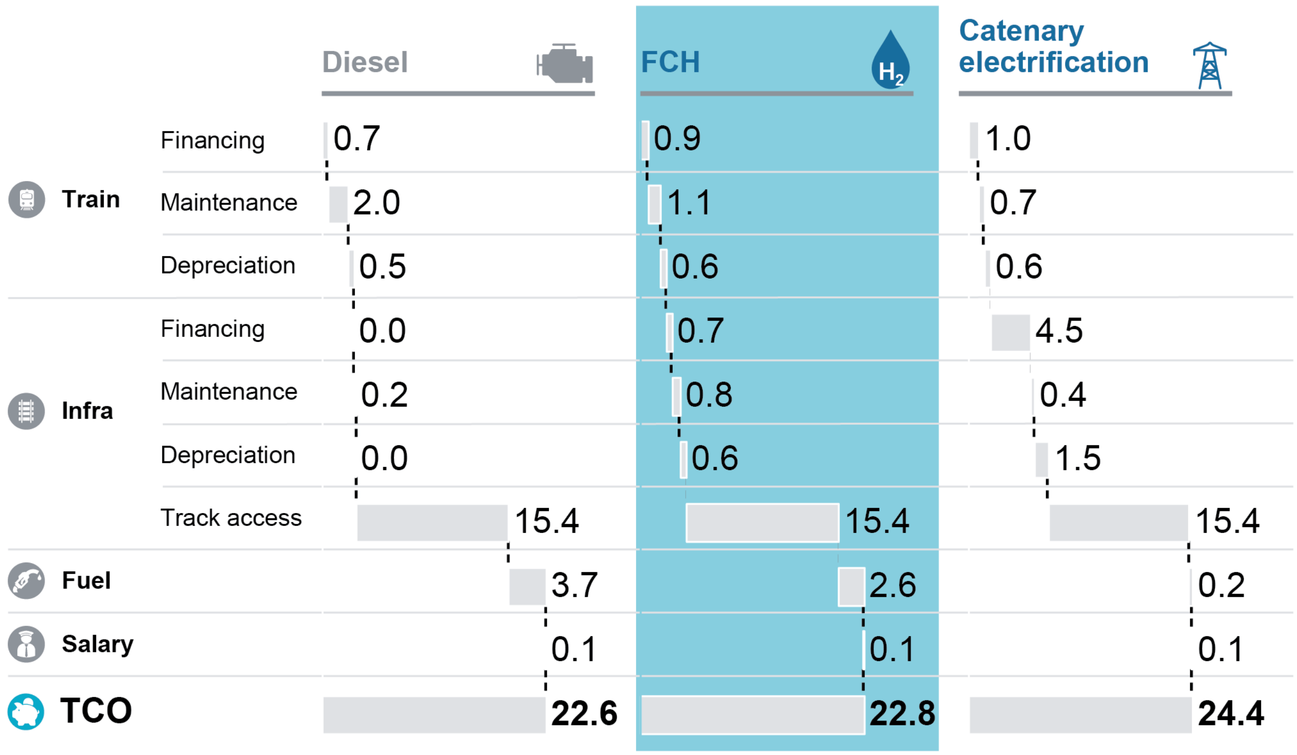


Figure 17: TCO analysis of different technological options for Tallinn – Narva (in EUR/km).

ENVIRONMENTAL PERSPECTIVE

The sourcing of the electricity used to power the electrolyser producing hydrogen for the trains in this case is critical. Due to the existing blend of power generation in Estonia, if grid electricity is utilised for hydrogen production, the FCH locomotives would produce more CO2 more than diesel trains. As such this case examines the potential impact when renewable energy is sourced for hydrogen production. If entirely renewable energy is sourced for the electrolyser, there is significant potential for emissions reduction. In the first year, these two trains would save 2,556 t CO2, 7.8 t NOX and 2.34 t PM10 emissions. Through 2030 upwards of 23,227 t CO2 could be saved.

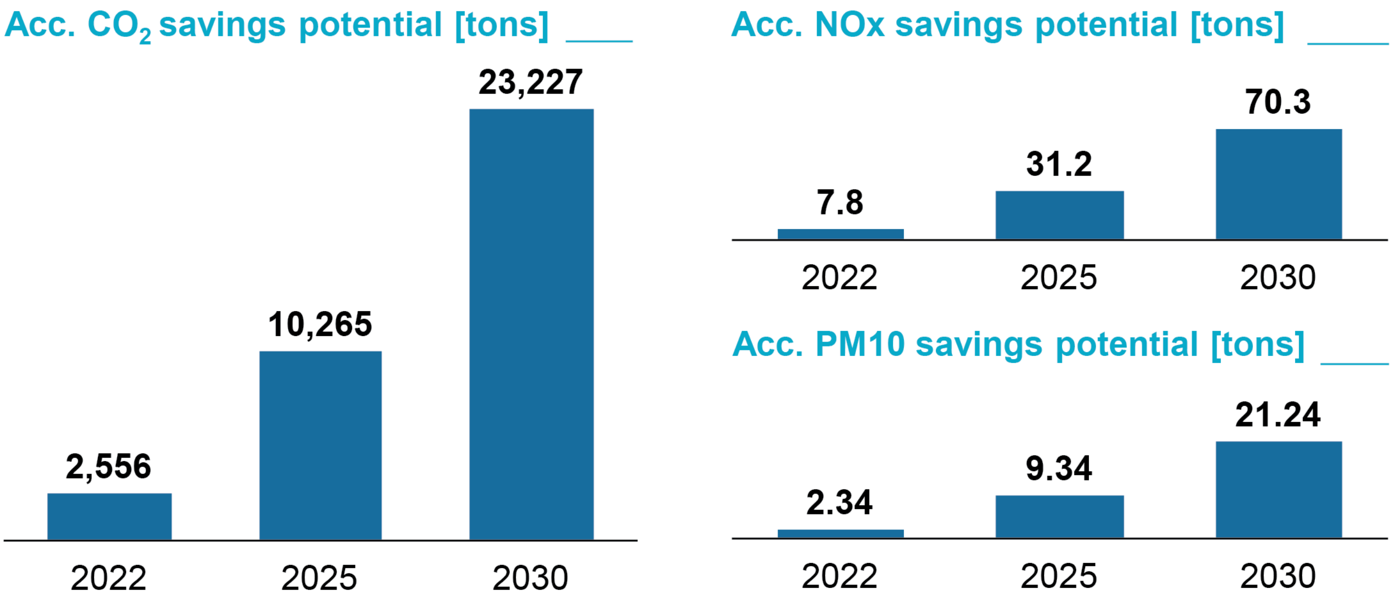


Figure 18: Emission saving potential for selected freight route based on two scenarios (in tons).

Tallinn has a population of approximately 450,000 people, and Narva has a population of approximately 60,000. If these trains are supplied with green hydrogen, then they can impact the local emissions that are generated from the rail traffic. The train route is near residential areas in Tallinn and Narva, and the numerous other communities along the route. The small size of the FCH deployment initially considered in this case significantly limits the environmental benefits that can be realised. If half the fleet of locomotives were to be retrofitted, these emissions savings would be exponentially increased.

BARRIERS FOR SEAMLESS IMPLEMENTATION

Two barriers which have particular impact on Mainline Locomotives were considered in this case. First the restricted international interoperability of the hydrogen trains, and second the maximum on-board hydrogen storage capacity of approximately 600 kg(H2). The route in this case currently carries freight from Russia and the trains can also be used to conduct operations in Russia. However, for FCH freight locomotives the constraints on international operations are quite large. The regulatory environment in Russia is quite different, unlike diesel there is insufficient hydrogen refuelling infrastructure, and the operator would be unable to access adequate service support. Additionally, long range international freight transport requires locomotives with significant range and hydrogen storage capacity. Compared with diesel, hydrogen requires a larger storage volume to provide the same amount of energy. Most modern locomotives simply do not have enough on-board space to accommodate the vast amount of hydrogen needed for long range freight services. Separate hydrogen storage cars have been discussed, but regulatory barriers related to pressurised connections between rolling stock will have to be addressed. Only after effective storage solutions have been created, long range mainline services will become more viable.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 11: Lack of technical knowledge on how to design use profile specific onboard hydrogen storage systems

Barrier 13: Optimisation potential via alternative hydrogen storage solutions

Barrier 14: Lack of solutions for sufficient hydrogen storage in Mainline Locomotives to allow for long range

Barrier 16: Lack of standardised FCH rail service and maintenance programs

Barrier 15: Lack of solutions to connect multiple tank systems across train cars

Barrier 31: Complex build-up of hydrogen refuelling infrastructure across a national rail network

Further details on these barriers can be found in in Report 3.

3.3.2. MAINLINE LOCOMOTIVE CASE: KALMAR – LINKÖPING (SWEDEN)

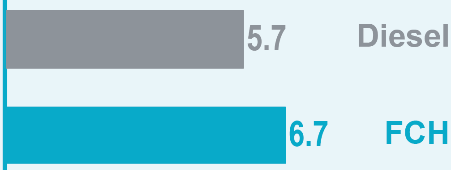
Kalmar - Linköping, Sweden: FCH freight and passenger service

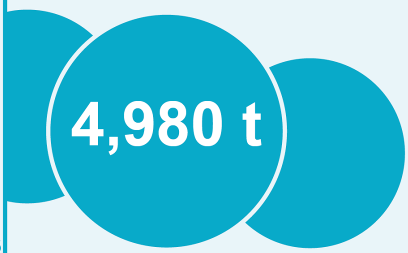
The route from Kalmar to Linköping is non-electrified and low utilised. Therefore, the possibility of using FCH Mainline Locomotives for both passenger and freight transport on this route would be conceivable.

In this case the use of 5 FCH Mainline Locomotives with an average power rating of 900 kW, an on-board storage of 450 kg hydrogen, a daily mileage of 600 km and a maximum tractive effort of 200 kN. With the potential new rolling stock on this relatively long route the FCH solution would be 18% more expensive than diesel locomotives.

Track length	230 km	**N° of rolling stock**	5 Locomotives
H_2 fuel consumption	0.48 kg/km	**Capacity/ load**	230 pax / 800 t

FCH Total Cost of Ownership [EUR/km_{train}]





Maximum CO_2 emission savings per year [tons]

INTRODUCTION

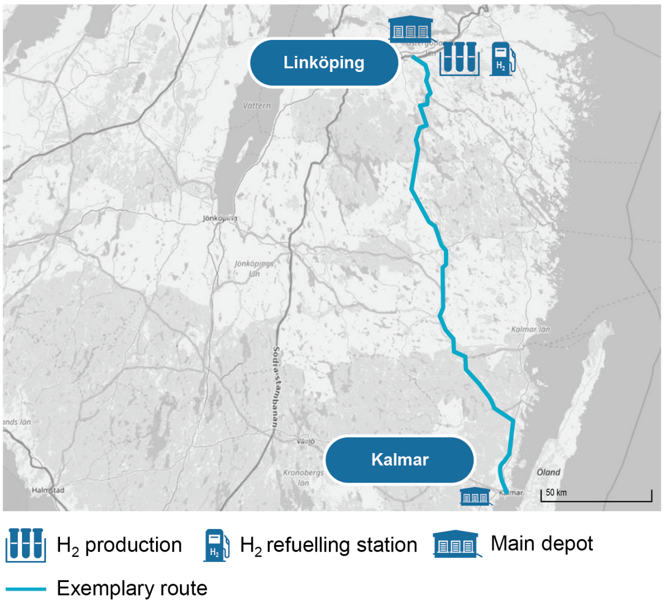
Kalmar – Linköping is a secondary route with reduced traffic and service currently operated by diesel units. There is a political interest in keeping the line alive and using it potentially for passenger and freight traffic. The route is serviced by Multiple Units currently and there is an interest in mainline applications on this route.

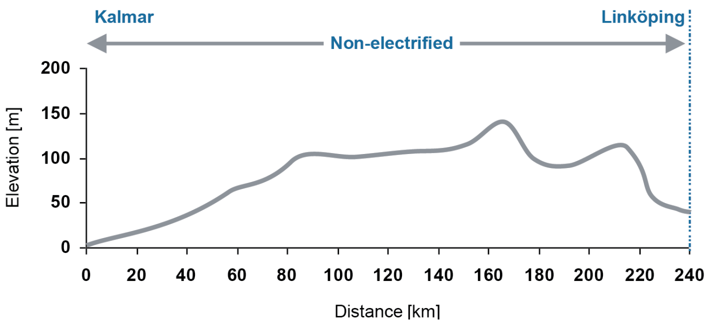
However, the diesel mainline passenger cars are outdated. The route is interesting because there is high traffic between these two cities or two regions and yet there is not a main road which connects these two cities. A direct train connection could have great potential to reduce road traffic and it also gives freight and passengers the advantage of faster connections.

The aim is to investigate the use of Mainline Locomotives, which also offer the potential for flexible use with passengers as well as the transport of goods. The connection of two medium-sized cities with a fast and flexible Mainline Locomotive without the use of high investments for possible electrification or the use of high-emission diesel trains is an interesting case.

In this case, the FCH trains can be a good alternative to secure the public infrastructure in rural areas, which may become increasingly important in terms of digitalisation and the trend towards more mobile working.

LOCATION





The route from Kalmar to Linköping is 235 km long and will have 10 stations on the way. It is a single line type and the route already exists. The share of electrification is around 1% but the operator wants to use the same trains as on electrified routes.

The route in question is currently a passenger route only which runs from Kalmar, situated on the Baltic Sea with its crossing to Öland, to Linköping.

Linköping is not only a city with an important university but it is also the hub for southern travellers to Stockholm. Key portions of the route only have a single track, and neighbouring routes involve a much larger detour to reach the same end point. While most of the lines in Sweden are operated by SJ, this line is operated by Kustpilen. The route is relatively flat with an elevation gain of approximately 160 m. The route involves a continental European and coastal climate, with mild temperature conditions ranging from -25 °C to 30 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[57]

BACKGROUND OF THE CASE STUDY

Östgötatrafiken and Kalmar Läns Trafik created a new traffic concept on Stångådalsbanan with the railcars. This was called Kustpilen and connected Linköping and Kalmar from 1996. Railcars of the Bombardier Itino Y31 series with the Kustpilen colour scheme have been in service there since 2010. In total six Y2 and four Y31 are available for passenger train services.

At the moment, the track is used 11 times a day with passengers, and freight trains are already operating partly on the route. To install an overarching concept of train operation that includes passenger and freight transport, 10 Mainline Locomotives would be necessary.

[57] Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

The Kalmar-Linköping route connects two university towns and the southern region of Sweden with Stockholm. In Linköping the SJ Hugh speed train X2000 stops, bringing people to Stockholm. Kalmar itself has an airport, which connects mainly Swedish cities but also holiday resorts. Important industries in the region are the food industry and the match industry. A total of 13,600 students are enrolled in the Kalmar region. Linköping is Sweden's seventh largest city with 106,502 inhabitants and has one of the most important universities in the country. Linköping is an industrial and shopping city. The Saab Aircraft Works are a major employer.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The potential FCH Mainline Locomotive service in question would operate the approximately 230 km from the central station in Kalmar to the central station in Linköping. Usually the Swedish operators order the trains with special equipment for heavy snowfall and icing. This case considers an initial deployment of 5 FCH Mainline Locomotives that are purchased new for these services.

Key data		Comment
Case specifications		
Deployment:	5 units	Mainline Locomotives flexible for freight or passenger transport
Expected daily mileage:	600 km	Non electrified route
Expected days of operation:	300 days	
FCH train specifications		
CAPEX per train set:	EUR 5,200,000	New Mainline Locomotives including design, locomotive body, fuel cell, hydrogen storage system, battery, electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.48 kg(H_2)/km	
Maintenance costs:	1.40 EUR/km	
Infrastructure specifications		
HRS installation schedule	1x ~1,500 kg(H_2)	350 bar
Production facility:	1x 4.0 MW	On-site facility installation, 350 bar

Table 17: Technical and commercial specifications for Kalmar - Lindköping (Sweden) case.

The FCH Mainline Locomotives in question will contain a hydrogen storage system, battery cell stacks, and a large fuel cell. The train will have a 450 kg hydrogen tank system operating at 350 bar pressure. The maximum range is calculated to be approximately 800 km with an average consumption of 0.48 kg(H2)/km for the locomotives in this case. The train has a maximum load of 800 t or a capacity of 230 passengers.

The daily duty cycle for train and the FCH-powered system operations is 15 h. Mainline Locomotives traditionally have high daily mileage, and in this case the FCH locomotives would have a daily mileage of 600 km. The maximum speed for the locomotive in this case would be 140 km/h but would on average reach 81 km/h. Based on the route and daily hydrogen demand, the locomotives will need to refill each day.

For this case one hydrogen refuelling station is considered, based in Linköping. The station should be able to refill the fleet each day and have the capacity to refuel 1,500 kg(H2) each day. In this case a refuelling time of less than 30 minutes is preferred. Each station will have storage for twice the daily hydrogen demand or refuelling capacity (~3,000 kg) in order to ensure that fleet flexibility is optimised. The HRS will also be coupled with an on-site electrolyser producing approximately 1,500 kg(H2) each day.

Parameter	Value	Notes
Max. power rating	3,200 kW	
Avg. power rating	900 kW	
Max. tractive effort	200 kN	
Max. capacity	800 t / 230 seats	
Max. speed	140 km/h	> Typical maximum speed ranges from 100 to 160 km/hour > Higher speed for passenger/ mixed operations
Hydrogen tank	~450 kg	> Typical tank volume ranges from 3,500 to 7,000 l of diesel
Avg. Consumption	~0.48 kg/km	
Max. range	~800 km	> Typical range of approximately 500 to 1,100 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography
Price	EUR 5.2 m	> New-built train
Lifetime	30 years	
Tractive motors	2,500 kW	
Compressor	79 kW	
Auxiliary and hotel power	750 kW	
Space	46 m^3	
Battery capacity	400 kWh	
Fuel cell size	400 kW	
Weight	91 t	

Table 18: Technical and commercial specifications for Kalmar - Lindköping (Sweden) case.

ECONOMICAL ASPECTS

For an FCH train the TCO is 6.7 EUR/km.[58] In this case study, a total estimated investment of EUR 9.5 - 11.5 m for the hydrogen infrastructure would be required. This figure includes 1,500 kg hydrogen storage and refuelling infrastructure that has been customised to the site requirements. For this infrastructure, the equipment will cost of EUR 3.9 m and have additional costs of EUR 0.7 m. The hydrogen production infrastructure will contain a standard electrolyser of 4 MW that has been modified for the case specifications. This leads to an electrolyser estimated cost of EUR 4.0 m and a compressor skid with an estimated cost of EUR 1.2 m.

[58] The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex.

The CAPEX for 5 trains, including batteries and FCH components, is EUR 26 m. This results in financing costs of 1.3 EUR/km based on a WACC of 7.4%. The train maintenance costs, including the planned replacement of fuel cells and batteries, amounts to 1.40 EUR/km. With an average consumption of 0.48 kg/km and on-site hydrogen production through electrolysis, fuel costs are expected to be 1.25 EUR/km. The electricity price is assumed to be 41.7 EUR/MWh.

Compared to the diesel option, the FCH solution has 0.9 EUR/km higher TCO. This difference is mainly driven by the CAPEX for the train and the infrastructure. The diesel price is assumed to be 0.87 EUR/l.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH train can be reduced by 0.57 EUR/km to 6.10 EUR/km total if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg including transportation. While this would lead to higher hydrogen costs per kg, it would lead to savings on the production infrastructure. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

Catenary-electric units and battery-powered trains are available as alternative solutions. Overall, the TCO for catenary-electric units is 16.52 EUR/km higher than the TCO for the FCH train. A catenary-electric unit would entail higher cost for financing. This is due to higher CAPEX for the catenary electrification. The catenary electrification also leads to significantly increased maintenance costs despite very low fuel costs overall.

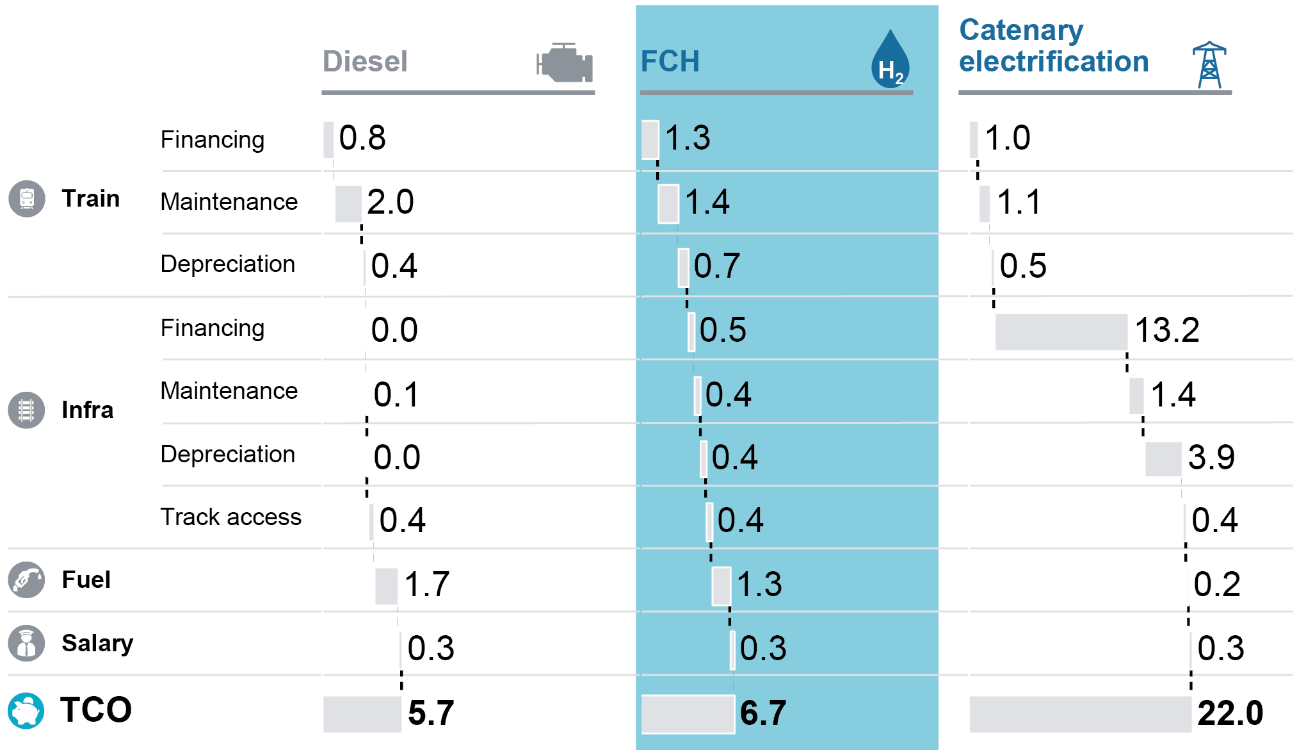


Figure 19: TCO analysis of different technological options for Kalmar and Linköping (in EUR/km).

ENVIRONMENTAL ASPECTS

The on-site hydrogen production will be supplied with electricity from the Swedish electricity grid. The current electricity mix with 40% nuclear, 40% hydro, 10% wind power, 6% biofuels and 4% other is already very beneficial for the environmental balance of FCH train applications on this specific route. If electricity is sourced with the same blend of sourcing as the Swedish grid, then these locomotives would already save 4,593 t of CO2 emissions in the first year. Accumulated over the years until 2030, the total CO2 emission saving potential would amount to 41,982 t. However, if entirely renewable energy is sourced, 45,248 t CO2 emissions can be eliminated.

At the same time, FCH train operation will also save NOx and PM10 emissions. With an assumed purely green electricity generation, 191.7 t NOx and 41.4 t could be saved until 2030.

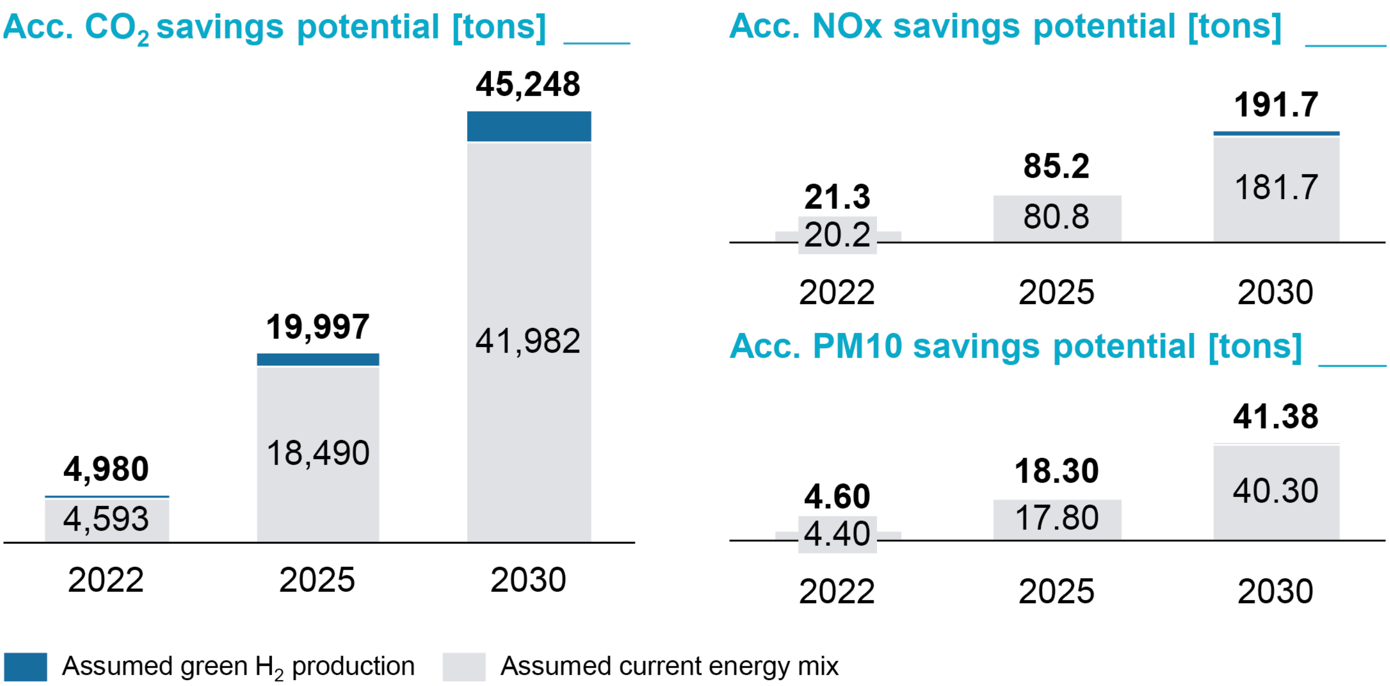


Figure 20: Emission saving potential for selected freight route based on two scenarios (in tons).

As in other cases, the use of FCH trains can have a positive effect on the smoke nuisance caused by trains. The core regions of Kalmar and Linköping are home to some 200,000 people, plus there are a variety of small villages and towns with populations between 200 and 8,000.

As in other cases, the use of FCH trains can have a positive effect on the noise emission caused by trains. Given the relatively low utilisation of the line, however, the effect is limited by the exchange of trains alone.

Additional environmental relief potential could be achieved by modernising the line. The use of hydrogen technology could modernise the entire line and increase its attractiveness. This, in turn, would motivate current motorists to take advantage of the rail option. Especially in the present case study it seems appropriate, since the railway is the fast alternative and Linköping in particular is already very well integrated into the Swedish rail network.

BARRIERS FOR SEAMLESS IMPLEMENTATION

In this case two barriers can be seen. First, ways must be found to cost-effectively produce large hydrogen quantities off-site. Second, hydrogen trains require a refuelling infrastructure, which must be made available independently of the train operator. For first barrier, in this case power plants or biofuel producers are located near the route (approx. 100 km radius). These could produce hydrogen cheaply using different technologies (electrolysis or reforming). However, the hydrogen would then would have to be delivered to the refuelling stations. Due to the high daily consumption, the operation of trucks is not necessarily economical. At the same time, very high standards apply to pipeline construction, and these approval processes are a challenge. Secondly, further clarification is also necessary when it comes to availability of hydrogen filling stations. As a rule, these filling stations must be provided by the rail network operator. This is already the case with diesel refuelling, and train operators pay a surcharge for fuel provision. The investment in the infrastructure (filling station or overhead line) is therefore not dependent on the actual train operator but on the infrastructure operator. In most cases, this can be regulated by the group strategy, but smaller operators particularly on more remote routes may encounter significant challenges here.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 25: Lack of specific permitting process for rail related hydrogen infrastructure

Barrier 31: Complex build-up of hydrogen refuelling infrastructure across a national rail network

Further details on these barriers can be found in in Report 3.

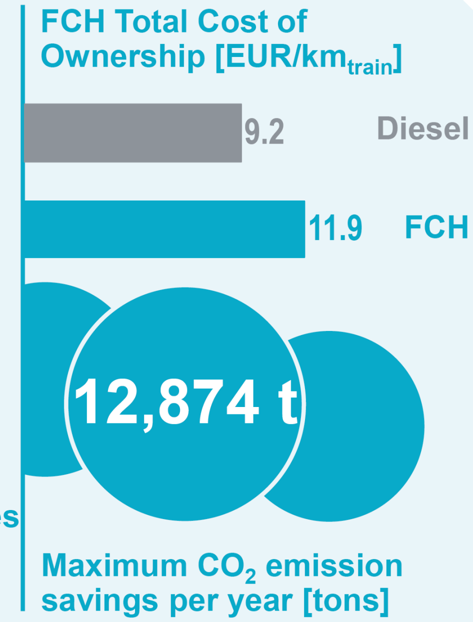
3.3.3. MAINLINE LOCOMOTIVE CASE: FRANKFURT (ODER) – HAMBURG (GERMANY)

Frankfurt (Oder) – Hamburg, Germany: Hydrogen powered freight

FCH Mainline Locomotives can be used to carry freight loads from Frankfurt (Oder) in the east of Germany to the Port of Hamburg. In doing so, they can help reduce the heavy congestion on popular mainline route segments and could eventually be used for cross-border operations, eliminating the need for time consuming train switches.

The 5 FCH Mainline Locomotives would have a daily mileage of approximately 750 km, a 765 kg hydrogen tank system, an average power rating of 1,350 kW and a maximum tractive effort of 300 kN. The TCO for the FCH Mainline Locomotive is 29% more than the diesel option.

Track length	720 km	**N° of rolling stock**	5 Locomotives
H_2 fuel consumption	0.82 kg/km	**Capacity/ load**	2,000 t



INTRODUCTION

This case examines how FCH Mainline Locomotives can be utilised on non-electrified freight routes to perform cross-border operations and reduce congestion on the heavily trafficked catenary electrified routes. In this case, a deployment of five Mainline Locomotives operating on lines in Germany from Frankfurt (Oder) to Hamburg will be analysed.

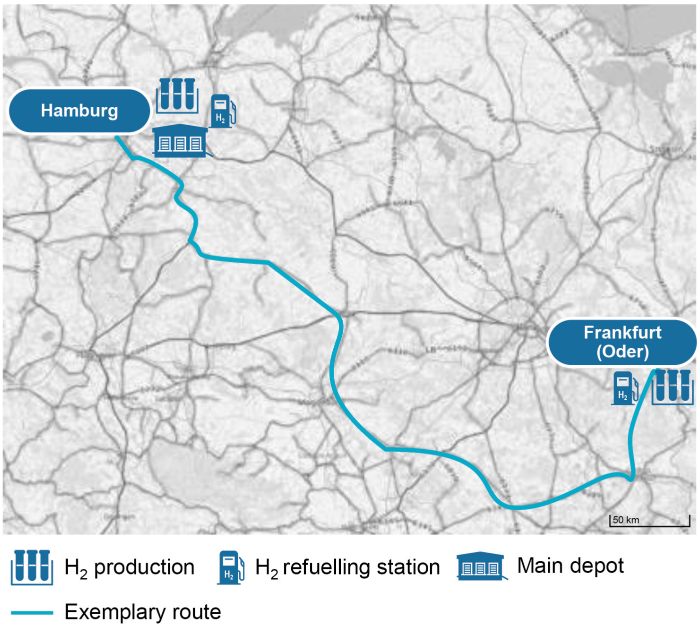
Reducing congestion on heavily trafficked freight corridors is an objective of many European freight rail operators. The majority of freight traffic in Germany travels on catenary electrified lines, but congestion is a growing problem for operators. Congestion on these popular routes leads to delays and slower delivery timelines. Additionally, less than 50% of Germany's rail border crossings are electrified.[59] Only two out of 24 rail crossings with the Czech Republic and Poland are electrified, and those that are involve different voltage systems on either side of the border.[60,61] This means that costly and time-consuming rolling stock changes have to be made at the border. The congestion and cross-border changes inevitably means delays and operational constraints that lead freight shippers to opt for truck transportation. Based on these conditions, it is worthwhile to examine whether FCH Mainline Locomotives, can be used in cross-border freight operations and to avoid congested electrified line segments or whether dual system locomotives could be used.

[59] 'Germany's Unelectrified Border Crossings Holding Back Rail Freight, Says APS', International Railway Journal (blog), 18 June 2018, https://www.railjournal.com/freight/germanys-unelectrified-border-crossings-holding-back-rail-freight-says-aps/.

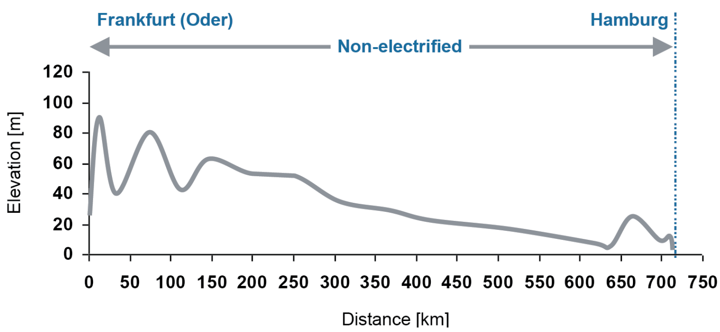
[60] 'Without Electrification, the Flood of HGVs Cannot Be Stopped', Allianz pro Schiene (blog), 16 June 2018, https://www.allianz-pro-schiene.de/en/press-releases/without-electrification-the-flood-of-hgvs-cannot-be-stopped/.

[61] Verkehrsverbund Berlin-Brandenburg, 'VBB - Cross-Border Railcars - Core Output - INTER-Regio-Rail - Removing Barriers to Regional Rail Transport', accessed 19 November 2018, http://www.central2013.eu/fileadmin/user_upload/Downloads/outputlib/InterRegioRail_3.2.8_3.2.9_Cross-border_railcars.pdf.

LOCATION



The route in question is a freight route which runs from Frankfurt (Oder) on the German border with Poland to the Port of Hamburg. The port is the second largest in Europe, and processes 136 million tons of cargo per year.[62] The rail route in question is a popular corridor for freight from Eastern Europe bound for the port. The route has a total length of approximately 720 km.



In this route segment the capacity of the track has been reached. Key portions of the route only have a single track, and neighbouring tracks which could serve as an alternative lack electrification. Constrained segments include Berlin to Stendal, where there are electrification constraints, and Stendal to Uelzen, where there is only one track.[63] The route involves continental European and coastal climates, with temperatures ranging from -25 °C to 40 °C. These location and specifications of the route directly impact the train engineering outlined in the specification subchapter of this case study.[64]

BACKGROUND OF THE CASE STUDY

Less congestion means faster delivery times, ability to carry more freight, greater fleet utilisation and ultimately more profitable services. Additionally, many freight products have to rely on road transport and are unable to utilise rail transport because of the speed. Thus, faster service times could allow rail transit to compete with other freight transit services for other products. However, in many corridors the only routes without congestion are those without catenary electrification. Increasing the freight utilisation of these non-electrified routes could reduce congestion on the electrified main routes. However, route frequency may still not be high enough to justify the investment in catenary electrification and diesel trains may remain an unattractive solution due to their environmental impact. This route also involves lots of rail traffic coming from Eastern Europe through Frankfurt (Oder) to the Port of Hamburg. However, time consuming rolling stock changes are often made because of differences in the catenary voltage. At other border crossings in Germany's east there is no cross-border catenary electrification at all. FCH Mainline Locomotives could prove to be an effective solution for rail operators in such cases, enabling greater route flexibility and faster delivery times with reduced environmental impacts.

[62] Port of Hamburg, 'Port of Hamburg Handling Figures', Port of Hamburg, accessed 19 November 2018, https://www.hafen-hamburg.de/statistics.
[63] Jürgen Murach, 'NSB – Corridor in Germany: Quality and Bottlenecks of Rail Infrastructure' (2016).
[64] Further details regarding the train design and the methodology behind the specification are explained in the focus topic 4.3.

ROUTE SPECIFICATION AND TRAIN CONFIGURATION

The potential FCH Mainline Locomotive service in question would operate from the freight terminal in Frankfurt (Oder) to one of the several freight terminals/yards in the Hamburg port area. In this case an initial deployment of five FCH Mainline Locomotives, which are purchased new for these services, are considered.

Key data		**Comment**
Case specifications		
Deployment:	5 units	
Expected daily mileage:	750 km	
Expected days of operation:	365 days	
FCH train specifications		
Purchasing costs:	EUR 5,440,000	New Mainline Locomotives including design, locomotive body, fuel cell, hydrogen storage system, battery, electronic equipment, inclusion of hydrogen ventilation systems, climate control, etc.
H_2 consumption:	0.82 kg(H_2)/km	
Maintenance costs:	1.08 EUR/km	
Infrastructure specifications		
HRS installation schedule	2x 1,600 kg(H_2)	Both in Hamburg and Frankfurt (Oder) - 350 bar
Production facility:	2x 4 MW	On-site facility installation, 350 bar

Table 19: Technical and commercial specifications for Frankfurt (Oder) – Hamburg (Germany) case.

The daily duty cycle for train and the FCH-powered system operations is 11 h. Freight Mainline Locomotives traditionally have high daily mileage, and in this case the FCH locomotives would have a daily mileage of approximately 750 km. The average speed for the trains on this route would be approximately 75 km/h. Based on the long route and daily hydrogen demand, the locomotives will need to refill each day, after completing the 720 km route in one direction. If the operator is seeking greater operational flexibility with the fleet of FCH Mainline Locomotives, then a larger on-board hydrogen storage capacity should be considered. This will allow the operator to send the locomotives on longer potentially multi-day and multi-stop routes. With such a large hydrogen storage system, refuelling at less frequent intervals could also help.

Max. power rating	Max. tractive effort	Max. speed	Hydrogen tank	Max. range	Price
5,800 kW	300 kN	140 km/h	~765 kg	~850 km	EUR 5.4 m
		> Typical maximum speed ranges from 100 to 160 km/hour > Higher speed for passenger/ mixed operations	> Typical tank volume ranges from 3,500 to 7,000 l of diesel	> Typical range of approximately 500 to 1,100 km > Depends e.g. on # of wagons/ coaches, their load, stops and topography	> New-built train
Avg. power rating	**Max. capacity**		**Avg. Consumption**		**Lifetime**
1,350 kW	2,000 t		~0.82 kg/km		30 years

Tractive motors	Compressor	Auxiliary and hotel power	Space
5,600 kW	134 kW	56 kW	79 m^3

Battery capacity	Fuel cell size	Weight
890 kWh	680 kW	101 t[65]

Table 20: Train specifications for Frankfurt (Oder) – Hamburg (Germany) case.

For this case two hydrogen refuelling stations are considered, one in Frankfurt (Oder) and one located in Hamburg. Each station should be able to refill approximately half of the fleet, approximately 1,600 kg(H2) each day. In this case a refuelling time of under 30 minutes is preferred, in line with existing diesel operations. Each station will also have on-site storage for twice the daily hydrogen demand or refuelling capacity (~3,200 kg) to ensure that fleet flexibility and operations are optimised. Each HRS will also be coupled with an on-site 4 MW electrolyser producing approximately 1,500 kg(H2) each day.

Locomotive specifications were defined for this route and the expected performance spectrum of the Mainline Locomotive, which allow a more precise calculation of the TCO. This basic concept design includes the following parameters: maximum tractive effort of 300 kN, power rating 5,800 kW (max.), 1,350 kW (average), battery capacity 890 kWh, fuel cell size 680 kW, traction motors 5,600 kW, compressors 134 kW, hotel power 56 kW. This configuration will result in a space requirement of 79.4 m3 and in a total weight for the unit of 101 t.

[65] The total weight should be examined. A reconfiguration of the axle system may be required if the maximum load of 22.5 t for each axle is exceeded.

ECONOMICAL ASPECTS

For an FCH train in this case the TCO is 11.9 EUR/km.[66] In this case study, a total estimated investment of approximately EUR 21 m for the hydrogen infrastructure would be required. This figure includes the two hydrogen refuelling stations of 1,600 kg H2 which have been customised to the site requirements and require a total investment of EUR 9.8 m. The hydrogen refuelling station equipment will cost EUR 8.2 m and then there will be EUR 1.6 m of other costs. For the hydrogen production, two standard 4 MW electrolysers have been modified for the case specifications. These electrolysers will cost EUR 8.6 m, the compressor skids will cost EUR 2.6 m, requiring a total investment of EUR 11.2 m.

The CAPEX for 5 trains, including batteries and FCH components, is EUR 27.2 m. This results in financing costs of 0.40 EUR/km based on a WACC of 3.5%. The train maintenance costs, including the planned replacement of fuel cells, amount to approximately 1.10 EUR/km. With an average consumption of 0.8 kg/km and on-site hydrogen production at each site, fuel costs are expected to be 5.40 EUR/km. The electricity price is assumed to be 105 EUR/MWh. With the current CO2 intensity of the existing grid electricity, additional electricity costs have been considered in order to procure an energy blend that will lead to CO2 neutral train operations compared with the incumbent diesel trains.

Compared to incumbent diesel technology, the FCH solution has 2.70 EUR/km higher TCO. This difference is mainly driven by higher CAPEX for the infrastructure and higher fuel costs. As seen in other FCH applications, some of these costs are offset by reduced maintenance costs for the FCH option. In this case the diesel price is assumed to be 1.0 EUR/l.

Furthermore, to analyse the impact that hydrogen price has on the overall TCO, hydrogen sourced at a flat rate has been included for comparative purposes. The overall TCO for the FCH train can be reduced by 3.80 EUR/km to 8.10 EUR/km total if hydrogen can be directly sourced for a flat rate of 3.00 EUR/kg including transportation. This would create large savings on fuel and hydrogen production infrastructure costs. The impact of the estimated flat rate indicates the potential TCO reduction that can be achieved in the future as the price for hydrogen declines.

For catenary electrification, and catenary-electric mainline units, another green solution, the overall TCO is 6.40 EUR/km, approximately EUR 5.50/km less than the FCH application. Switching to catenary-electric trains on such a service would require a large investment in the catenary infrastructure. 20% of these overall electrification costs for this route have been assumed as infrastructure costs. This results from the assumptions about the additional traffic, beyond the 5 trains in this case, that would make use of this route if there was catenary electrification. Additionally, development and construction of the catenary infrastructure would be an extensive multi-year process. If the operator is looking for a sustainable way of reducing congestion that also allows for cross-border operations then catenary may not be the optimal solution.

[66] The methodology used for the calculation of the TCO is based on market research and stakeholder interviews. For further details please see the detailed description of the TCO calculation in the Annex

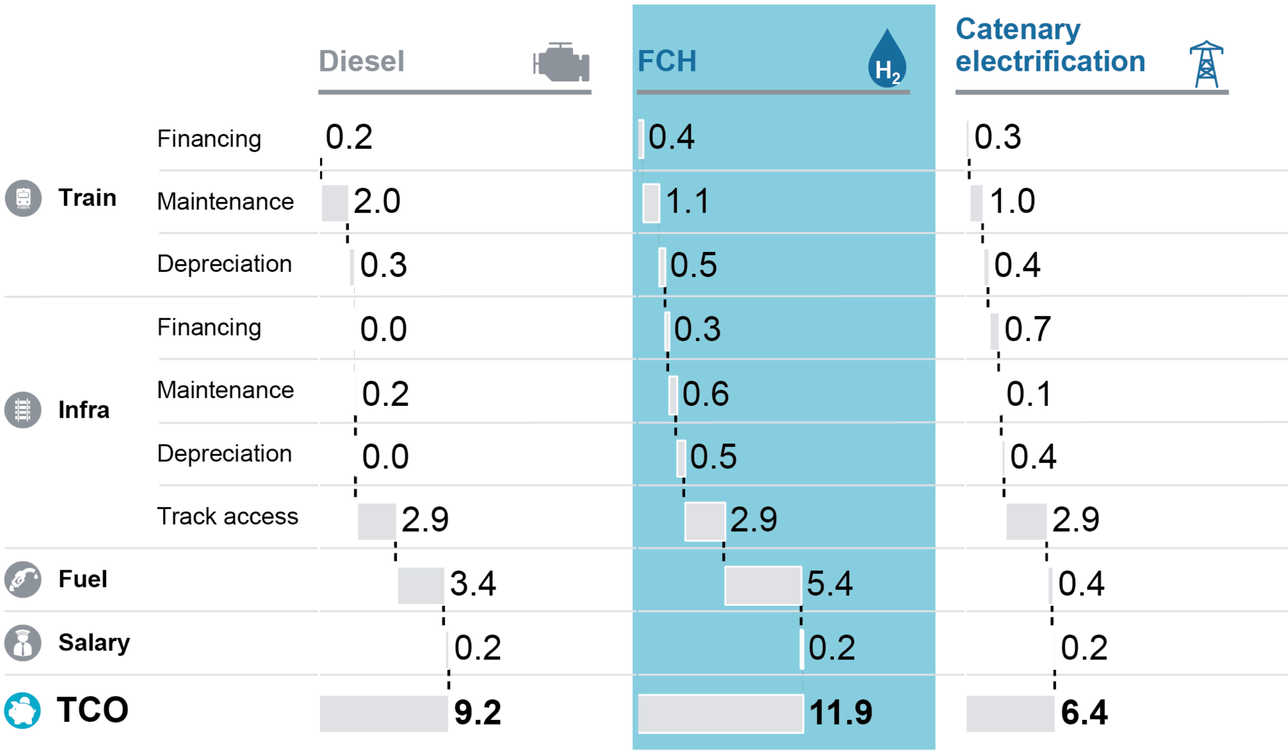


Figure 21: TCO analysis of different technological options for Frankfurt (Oder) – Hamburg (in EUR/km)[67]

ENVIRONMENTAL PERSPECTIVE

If entirely renewable energy is sourced for hydrogen production in this case than, 12,875 t CO2 and 32.4 t NOx emissions can be eliminated in the first year. PM10 emissions reductions of 11.78 t, particularly important for communities neighbouring the route, can also be realised. In this case, if the operator is targeting emissions reductions with the deployment of FCH Mainline Locomotives, then specific sourcing of renewable energy is important. If electricity with the same blend of sourcing as the German grid were used, then these locomotives would actually generate more CO2 more than diesel locomotives. While German electricity does have a blend of renewable sources, approximately 55% of the domestic production still comes from coal and gas.[68]

It is also important to note that if such a deployment of FCH trains was able to reduce congestion and cross-border switching time, and more effectively enable rail freight to compete with freight trucking, then additional environmental benefits can be realised. Freight that is carried by catenary-electrified trains and FCH trains as opposed to diesel trucks will have a lower overall environmental impact.

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[67] All single cost items were calculated. If values of the individual cost items are represented with 0.0 EUR/km, the value is below 0.05 EUR/km. However, the value was taken into account in the overall calculation. All values are given in EUR per train-km. Track access charges (TAC) are based on the minimum access packages. The figures for the TAC do not allow any clear comparison of track access charges between different markets to be made. Calculation based on a non-electrified route.

[68] International Energy Agency, 'Statistics | Germany - Electricity Generation by Fuel (Chart)', International Energy Agency: Statistics, accessed 19 November 2018, https://www.iea.org/statistics/?country=GERMANY&year=2016&category=Key%20indicators&indicator=ElecGenByFuel&mode=chart&categoryBrowse=false&dataTable=ELECTRICITYANDHEAT&showDataTable=false.

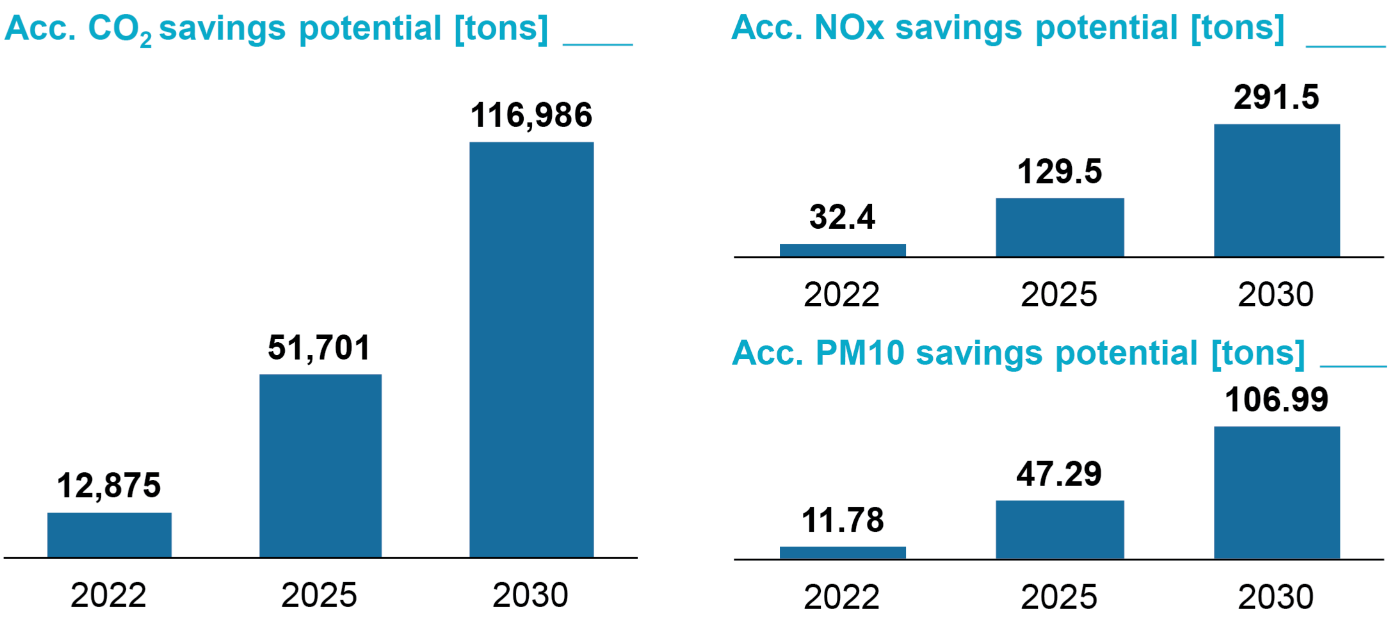


Figure 22: Emission saving potential for selected freight route based on green electricity scenario (in tons).

If renewable energy is sourced, these locomotives provide an attractive option to expanding freight services without the local emissions associated with diesel and the costs associated with catenary electrification. There are numerous cities and communities along the route. These locomotives would save significant amounts of emissions in Frankfurt (Oder), Cottbus, Stendal, Lueneberg, Magdeburg and Hamburg. In the port area, where emissions from ships and other diesel vehicles are already excessive, any emissions reductions that can be realised are very valuable.[69]

BARRIERS FOR SEAMLESS IMPLEMENTATION

Due to the nature of Mainline Locomotive operations there are potentially more barriers preventing deployment. First, FCH locomotives need to have a means for refuelling, thus the deployment of a broader rail HRS network is critical for Mainline Locomotive deployment. Without such a standardised network the rail operators can only operate FCH locomotives on fixed routes, seriously constraining operational flexibility. Second, concepts for storing upwards of 1-2 t of hydrogen within a locomotive's body have not yet been developed. Third, in terms of legal basis, Germany is by far the most developed regulatory environment for hydrogen in Europe.[70] However, more regulatory development is needed to recognise hydrogen as a full-scale fuel source, reassess hydrogen purity certification standards and enable the approval of more authorised certification authorities. Lastly, for Mainline Locomotives to be able to operate across regions and ultimately across borders, there needs to be legal and regulatory harmonisation on a national basis and on a European level. The European Union needs to set base standards for hydrogen's certification as a fuel, safety standards, and other critical regulatory areas to enable broader adoption.

[69] 'Port of Hamburg Magazine: Transport on Rails' (Hafen Hamburg, 04.15).
[70] 'Database | HyLAW Online Database'.

The following barriers have been identified as particularly relevant for the deployment of the FCH trains considered in this case:

Barrier 14: Lack of solutions for sufficient hydrogen storage in Mainline Locomotives to allow for long range;

Barrier 15: Lack of solutions to connect multiple tank systems across train cars;

Barrier 24: Lack of efficient and appropriate regulatory structures for FCH train approval (safety, environment, and fuel cell system standardisation);

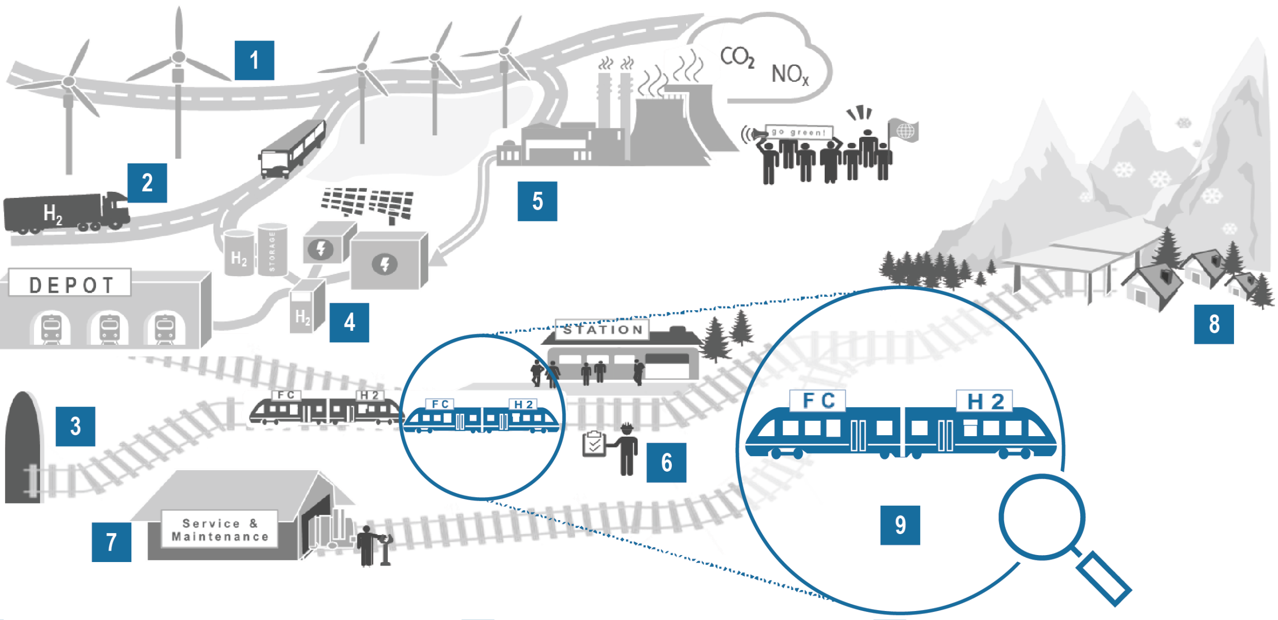
Barrier 25: Lack of specific permitting process for rail related hydrogen infrastructure;

Barrier 31: Complex build-up of hydrogen refuelling infrastructure across a national rail network.

Further details on these barriers can be found in in Report 3.

4. FOCUS TOPICS DERIVED FROM THE CASE STUDIES

The case studies examined in Chapter 3 show the route specifications and generate a requirement profile for the potential FCH trains. The resulting train and infrastructure specifications serve as a basis for the calculation of the TCO and the environmental impact. In addition to the technical and commercial considerations, some wider issues regarding the implementation of FCH technology in railway environment also become apparent through these detailed case studies. This chapter will therefore analyse these more general considerations related to implementation called focus topics and provide the relevant case study where this issue was visible. The focus topics shown in the figure shall be considered:



- **1** Renewable H_2 generation via electrolysis
- **2** Multimodal approach with buses/trucks/etc.
- **3** Interoperability with other infrastructure
- **4** H_2 refuelling station
- **5** Industrial H_2 supply
- **6** Regulations and permitting
- **7** Service and maintenance requirements
- **8** Safety/public acceptance of H_2 technology
- **9** Technical requirements of the FCH technology
- **10** Condition of the railway infrastructure

Figure 23: Schematic of FCH train eco-system including selected focus topics.

4.1. RENEWABLE H2 GENERATION VIA ELECTROLYSIS

Renewable H2 generation via electrolysis is especially important in regions where there is a potential oversupply on renewable energy currently or in the future. Some areas in Europe (e.g. provinces of Groningen and Friesland) aspire to eliminate emissions by 2030.[71] Fuelling regional train services with renewable hydrogen is a lever for the mobility sector to contribute to the emission reduction target (CO2 as well as particulate matter).

As an example, the Northern Netherlands have a significant potential for renewable electricity generation that can be used for hydrogen production. The locally favourable wind conditions have resulted in the development of 613 MW of on- and offshore wind generation in the region.[72] At the same time Dutch natural gas reserves are nearly depleted and earthquakes from gas exploration trigger an energy transition that goes beyond renewable electricity generation. Hydrogen production from local renewable electricity via electrolysis is one option to decarbonise the industry and transport sector.

Electrolysis for power-to-gas plants that generate hydrogen for transport applications is state-of-the-art technology and has been demonstrated and tested. Europe has been at the forefront of demonstrating the feasibility of these hydrogen generation assets.[73] However, they have not yet been deployed at large multi-MW commercial scale that would be necessary for large FCH train fleets. Therefore, key considerations are pointed out below that should be considered if large scale production of hydrogen from renewable electricity is intended. The case description has focused on on-site electrolysis that is directly linked to the refuelling stations. This concept will typically need to cover the following aspects.

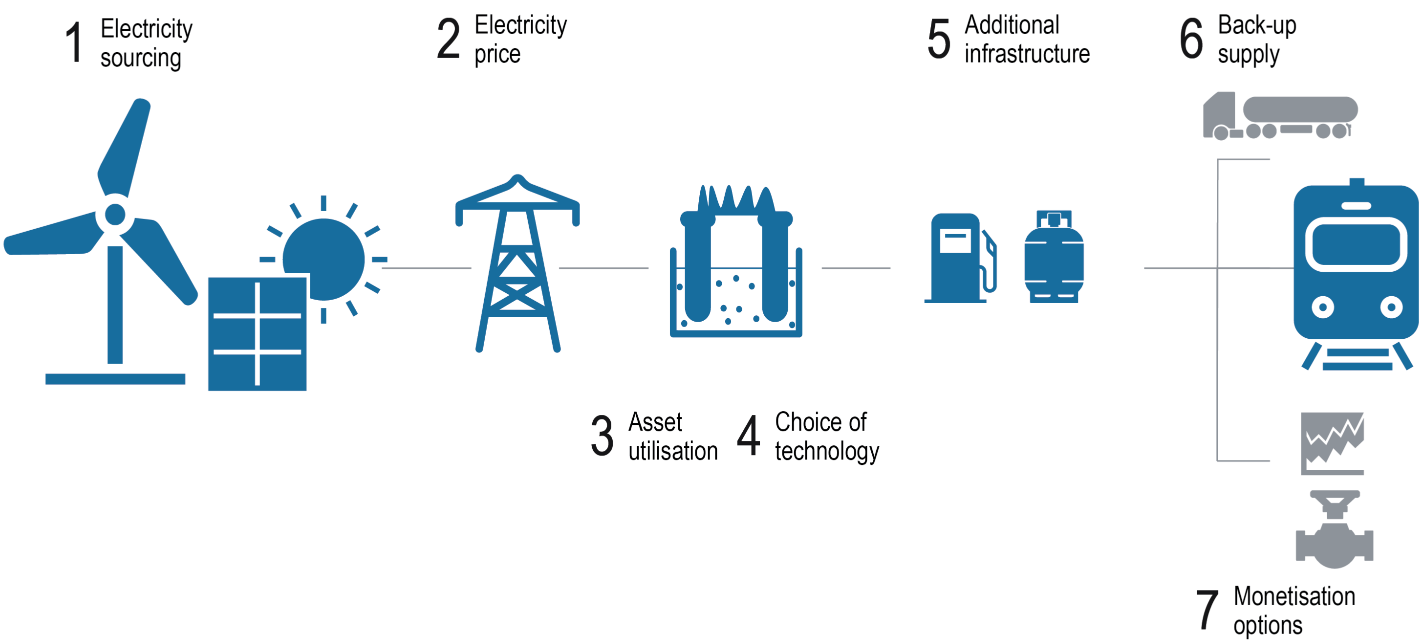


Figure 24: Schematic drawing of hydrogen generation via electrolysis.

[71] van Wijk, "The Green Hydrogen Economy in the Northern Netherlands."
[72] As of 2015, Government of the Netherlands, accessed November 29, 2018 https://www.clo.nl/en/indicators/en038624-wind-energy-capacity
[73] With a currently installed power-to-gas capacity of 25.5MW (as of Oct. 2018).

1. Electricity sourcing

To implement renewable hydrogen to fuel a train service, the electricity that is used in the hydrogen production needs to be renewable. As electricity cost is one of the main variables for the cost of hydrogen produced, it needs to be carefully analysed. There are mainly two ways that this can be ensured:

Via the electricity provider: Typically, a power-to-gas installation sources electricity from an electric utility company from the central grid. Securing exclusively renewable energy depends on the offering of the local electric utility. For renewable electricity supply at industrial scale detailed inquiries have to be made.[74] One additional caveat is that the service might come at above market pricing.

Via a direct connection to a renewable generation asset: In some cases, the power-to-gas installations can have direct access to renewable energy production. In these relatively rare cases, the generation asset is directly connected to the electrolysers. This option is only feasible if the electrolysis (and refuelling station) is located in the vicinity of a sufficiently sized wind or solar park. Sourcing the renewable energy directly avoids grid charges (see also consideration 2) and could potentially use electricity that otherwise would be wasted. However, the fluctuating nature of renewable electricity production in contrast to continuous demand for hydrogen supply for the trains needs to be carefully considered (see consideration 3).

2. Electricity pricing

The driving economic factor for electrolytic hydrogen is the cost of electricity. It constitutes a large share of the hydrogen cost. The electricity price has three core components:

Price for electricity generation: It includes all aspects of producing the electricity and recovering the investments in the generation assets. It is dependent on the asset mix of installed capacities (e.g. on- and offshore wind, solar, biogas etc.) and the overall market structure. The main lever to decrease the price is long-term contracting of large scale volumes. Electrolysis installations have the potential to take off large volumes that can realise a good bargaining position with the electric utility. An average price difference for large scale consumption (around 1,000 GWh per year) as opposed to medium scale consumption (around 8.5 GWh a year) in the Netherlands was close to 34%.[75] This off-take effect should be considered if multiple smaller HRS with electrolysis units are planned. Depending on the pricing schemes of the electric utility it is worth considering whether one central production site would be more suitable to allow for lower electricity prices.

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[74] Typically secured by long-term power purchase agreements with renewable generation assets.
[75] Ecofys, Fraunhofer ISI (2014), accessed: November 29, 2018
https://www.ecofys.com/files/files/ecofys-fraunhoferisi-2014-comparison-industrial-electricity-prices.pdf

Grid cost (grid fees): They include all electricity transmission and distribution grid related costs. Typically, larger consumers pay reduced grid fees depending on their consumption patterns. The opportunity to reduce these costs needs to be investigated to find the optimal set-up to pay minimal electricity prices.

Taxes (incl. fees and surcharges): They include public contributions and potentially earmarked surcharges that represent user financed subsidies for certain public causes (e.g. in Germany the EEG surcharge to foster the expansion of renewable energy generation capacities). As with the grid fees, the tax costs typically have exception options. Large scale industrial customers are often exempt in order to strengthen their international competitiveness. The exemption thresholds should be considered during the project concept phase.

As a key lever for the business case of power-to-gas from renewable energy, the electricity price has many flexible components that can be optimised. The most essential tool for optimisation is the scale of electricity consumption.

3. Asset utilisation

The second key lever for the business case next to the electricity price is the utilisation time of the electrolysis. Those two factors mainly define the economics of a power-to-gas investment. The utilisation for an electrolysis unit is typically defined by the full time equivalent (FTE) load hours (number of hours under full capacity operation). The figures below depict the effects of three different levels of utilisation and different levels of electricity cost on the renewable hydrogen cost. The cost difference of renewable hydrogen between 2,500 and 7,000 load hours utilisation can certainly be around one quarter.

Frequent and stable off-take of large quantities of renewable hydrogen is desired to secure a high utilisation. Train services provide a higher planning security on fuel demand which is advantageous for a stable long-term business plan.

4. Choice of electrolysis technologies

There are two main electrolysis technologies to choose from: Alkaline or polymer electrolyte membrane (PEM) electrolysis. The choice will mainly influence CAPEX and OPEX but might also impact the business model that can be chosen for the installation.

Alkaline electrolysis is cheaper in the initial investment. It typically consumes less electricity per kg of hydrogen produced and has a higher electrolysis stack lifetime. Alkaline electrolysis is more demanding in its operating conditions. It is expected to be best operated between 25 to 100 percent load which limits the operational flexibility. Furthermore, it requires the handling of lye which needs to be handled carefully. Overall, alkaline electrolysis technology is well suited to be operated under stable conditions with no substantial changes in load.

PEM electrolysers are more flexible in operations but require an higher initial CAPEX as well as operational expenditures. System lifetime is smaller by a factor of 2 which means more stack replacements become necessary over the system's lifetime. The system can be run flexibly with peak power off-take capacities of up to 160% (for up to 10 minutes).[76] The technology is therefore well suited to provide balancing services to the market that can lead to further revenue opportunities (see consideration 7).

In terms of the business model decision, it needs to be understood that the technology choice will impact the ability of the installation to profit from flexibility services to the electricity grid. PEM offers more options due to its operational set-up while alkaline electrolysers are more mature but restricted in their operational versatility (for more see below).

5. Additional infrastructure

Choosing an on-site electrolysis set-up as indicated by the case in the Northern Netherlands means adding additional infrastructure into the scope of the hydrogen refuelling facilities. It will take additional space and require additional permitting procedures. This is mainly due to four factors:

- Additional storage tank capacity to optimally manage the hydrogen production level;
- Additional compression capacity to operate the increased storage;
- Back-up systems depending on the operating model chosen (e.g. for electricity);
- Electricity grid connection that is sufficient in size to allow for multiple MW take-off from the installation (incl. flexibility for grid balancing services).

6. Back-up hydrogen supply

An on-site power-to-gas installation also carries some risk for the hydrogen supply if the installation has to undergo planned or unplanned maintenance. In these situations, alternative services have to be in place as back-up solutions. A back-up supply with hydrogen from external suppliers should be in place. It is vital to ensure that the train service level will not be disrupted by any unforeseen interruption of the fuel production. Respective back-up agreements with industrial hydrogen suppliers or system redundancy have to be foreseen.

Production of hydrogen from renewable electricity is possible from a technical perspective and has already been demonstrated. For larger fleet installations the key criterion is to provide a sufficient amount of fuel to the FCH train when it is required. Interruptions of the train service due to a lack of fuel have to be avoided. This underlying threshold can form the basis for any further optimisation of utilisation vs. additional hydrogen storage to obtain the lowest possible electricity price for hydrogen production. In general, large hydrogen refuelling stations for trains with steadily operating fleets are well positioned to obtain lower electricity prices due to their continuous and high consumption thereof.

[76] FCH JU, Tractebel, Hinicio (2017): Study on early business cases for H2 in energy storage and more broadly power to H2 applications, accessed November 29, 2018 https://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

4.2. MULTIMODAL APPROACH

Multimodal synergies could be achieved by sharing hydrogen infrastructure with the public bus operator, and, at a later stage, private hydrogen vehicles, and the fleet of city vehicles, like garbage trucks. Through this multimodal approach, the fuel and infrastructure costs of deploying FCH trains can be reduced by sharing investment and operating costs with the other operators.

To illustrate this approach, the city of Toulouse can be taken as an example. Capturing savings involves inclusion of stakeholders interested in using hydrogen and tailoring of infrastructure to their needs. In Toulouse, the city bus operator aims to reduce its carbon footprint and eliminate diesel in its fleet of approximately 500 buses.[77] In pursuing this goal, FCH could be used to power an initial deployment of 30 buses. For such a deployment of 30, 12-m buses, conservative assumptions suggest a daily demand of 900 kg of hydrogen (assumed daily mileage of 300 km and consumption of 10 kg of hydrogen per 100 km).

There are two potential scenarios for sharing the infrastructure needed to produce hydrogen and refuel vehicles. This first option involves setting up the infrastructure with a total higher capacity (for daily production and refuelling of ~1,150 kg of hydrogen with a ~2.3-ton storage capacity) and sharing both the hydrogen supply and all relevant costs (in this case on a 20/80 basis as daily demand for hydrogen is lower for the trains). Sharing costs creates a 3% reduction in the FCH Multiple Unit TCO with a potential for further reductions if more hydrogen buses are introduced (e.g. 5.5% reduction if a total fleet of 40 buses is introduced) or if other vehicles use this infrastructure. However, the operational needs of each user must be accommodated and infrastructure will need to handle the varying hydrogen demand, duty cycles, geographic locations, and refuelling connection needs involved.

Option two involves building infrastructure with a higher production capacity and selling the excess of produced hydrogen at a set price to external parties who operate their own refuelling stations built to their needs. Assuming the same fleet of 30, 12m buses,[78,79] a potential TCO reduction due to external hydrogen sales is expected in the range of 3 - 8% (assuming a selling price of 5.5 - 6.0 EUR/kg of hydrogen).

In both scenarios, relevant infrastructure needs to be designed to meet demand and operator needs. For example, in Toulouse, the bus depots are located anywhere from 3 - 8 km away from the railroad depot. This distance significantly limits the potential for multimodal collaboration. This would mean synergies can only be captured in production with separate refuelling stations located at the respective depots and hydrogen transfer via truck or pipeline. An alternative could be a change in bus operational patterns, but that is unlikely given the large distance.

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[77] 'Accueil | Tisséo', accessed 13 November 2018, https://www.tisseo.fr/.
[78] 'Large Scale Operation of Clean Bus Fleets in Toulouse and Preparation of Sustainable Supply Structures for Alternative Fuels/France | Eltis', accessed 13 November 2018, http://www.eltis.org/discover/case-studies/large-scale-operation-clean-bus-fleets-toulouse-and-preparation-sustainable.
[79] 'Les bus à hydrogène se déploient en Europe', Techniques de l'Ingénieur (blog), accessed 13 November 2018,https://www.techniques-ingenieur.fr/actualite/articles/les-bus-a-hydrogene-se-deploient-en-europe-57995/.

In this case, the relatively small fleet of trains requires a limited percentage of the overall hydrogen produced by the station. Based on this result, the infrastructure could be located at a third location, convenient for both parties, or the production infrastructure could be located at the bus depot, and hydrogen could be transferred via pipeline to a refuelling station in the rail yard. However, pipelines involve complex permitting processes and can take long periods to develop. As with other potential synergies, this would entail close cooperation between the rail operator and the bus operator in cost sharing and ensuring adequate hydrogen availability for the use of both parties.

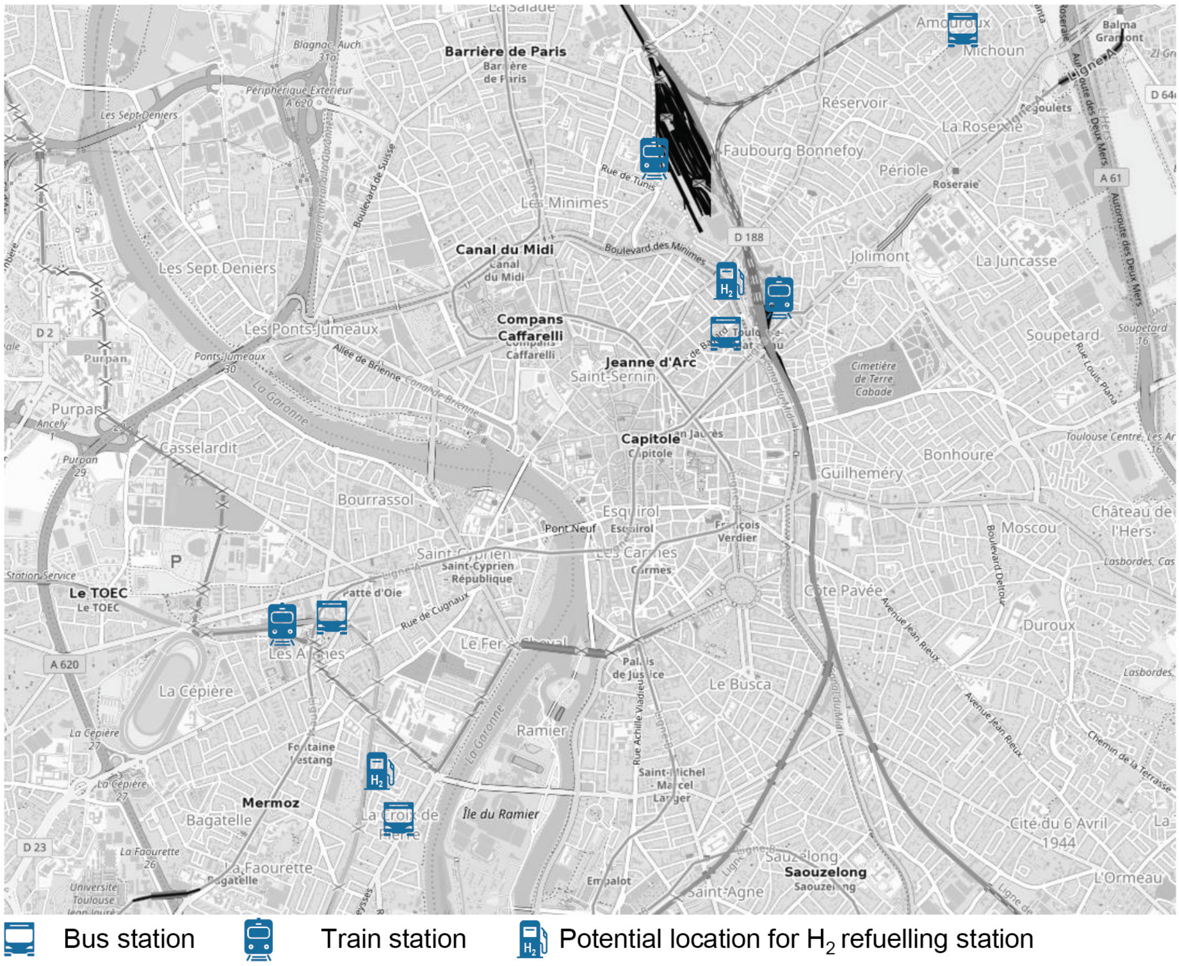

Figure 25: Map of Toulouse with locations of train station and bus stations indicating potential location for the hydrogen refuelling station.[80]

[80] Alexander Matheisen, OpenRailwayMap, accessed 13 November 2018, https://www.openrailwaymap.org/en/imprint.

4.3. INTEROPERABILITY WITH OTHER INFRASTRUCTURE

For effective rail transportation, the whole ecosystem of rail infrastructure has to function cohesively. This means bridges, tunnels, rail track, roads, stations, platforms, depots, catenary electrification, refuelling stations, and other components of the rail environment all need to be interoperable regardless of manufacturer or component owner. Across Europe, the European Union is pushing for widespread European interoperability of rail systems, regardless of country. The aim is to create a Single European Railway Area.[81] The introduction of hydrogen and fuel cells into this environment is significant, as existing processes, structures, and assumptions about the interoperability of the system will need to be re-evaluated in line with the unique considerations that come with hydrogen. This is particularly relevant when it comes to using hydrogen safely.

For the designs of FCH trains, the specific constraints of the route and the broader network that the trains could operate on should be considered. Hydrogen storage on-board trains may introduce unique constraints when used as a fuel, even though trains can carry hazardous materials, gases and chemicals as freight.

The height and width of tunnels, bridges etc. should be considered in the vehicle concept and designs. For example, if hydrogen stored on the roof of FCH Multiple Units leads to changes in train dimensions, then issues with clearance under overhead objects will need to be examined. Furthermore, roof-based hydrogen storage may necessitate an examination of potential interactions with any overhead electrified catenary wiring, particularly in bi-mode units that also use a pantograph.

When focusing on safety and the interoperability of the FCH trains, tunnels, underpasses, bridges, stations with roofs, over-track stations, train workshops and other enclosed areas where trains would be present are of relevance. Essentially, any area where hydrogen could potentially become trapped and be ignited would need examination. Thus, these are the structures that may require modifications to accommodate FCH train operations. The installation of hydrogen sensors would be a common measure in many areas, particularly in stretches of tunnel, workshops and in enclosed stations. Additionally, ventilation systems or gas extraction systems and other ATEX compliant electric components may be required depending on the infrastructure in question. For some infrastructure no changes may be necessary. This could be the case where existing standards and requirements for transporting hazardous materials on-board trains may be already be in place.

The broader interoperability of the hydrogen infrastructure and ecosystem is also key to full scale deployment of FCH trains. The location of the hydrogen production and refuelling infrastructure will need to be carefully considered. This should be done in line with existing operator requirements and other operations in the rail yards and vicinity of refuelling stations.

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[81] Mobility and Transport - European Commission, "What Is the EU Doing to Improve Security and Safety of Transport in the EU?," Mobility and Transport, accessed December 4, 2018, /transport/themes/security_en.

Additionally, in many European countries the owner and operators of rail infrastructure often do not own and operate the trains. In some cases, passenger train services, freight services, rail stations, the actual rail track, and the energy provision is all controlled by different companies. In such cases, one single entity cannot pursue hydrogen trains alone. The train operator would need to procure the FCH trains, the energy provider and infrastructure operator would need to develop the hydrogen production and refuelling infrastructure, and then the station operator would need to invest in hydrogen sensors and ventilation systems. In such a case, close cooperation and planning across all the involved parties is needed for trains to be functional and interoperable across the rail system.

Vehicles and infrastructure should also be designed with broad standardisation in mind. Interoperability and standardisation work hand in hand. Standardised infrastructure is key to enabling the interoperability of different FCH trains regardless of application type (Multiple Unit, Shunter and Mainline Locomotive) and manufacturer. Increasing the standardisation will involve the collaboration of key stakeholders like the operator, infrastructure suppliers, manufacturers, and component suppliers.

In some cases, train and rail interoperability may also be advanced by the deployment of FCH trains. The interoperability of FCH trains is not constrained by catenary electrification. FCH trains can drive into regions or shunting yards where electrification is not present. In another example, FCH trains, unlike catenary-electric alternatives, do not have to rely on the installation of catenary wiring and do not have to be designed for different catenary voltage levels. Without the installation of special dual voltage systems, FCH trains could simply cross the border between Germany and Poland, France and Spain, and numerous other countries across Europe. This is particularly advantageous in European countries where cross-border interoperability of existing systems has not been achieved.

Overall, there was no evidence that FCH trains pose significant interoperability challenges. The opposite is the case. Hydrogen makes it possible to operate trains across national borders, on a wide variety of routes without electrification and also in specially protected areas due to the absence of emissions.

4.4. HYDROGEN REFUELLING STATION

Hydrogen as a zero-emission fuel requires the implementation of new refuelling infrastructure. For gaseous fuels like hydrogen or natural gas this requires higher investments in comparison to liquid fossil fuels. However, especially for applications that operate in a fleet environment, the economic impact on TCO can be reduced. This is because fleet vehicles return to the same spot for refuelling every day and can ensure a constant take-off of fuel at a refuelling station over the year.

Today, more than 200 HRS are in operation globally with the majority being deployed in Asia (Japan), Europe (Germany) and the USA (California). The technology has reached a maturity level that allows for commercial deployment. Refuelling station equipment and systems can be obtained from multiple suppliers around the globe. For FCH trains the HRS will typically be built for the specific purpose of refuelling the trains and will need to be designed with a capacity to supply the fleet at peak consumption (e.g. heavy work week schedule in winter times when the train fleet consumption is highest).

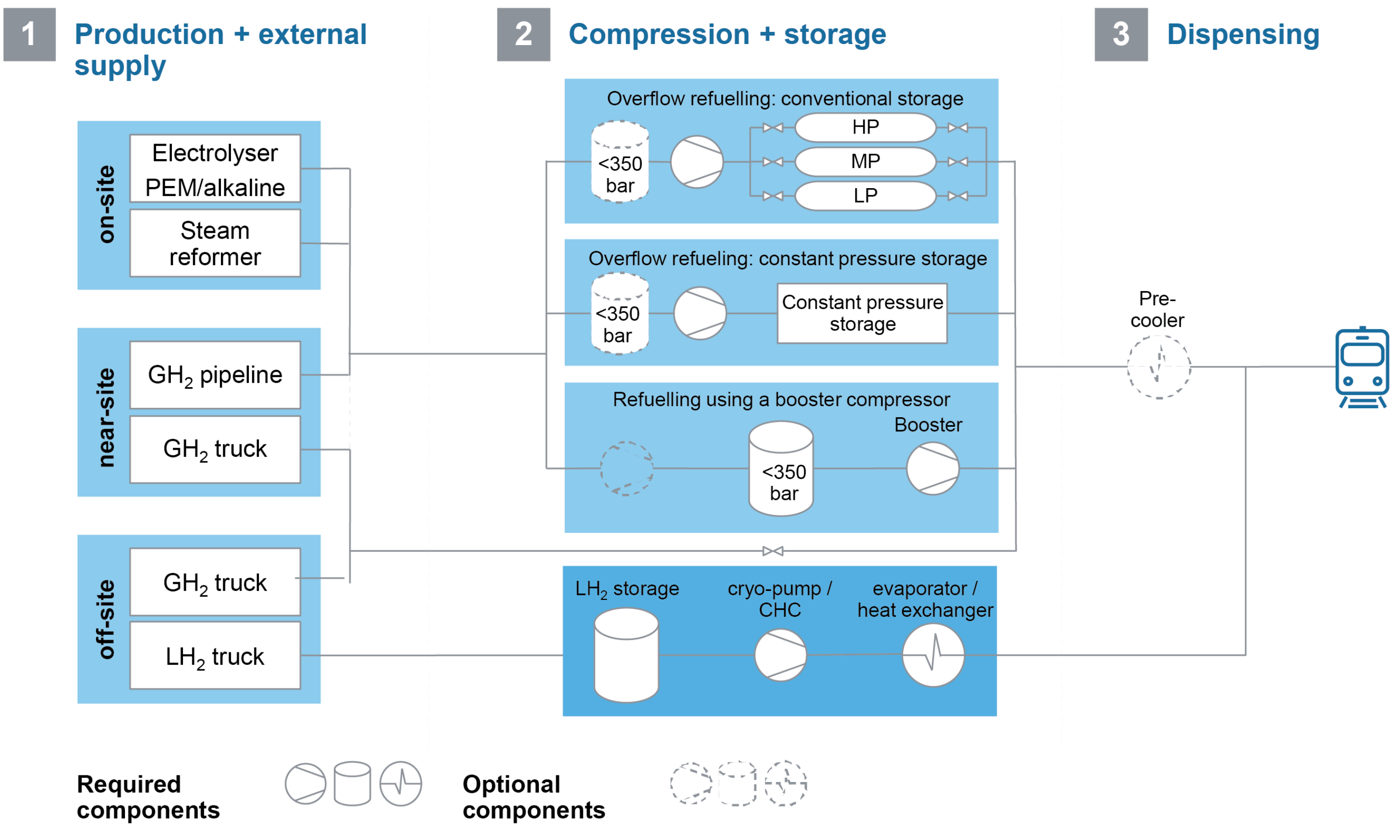

Figure 26: Schematic overview of HRS pathways[82]

[82] Reuter et al.

The diagram above is derived from the FCH JU-funded project NewBusFuel that has investigated various HRS designs for filling large FCH bus fleets at 350 bar pressure in detail.[83,84] HRS for trains can be compared to HRS systems designed for fuel cell buses to a large extent as they also fill large volumes at the same pressure level of 350 bar. Therefore, the technical details will only be introduced on a high level and point towards key considerations for implementation.

The HRS can typically be split into three main parts: production or external supply, compression and storage, and dispensing. For each part, the key considerations for implementation will be introduced.

1. Production or external supply

In general, two main categories for hydrogen supply to a refuelling station exist: on-site production or off-/near-site delivery.

On-site production: Hydrogen can be produced on-site at the refuelling station, often using either electrolysis (from electricity) or steam methane reforming (from natural gas). On-site production avoids costs and emissions from fuel delivery but also requires sufficient space and energy supply at the refuelling station. Depending on the refuelling station location, obtaining an operating permit is mostly possible but needs thorough examination within the applicable regulatory framework (e.g. safety distances, storage volumes). The specific case of using fluctuating renewable electricity, e.g. from offshore wind farms to produce hydrogen, is described in the focus topic of the case study in the Northern Netherlands.

External supply: Alternatively, hydrogen is often supplied from a production site that is in the vicinity (near-site) of the refuelling station or farther away (off-site). From these production sites the hydrogen can be delivered via pipeline or with a truck on the road (in gaseous or liquid form). Each option needs to be compared in terms of availability, investments, delivery distance and delivery volumes. The supply option chosen also has implications for the technology that is used downstream within the refuelling station. The different available options must be explored already in the concept phase of a project initiation.

2. Compression and storage

Two central elements of any refuelling station independent of the supply mode are the compression and storage parts.

On-site storage: The storage within a refuelling station is typically used for two purposes. First, it can be the main supply storage of the station and holds a sufficient amount of fuel to supply the fleet of FCH trains for multiple days (often two days of daily refuelling capacity is suggested). While gaseous storage can be supplied from more widely available gaseous hydrogen supply sources, liquid hydrogen storage has much higher energy density and can store significantly more energy in less space.

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[83] The topic of HRS is broadly discussed in the NewBusFuel project report, which is recommended for further reading.

[84] Benjamin Reuter et al., 'New Bus ReFuelling for European Hydrogen Bus Depots' (Fuel Cells and Hydrogen Joint Undertaking), accessed 23 November 2018, http://newbusfuel.eu/wp-content/uploads/2015/09/NBF_SummaryReport_download.pdf.

Second, high-pressure storage elements (up to 875 bar) are used for the refuelling process of the trains. Mostly, hydrogen is stored at a higher pressure than within the FCH train to enable a trans-fill of gas from the high-pressure storage within the station to the lower pressure storage tank within the FCH train. For each purpose different types of storage technologies are used. Optimisation in the conceptual project phase is necessary. Hydrogen storage is one of the key influencing factors for the permitting of refuelling stations. In many national regulations, codes and standards on the amount of hydrogen stored in one place are critical for the possibility to obtain a permit for operation (e.g. maximum hydrogen quantities allowed, safety distances, complexity of permitting process). The FCH JU-funded project, HyLaw, has established an extensive database on the regulatory framework applicable in various European countries. It should be used as a starting point for guidance on regulation and permitting.[85] Further information is provided in the focus topic of the Latvian case study.

Compression: In order to enable gas flows within the hydrogen refuelling station and to the FCH trains, compression technologies are at the heart of every station. Depending on the physical state of the gas after delivery (gaseous, liquid) either gas compressors or pumps that compress liquid hydrogen are used. The machines elevate the hydrogen gas pressure to the required levels for the refuelling processes, e.g. to the previously introduced high-pressure storage. Often, multiple compressors or pumps are installed within one station to provide a sufficient level of redundancy to prevent downtime in the case of planned or unplanned maintenance. Due to the intense operation of compression equipment, wear and tear is among the highest here of all parts within a refuelling station. However, thorough service and maintenance planning and execution enable high levels of availability.

3. Dispensing

The hydrogen fuel dispensers are the interface to the FCH trains. The number of dispensers will define how many trains can be filled in parallel. It is typically the main part of the refuelling infrastructure that is in constant interaction with humans, so it should be safe, ergonomic and easy to use. The following aspects should be specifically considered:

Accessibility to the refuelling connection on the train: The interface between FCH train and HRS should already be considered in the design phase for both applications. Ideally, the refuelling connector of the FCH train can be easily reached without supporting devices (e.g. ladders) to refuel the trains. Furthermore, a single refuelling connection point for a single on-board tank system on the FCH train is advisable. For example, if a 4-car Multiple Unit had two separate tank systems (e.g. one per two-car subsystem), it would require additional investments in two dispensers to fill the two tank systems at the same time.

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[85] 'Database | HyLAW Online Database'.

Refuelling connector: The refuelling connector (station and train side) defines the amount of hydrogen that can be dispensed per time unit. Various standardised types of refuelling connectors already exist for passenger cars and commercial vehicles. They allow for a hydrogen refuelling speed of up to 120 g/s or 7.2 kg/min. The development of a proprietary train refuelling connector could be considered to decrease the refuelling time of a train. For example, from an operational perspective refuelling multiple trains at one depot in less time could potentially save on the number of dispensers needed for refuelling and could also reduce working hours of refuelling staff.

Refuelling protocol: The refuelling protocol defines the refuelling speed (pressure ramp, i.e. increase of pressure in the tank per time unit) if it is not otherwise constrained, e.g. by the refuelling connector. The refuelling protocol needs to ensure that the refuelling is conducted in a safe manner, i.e. that the maximum pressure and temperature are not exceeded. Existing refuelling protocols from e.g. the commercial vehicle segment can be used. A specific hydrogen refuelling protocol for trains could be developed if it is required to improve the commercial performance, i.e. reduce refuelling times to allow more trains to be filled in less time. In a new protocol, also gas pre-cooling could be considered as an option to increase the refuelling speed even though today it is typically not used for 350 bar refuelling. However, industry stakeholders currently do not consider this a barrier for the technology.

In combination, the parts described above can be optimised and tailored to the specific requirements of the FCH train fleet. In this specific case study example, the hydrogen refuelling station is relatively small as it only has to provide fuel for two trains (240 kg/d). Furthermore, the HRS is currently envisaged at a depot that is 23 km away from the first stop of the route. Based on the above, the size of refuelling infrastructure should be carefully considered. The cost of the HRS per kilogram of hydrogen decreases when the overall capacity increases (see TCO sensitivity of Report 1 for further information). Therefore, new fleets ideally should have a high daily consumption while the HRS is built for the specific purpose of refuelling the fleet. Unnecessary overcapacity should be avoided if no short-term expansion of the fleet is planned. Any underutilisation would lead to an increased TCO per train. HRS infrastructure suppliers can today design modular solutions that allow for the integration of additional storage and compression equipment if a fleet of FCH trains grows. From an operational perspective the HRS should ideally be in the close vicinity of the main starting station to avoid long trips to the HRS without carrying any passengers.

In conclusion, HRS are state-of-the-art technology that have been built for various applications already. The infrastructure industry is confident that FCH trains can also be supplied with hydrogen safely and reliably. However, optimisation potential exists for cost reduction, tailoring refuelling stations to the specific usage specifications and increasing the performance along the value chain.

4.5. INDUSTRIAL H2 SUPPLY

Hydrogen supply from industrial production plants can be an attractive, economical solution for FCH trains with some environmental benefits. Many chemical plants use hydrogen as a process gas within their production.[86] Some process plants even produce excess hydrogen that cannot be used further and is instead burnt for its calorific heating value or simply flared and lost.[87] For fuel cell applications these sources of hydrogen can offer significantly better economics depending on the local circumstances. In an ideal case the site of fuel consumption and production are co-located in order to avoid transport costs. If the hydrogen has no further use in the production process, it could be used with value in transport. While the costs for investing into a stand-alone production plant are saved, some additional investment for hydrogen gas purification might be necessary to produce the pure hydrogen gas that is required for PEM fuel cells.[88] Typical industries that might generate excess hydrogen in their production processes are, for example, oil & gas refining, chlorine production, fertiliser production, methanol synthesis, steel production or glass manufacturing.

The case study of the Gdansk shunting yard provides an example where such an industrial H2 supply might be feasible and preferable. The Gdansk shunting yard is co-located with Poland's second biggest refinery complex, owned and operated by Groupa LOTOS. The refinery produces up to 16 tons of hydrogen per hour with a steam methane reforming (SMR) plant that uses natural gas as a feedstock. The refinery uses the hydrogen to remove sulphur and to saturate carbohydrate bonds after cracking processes, for instance. The hydrogen can also be used to fuel the Shunters and could potentially also be used to supply other transport applications like buses or cars.

In order to make use of the already existing hydrogen production capacity of the Gdansk refinery, typically the following three elements have to be implemented:

> **Hydrogen purification:** The SMR plant produces hydrogen with a quality of 3.7 (i.e. 99.97 % mol H2). In order to use the hydrogen in fuel cell applications a quality of 5.0 or better (e.g. 99.999 % mol H2 or SAE J 2719) should be used in order to protect the fuel cell membrane from toxic substances like sulphur compounds. In the case of the Gdansk refinery, typical impurities like CO, CO2, CH4, O2, H2O and N2 have to be removed. A Pressure Swing Adsorption (PSA) process unit will therefore be built to purify the hydrogen. This purification process is a standard gas treatment step that is widely used and well known in the chemical industry. However, the additional investment required needs to be considered in relation to the required purification quantities. PSA plants can be installed in different sizes typically starting in the range of tens of kg per hour capacity. For hydrogen refuelling projects, the daily fuel dispensed should therefore at least exceed 150 200 kg per day. In the Gdansk case example, a larger unit for approximately 2,400 kg per day (100 kg/h; 1,100 Nm^3/h). However, only a part of the available capacity shall be used for a potential Shunter operation. The figure below provides a simplified flow chart of a four-bed PSA and an example of an installed industrial PSA installation.

[86] 'Hydrogen in Industry | Hydrogen', accessed 4 December 2018, https://hydrogeneurope.eu/hydrogen-industry.
[87] DANIEL Braxenholm, 'By-Product Hydrogen to Fuel Cell Vehicles', 2016.
[88] P. P. Edwards et al., 'Hydrogen and Fuel Cells: Towards a Sustainable Energy Future', Energy Policy, Foresight Sustainable Energy Management and the Built Environment Project, 36, no. 12 (1 December 2008): 4356–62, https://doi.org/10.1016/j.enpol.2008.09.036.

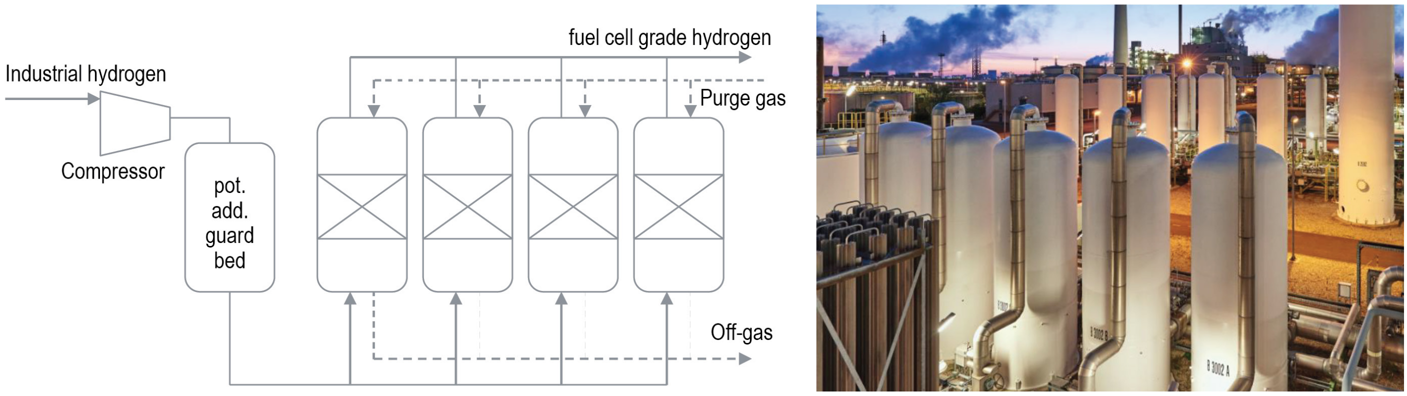

Figure 27: Process flow PSA (simplified) and PSA installation.

Hydrogen quality control: In order to control the quality of the hydrogen gas after processing in the PSA plant, dedicated measurement equipment has to be installed. The measurement equipment will either check constantly (in stream) or from time to time measure the level of specific impurities. Respective measurement equipment should be tailored towards the typical impurities that would be expected from the production process. For example, if natural gas with high sulphur content is used, specific measurement for sulphur compounds should be installed. Under normal operating conditions a well-configured PSA process should remove all toxic components with high process stability, so that the fuel cells will last according to specification.

Hydrogen supply to the refuelling station: After the hydrogen gas is purified and quality controlled, the gas can be stored, filled into hydrogen trailers or directly distributed to the point of use via pipeline. The latter could be the most cost efficient possibility to distribute the gas to the refuelling station for the Shunters in Gdansk. This will mainly depend on the length of the additional piping required to reach the station and any additional civil works and permitting that might be required. The current plans estimate a pipeline length of 1 km from the PSA to the refuelling station in Gdansk but an option with tube trailers is also being considered (200 or 300 bar pressure). In an ideal case, the refuelling station for the Shunters will be located close to rail tracks that are situated on the site of the refinery. Existing pipeline bridges can then be used to reach the station. Furthermore, the permitting process is expected to be simpler within an existing chemical complex with existing safety systems and limited accessibility to the public. However, the volumes consumed by the FCH trains have to justify the necessary investments in the selected solution. Experts estimate that a consumption of more than 2,000 kg/day and a multi-year supply contract are required to justify an investment.

Based on the parameters described above, rail operators can profit from locating refuelling infrastructure close to industrial hydrogen sources. This should be analysed as an option for fuel supply within the project development phase as it could potentially supply hydrogen at very low cost (1 – 2 EUR/kg for SMR-produced hydrogen – depending on natural gas price, without purification, delivery and refuelling[89]). In general, higher and more frequent off-take volumes of hydrogen improve the business case to justify the additional investment (e.g. less frequent demand might require additional hydrogen storage at the station). The connection of the production plant to the hydrogen refuelling station should not be underestimated. Both facilities should ideally be co-located, i.e. the production plant and refuelling station should be in close proximity. While the overall economics can be significantly increased, it should be noted that most of the hydrogen from industrial sources is produced from fossil fuels like natural gas. While this will not create a fully renewable supply chain, overall CO2 emission can still be reduced by more than 30% in comparison to burning fossil liquid fuels in combustion engines. Furthermore, local emissions from train operation are avoided with FCH trains. For production plants that have excess hydrogen that would otherwise not be used, this becomes an especially viable way to save energy and use the hydrogen to create added value.

[89] Foster Wheeler via gasworld.com | special features | September 2014

4.6. REGULATIONS/PERMITTING

With the deployment of hydrogen and fuel cell systems in the rail environment, the regulatory frameworks for rail and for hydrogen will need to be adapted. Existing regulatory and permitting structures for hydrogen, fuel cells and related infrastructure are not specific to rail applications, and rail regulations have not been adapted to properly account for the introduction of hydrogen.

In the concrete context of developing railway application projects, two main factors come to mind that would need to be considered: Permitting/regulation related to the vehicle technology itself and permitting/regulation related to the individual project development. The figure below illustrates the different features included in the two categories and the related main considerations that need to be taken in the context of permitting/regulation.

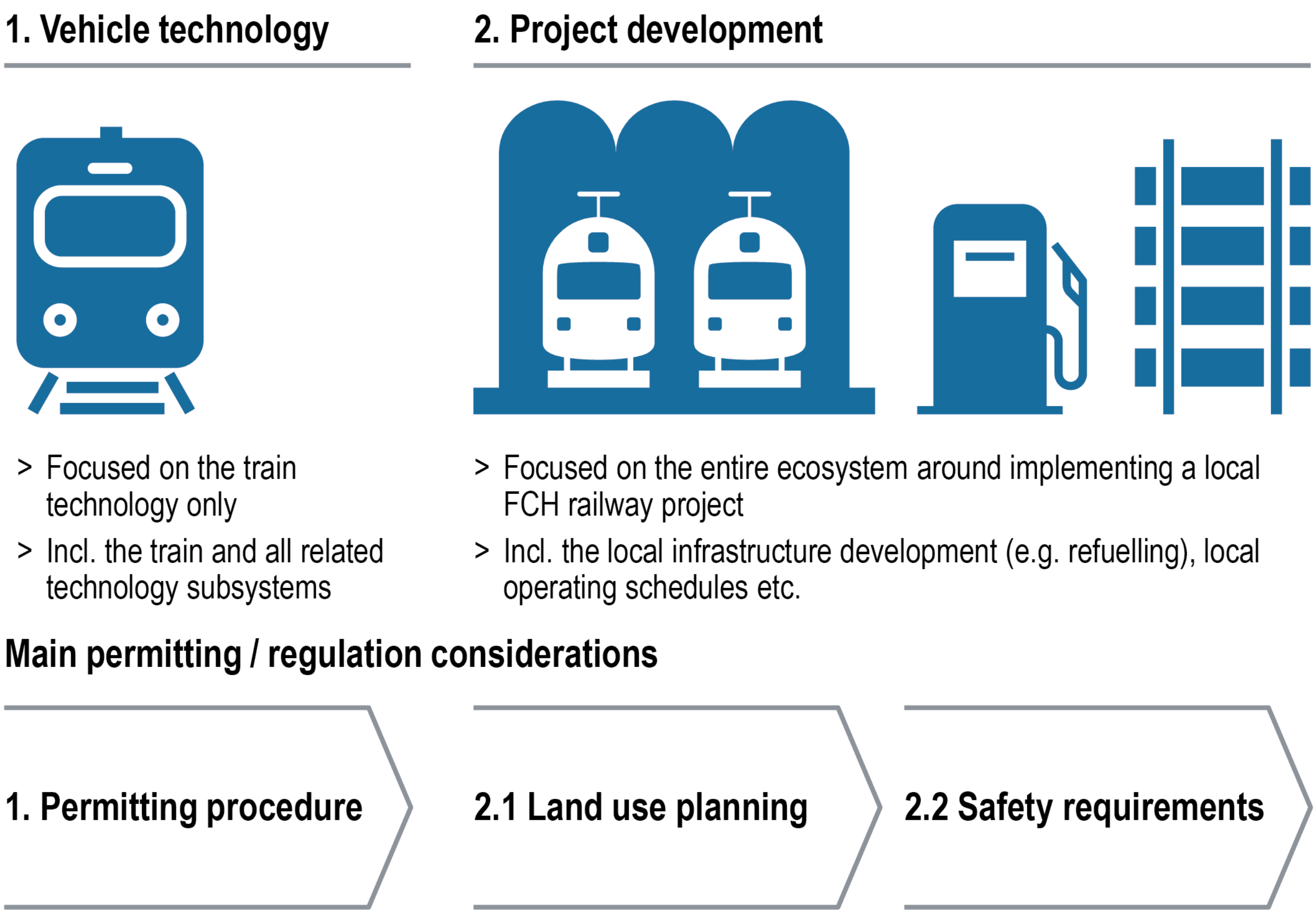

Figure 28: Main permitting/regulation considerations.

1. Permitting procedure

Before the operation of rolling stock can begin, it must be authorised to be placed in service.

The permitting procedure should assess the technology used and ensure it respects the Technical Specifications for Interoperability (TSIs) of the trans-European rail system. TSIs are defined by the European Railway Agency and adopted by the European Commission;

- The permitting procedure involves most stakeholders and implies a strong alignment between the technology developers, the manufacturers, the contracting authority ordering the rolling stock and the regulatory authority;
- In addition to that, there is a second national hurdle for the technology permitting: Railway undertakings are under the national railway authority's supervision (e.g. the Federal Railway Authority in Germany) and it is they who grant the authorisation to operate rolling stock on a national/regional level.

2.1. Land use planning

Before developing a local railway project incl. HRS, a land use plan must be delivered to the regulatory authority (local or municipal).

- It turns out that in most countries, there is no specific land use planning for hydrogen related structures. Indeed, permitting of an FCH infrastructure is in most parts not explicitly regulated and can only reference existing conventional infrastructure. Therefore, attention needs to be paid to land use planning and to the underlying risks of its uncertainty;
- One particular example is that in most European countries, hydrogen on-site production results in the HRS being classified as an industrial activity, which means it should be implemented as an industrial zone. Therefore, it is important to bear in mind the existing land use in place around the railway depots in order to scope new hydrogen projects in line with existing permissions.

2.2. Safety requirements

A number of safety issues are regulated on a European and on a national level and must be addressed in order to operate an FCH technology in a public railway context.

- The owner of the rolling stock must ensure that the equipment and the rolling stock are covered by the legislative acts and the locomotive OEM fire safety rules. The owner must also define a fire safety equipment maintenance and usage schedule that needs to be approved by the railway operators. Therefore, manufacturers, designers and rolling stock owners should consider defining plans that are up to international standards and guidelines;
- A risk assessment must be performed by a dedicated national accreditation body to ensure the rolling stock is in line with the regulations. Additionally, a safety certificate must be delivered by the regulatory authority to access the public-use railway infrastructures. Therefore, a good knowledge of the requirements and the procedures is suggested in order to begin the operation without delays.

4.7. SERVICE AND MAINTENANCE REQUIREMENTS

Service and maintenance of FCH trains, like today's existing diesel and electric rolling stock, is crucial for ensuring rolling stock availability and effective passenger, freight or shunting operations. A large amount of the service and maintenance required by FCH trains will be consistent with existing electric and diesel train maintenance. Service and maintenance for non-powertrain related components should remain close to what is performed today. However, all operators of FCH trains will have to adjust their maintenance operations, schedules and planning according to the needs of FCH powertrain systems and the specific needs of the individual rolling stock that they are deploying.

Depending on the service and maintenance required, service frequency intervals for specific components could range from weekly to only once in a train's lifetime. When analysing the service and maintenance required for FCH rail deployments, the requirements for the rolling stock and FCH system components should be analysed in addition to the service and maintenance requirements for electrolyser, hydrogen refuelling station, and other infrastructure.

Uniquely to FCH powertrains, unlike diesel engines, fuel cells do not have moving parts and many of the problems associated with complex internal combustion components breaking down. Experts indicate that in the long run, FCH technology will have lower service and maintenance requirements and costs when compared with incumbent diesel technology. In the short term, investments will need to be made in training staff, new equipment and service processes, but once the higher costs associated with technological uptake are overcome, operators should be able to realise savings.

For the maintenance of the FCH powertrain in this case and for other FCH trains, the fuel cell stacks, tractive batteries and hydrogen storage tanks are key. Each one of these components has individual service requirements, and will have to be tested, repaired and replaced at different intervals. Fuel cell stacks, unlike diesel trains, typically do not have components that break. Instead, FCH stacks slowly degrade and lose their performance potential over the course of their lifetime. They require regular performance testing and will eventually need to be replaced. In this case, this replacement threshold is approximately 20,000 hours. This means that over the locomotives' 40 year lifetime, operating every day of the year for 11 hours, the fuel cells stack would have to be rebuilt approximately 4-5 times.

For the hydrogen storage tanks used in this case, regular testing of tank integrity will be required based on manufacturer standards. Repeated compression and decompression of tanks gradually impacts the tank's strength. The tanks considered in this case will have a lifetime of 5,000 fills. Based on daily filling over the train's 40 year lifetime, the tanks will need to be replaced three times. For other FCH train applications this lifetime could vary depending on the type of tanks used and the refilling cycles the trains would encounter over their lifetime.

The lifetime and performance of the traction battery is different than that of the fuel cell and hydrogen storage tanks. Factors like charging cycles, battery depletion, extreme temperatures and other duty cycle related factors can have varying impacts on the lifetime of the battery. In this case, with an approximated battery lifetime of 100,000 hours the batteries would have to be replaced at least once in the train's lifetime. However, colder operating temperatures or unexpected depletion of the battery could substantially change this and could potentially necessitate even more battery replacements.

In addition to the new requirements posed by new powertrain and refuelling systems, train maintenance workshops will have to be built or modified and maintenance staff will have to be retrained. Modifications include the installation of hydrogen defuelling systems designed to safely remove hydrogen from train storage tanks, power connections for overnight train and fuel cell heating, and in the event a train workshop does not have equipment to service the train's roof such equipment will need to be installed.

Additionally, since hydrogen is a flammable gas, modifications will need to be made to workshops to ensure that the proper hydrogen detection and emergency systems are in place. In case of hydrogen leakage, a safety system with hydrogen sensors, roof ventilation or gas extraction systems and the ability to disable workshop electricity is required. Additional explosion proof emergency lighting will also need to be installed. These investments could cost between EUR 100,000 and EUR 500,000 but will depend on what equipment already exists in current workshops, facility size, and whether the operator decides to invest in building a new facility or opts to modify existing ones.

The associated infrastructure for hydrogen production and the refuelling station will also require regular maintenance to ensure continued operation of the FCH trains. The electrolyser itself, the hydrogen production storage tanks, the compressors, the refuelling station equipment including storage tanks, and the dispensers will all need regular inspections, testing, repairs, and in some cases replacement. In this case the electrolyser has a lifetime of 50,000 hours and, based on year-round operations of 11 hours per day, would need to be replaced every 10 – 12 years. This could vary depending on the individual operating conditions. The other associated infrastructure components like storage tanks and compressors will have lifetimes averaging between 10 and 20 years and will need replacement when deemed necessary based on the results of regular inspections.

Beyond the scheduled maintenance for both train components and infrastructure, irregular maintenance will also be needed frequently. Accidents, wear and tear, and issues with components will necessitate unscheduled maintenance, just as in diesel and catenary-electric trains in use today.

4.8. SAFETY AND PUBLIC ACCEPTANCE OF HYDROGEN TECHNOLOGY

New technological developments like fuel cells and hydrogen or renewable electricity generation by wind farms and solar panels will always be under particular public scrutiny. The inherent dilemma lies in the aspect of novelty and the associated lack of knowledge about the technologies. For the train segment, this becomes even more relevant as all use cases and implementation projects are realised in close proximity to public communities. Especially in larger front-runner cities like Hamburg, FCH rail applications have strong exposure to public opinion as they are developed and constructed in the context of the everyday life of citizens.

Because it is a topic of high relevance to local public communities, many efforts have been made to address the hydrogen safety topic in the last decade. Projects like HySafe, HyApproval and HyTrust have tackled the issue from different angles. The main technical aspects around flammability, leakage and handling of hydrogen have been thoroughly analysed and protocols as well as control mechanisms have been continuously improved. Newly developed projects should make sure they comply with the existing standards and guidelines. Respective certification schemes could represent a first step towards obtaining external expert approval as a means to communicate better on safety aspects.

Commonly, the existing projects have found that the lack of knowledge and awareness about the fuel cell and hydrogen technology are the most persistent causes for public opposition to local project developments. The recommended way to deal with these issues has always been to have sound stakeholder management for new projects and processes. This is a universal finding of many projects in the context that a well-managed integration of all associated stakeholders de-risks the project implementation by moderating the concerns of public communities. Therefore, fuel cell and hydrogen application projects in the train sector should consider structuring their stakeholder management processes along three major dimensions.

For the development of FCH railway applications this means that new developments should consider making stakeholder management part of their core activities. Particularly developments in densely populated urban areas like Hamburg would need to consider in detail how to address persisting hydrogen safety concerns, overcoming the structural knowledge and awareness gap of the involved parties. Dedicated concepts to involve especially first responders like the local fire brigade have shown promising effects in moderating public concerns.[90] In addition to that, spill-over knowledge from other related mobility sectors (e.g. public buses etc.) could be used to select the most promising formats and messages for key stakeholders.

[90] Backhaus, Bunzeck (2010): Planning and permitting procedures for hydrogen refuelling stations – Accessed: 05.12.2018 - https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-E--10-051

4.9. TECHNICAL REQUIREMENTS OF THE FCH TECHNOLOGY

The core of a FCH power system is characterised by the electrodes, the electrolyte, and the bipolar plate. However, the whole system that is needed in order to operate the FCH technology and especially the fuel cells in the train is more complex. Compared to the size of the fuel cell, additional equipment can make up quite a large share of the whole powertrain. The extra components required depend greatly on the type of fuel cell. On all fuel cells the air and fuel will need to be circulated through the stack using pumps or blowers. Often compressors will be used, which will sometimes be accompanied by the use of intercoolers, as in internal combustion engines. The direct current (DC) output of a fuel cell stack will need some kind of power conditioning. This may be as simple as a voltage regulator a DC/DC converter or a DC/AC inverter.

Electric motors, which drive the pumps, blowers, and compressors mentioned above, will be a part of the FCH system. Furthermore, electric motors are needed to operate all pumps, compressors or blowers. Industrial standard solutions are often used for these electric motors, which on the one hand dissipate the heat by air cooling, but on the other hand can also compress the air. Most problematic is the supply and storage of the hydrogen itself. The hydrogen tanks are always part of the main system and directly connected to the fuel cell. Current observations indicate that the approval of hydrogen connectors between train parts (for example for Multiple Units between the different units, but also Mainline Locomotives to a potential tender) is expensive or not possible at the moment. This is the case for high-pressure and low-pressure lines, but also for liquefied hydrogen. This limitation means that the hydrogen tanks must always be accommodated in the same segment as the fuel cells. The solution also defines an essential barrier, since the unconnected hydrogen tanks also influence the refuelling process. Of course, further components such as valves, air filter systems, power control units, super capacitors and temperature controllers are also necessary, which will not be studied here in detail.

Depending on the operated output power of the fuel cell and the working pressure, especially for PEM fuel cells the air feed using a defined compressor (e.g. Lysholm compressor) can be calculated. Therefore an air stoichiometry of 2 and an average cell voltage of 0.65 V are used. These parameters will also define the efficiency of the fuel cell, which is considered to be around 54%. After the calculation of the mass flow rate of air the mass flow factor can be derived. The compressor power can then be calculated via the rotor speed and the temperature rise that will take place, based on the efficiency of the compressor (e.g. 70 – 80% can be taken as the efficiency of a compressor).

Since the electric motor for the compressor will not reach 100% efficiency, further losses of power have to be taken into consideration. At the same time, the temperature rise will give an indication how much cooling energy is needed. In these calculations, net values are assumed for the fuel cell stack because the cooling is very dependent on the structural specifications of the respective train. This means that in addition to the Fuel Cell Power specification of 400 kW, for example, approx. 10 – 30% power must be taken into account for cooling on top. However, many manufacturers specify the net power for their premanufactured fuel stacks.

The use of batteries in association with a fuel cell can reduce the cost of a fuel cell-based power system. This is especially the case when powering certain types of electronic equipment. The essence of a fuel cell hybrid is that the fuel cell works quite close to its maximum power at all times. When the total system power requirements are low, then the surplus electrical energy is stored in a rechargeable battery or capacitor. When the power requirements exceed those that can be provided by the fuel cell, then energy is taken from the battery or capacitor. This presupposes that the power requirements are quite variable.

In addition to cooling and compressor performance, the coordination of the fuel cells system with the battery system must be carefully considered. This hybridisation of the powertrain is of particular importance, as the costs for the fuel cells can be further reduced by the correct design of the battery on the basis of a defined use case, as is the case in the individual case studies. As a rule, the fuel cell can thus be designed for the average power in the calculated load profile. Power peaks due to acceleration or short uphill drives are compensated by the battery system. This hybridisation differs significantly in the individual applications. While in Multiple Units especially the energy is needed for the large amount of stops at the stations, Shunters with long idle times can also use batteries for normal operation and the fuel cell provides a constant charge. In Mainline Locomotives it is mainly power differences caused by the elevation profile of the track that are compensated.

The technical specification of the train will be sketched using the case study in Estonia. The desired specification of the train is a maximum power rating of 2,800 kW with a tractive effort of 405 kN at a maximum load of 5,000 t. The maximum power rating of the train is 2,800 kW. For acceleration of the train from a standstill, a battery capacity of approximately 600 kWh is already necessary, which is needed for the tractive motors of 2,800 kW and the low maximum hotel power of 28 kW. Additionally, a net fuel cell capacity of 1,150 kW is available for the train. This can continuously charge the battery and at the same time provide the average specified power rating of 1,200 kW. With a load factor of 5,000 t including the weight of the Mainline Locomotive, the average tractive effort at an average speed of 60 km/h is approximately 72 kN.

Based on this system, the space requirement and the weight of the powertrain were then calculated using standard parameters from currently existing technologies. Starting from a Mainline Locomotive with a weight of 80 t, the integration of the FCH system of 1150 kW (5x 200 kW, 1x 100 kW, 1x 50 kW) of 4.5 t, the battery system of 8.9 t and the hydrogen tank of 12.9 t resulted in a total weight of 106 t. For the calculation of space requirement all necessary further equipment was included. Inverters, cooling systems, compressors, etc. are taken into account. With an FCH system of 6 m3, a battery system of 10 m3 and a hydrogen tank of 86 m3 the total space requirement is 102 m3 for the fuel cell powertrain. The space requirement thus exceeds the capacity of a typical Mainline Locomotive. Therefore, other solutions have to be found to achieve the required amount of hydrogen for the specified range. In this case, tenders are particularly suitable.

In addition to this basic concept design, detailed concept designs calculating the minimum cost and highest benefits for the train application have to be carried out. This has to be done taking a special architecture based on fuel cells, supercapacitors and batteries into account. Using three converters with batteries and supercapacitors, the following exemplary load profile can be covered:

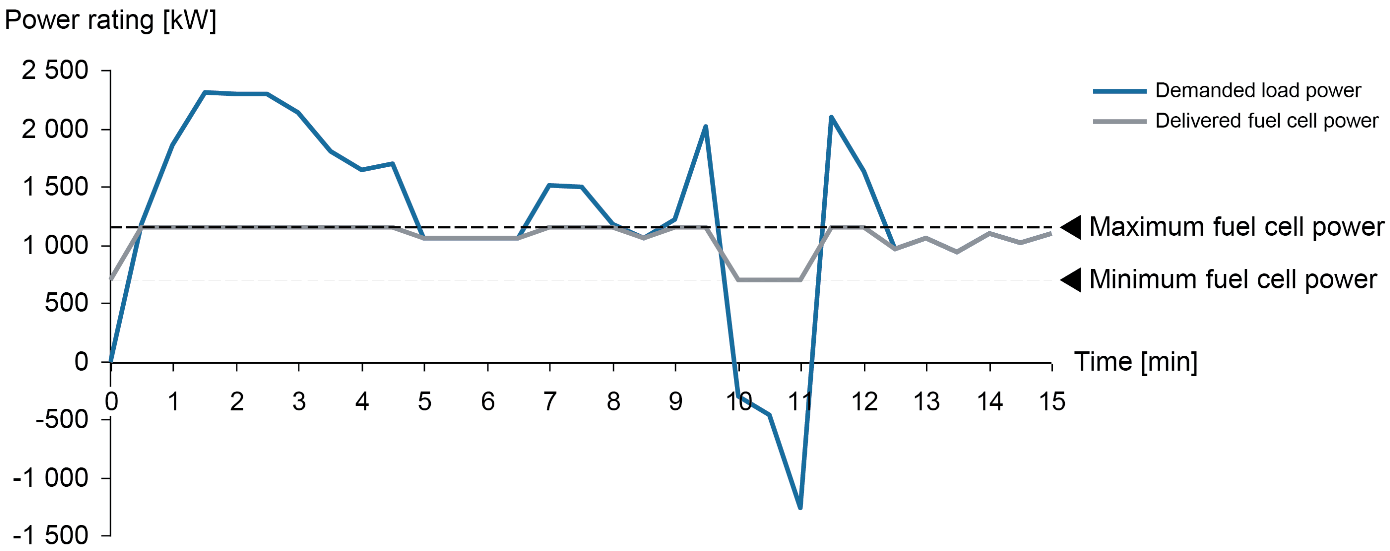

Figure 29: Illustrative load profile for Estonian case study (0 – 15 min).

The figure above shows an example of the load profile for the first 15 minutes of the Estonian case based on a high level simulation of the train system. The FCH system will operate in the range of 700 kW 1,150 kW. If the demanded load power is below this power regime the energy will be stored in the secondary energy sources. If the demanded power is higher than 1,150 kW the secondary energy sources will provide the energy needed. Of course, the load profile can be further smoothened using the battery capacity. The peak power will define the maximum supercapacitor and battery power needed. The total energy storage is calculated based on the maximum energy that must be supplied to the engines without recharging by the fuel cells including buffer energy of 25%.

4.10. CONDITION OF THE RAILWAY INFRASTRUCTURE

Hydrogen technology does not place extra demands on the existing infrastructure and does not require complex electrification of lines. FCH trains can be used flexibly and can also be operated over long distances. The hydrogen required can be produced directly on site using electrolysers. These low basic infrastructure requirements are particularly interesting for areas with low investment rates and low line utilisation rates. In the following, the situation of the railway infrastructure will be exemplary examined in more detail.

Due to the high investment backlog in the renovation of the rail infrastructure, including overhead lines and the lack of nationwide electrification, a clean solution can be developed by using flexible and modern FCH trains. However, this cannot be done without developing an overall strategy that also considers the clean production of hydrogen.

In East- and South-East-Europe the railway infrastructure is partly or completely in a critical state. For example, in Rumania, the total length of speed restrictions at the end of 2017 was 702,606 km. 65% of all the railway lines and bridges could collapse at any given time, and most are over 60% beyond the date when repairs should have been carried out; some may be as much as 85% past the date. 350 km of railway lines become unsuitable and only 12 km are rehabilitated each year. Out of 13,680 km of railways, around 72.4% (9,908 km) are no longer safe and the operating speed is highly restricted.

On the railway network, there is a total of 17,734 bridges with a total length of 188.5 km. 65.73% of bridges are extremely damaged. Over 72.6% of bridges are ruined. 28% are beyond their expected lifetime. The state of those bridges considerably affects the delays by necessitating speed restrictions for safety reasons.

The number of dangerous points recorded at the end of 2017 was 1,206, of which 35.5% are class I and 21.6% of them are on the main lines. Other infrastructure elements, such as earthworks, contact points, power transformers, electrical contact lines or signalling installations are also in risky condition. In 2017, only 21% of all planned and necessary repair work took place.

The figure below benchmarks Romania's investments made in the railway infrastructure against its European counterparts for the period 2013-2015. Rumania, but also other countries like Greece have rather low investments per year in their railway infrastructure.

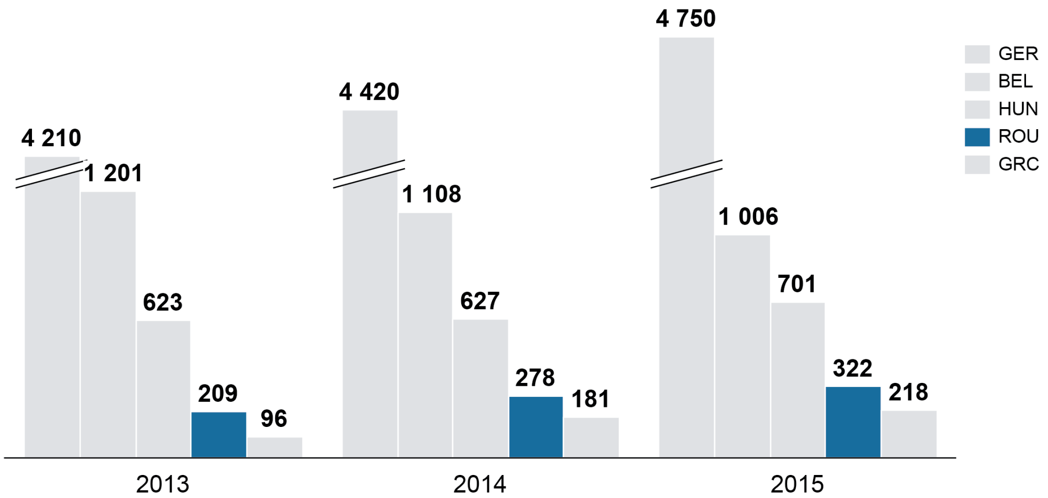

Figure 30: Investments made in the railway infrastructure in Europe for selected countries (in EUR m per year)

Looking at the European Railway Performance Index, which used a scale of 1 (extremely underdeveloped) to 10 (extensive and efficient) to measure the quality of railroad infrastructure, many countries are ranked below an average performance index of 5. The performance is analysed on the basis of intensity of use, including passenger volume and freight volume, the quality of service taking into account punctuality of regional trains, long distance trains, high speed rail and average fare per passenger per kilometre, and safety including accidents per train kilometre travelled as well as fatalities per train kilometre travelled.[91]

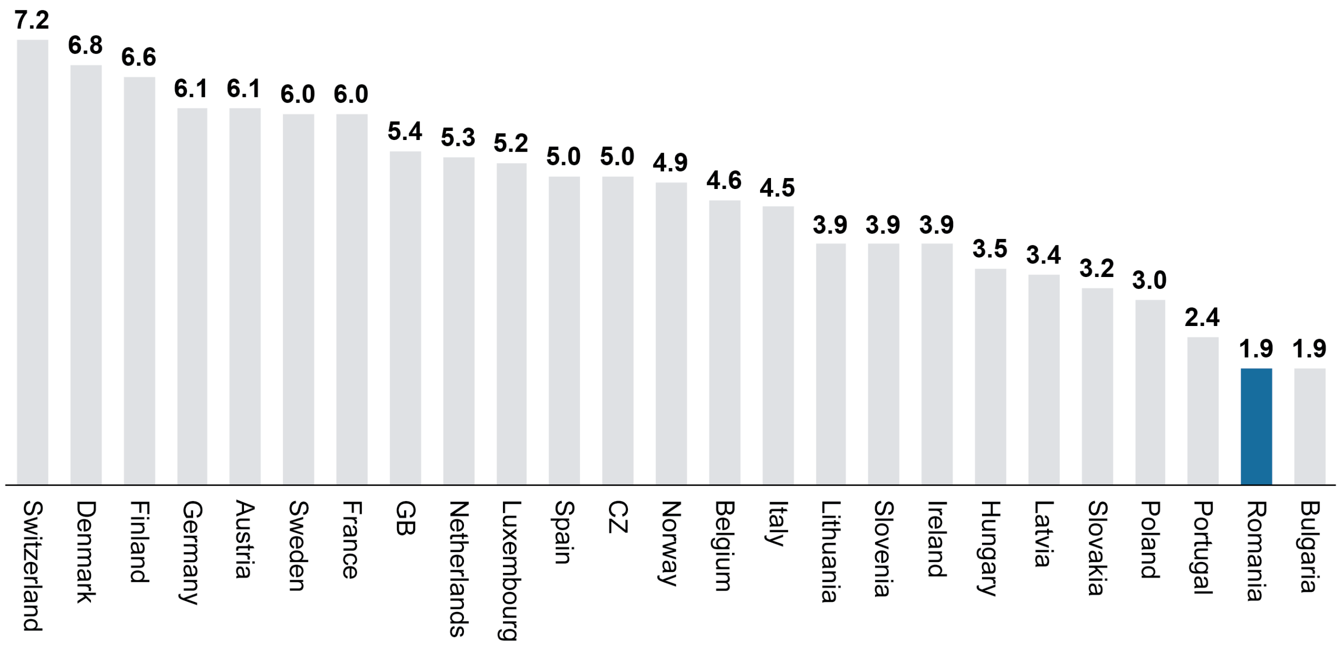

Figure 31: European Railway Performance Index (absolute value, 10 best, 0 worst).

The above figure shows that Romania, Bulgaria, but also Poland and Slovakia hold one of the bottom spots in terms of European rail. This situation is exemplary for many countries with low economic performance. Modern technology such as the promotion of hydrogen train technology can help to significantly reduce the emissions caused by the relatively old vehicle fleet.

[91] 'The 2017 European Railway Performance Index', https://www.bcg.com, accessed 20 November 2018, https://www.bcg.com/publications/2017/transportation-travel-tourism-2017-european-railway-performance-index.aspx.

ANNEX 1: TCO INPUT PARAMETERS

In the following chapter, the different TCO items and sources for input parameters for the TCO will be explained in more detail. The Total Cost of Ownership (TCO) is the sum of all costs related to the train (financing, maintenance, depreciation), the related infrastructure strongly depending on the technology (financing, maintenance, depreciation, rail track fee), fuel costs and salaries.

TRAIN RELATED COSTS

In relation to the train itself, the CAPEX necessary for either a new acquisition of trains or for a retrofit are considered, also taking into account the number of car units per train. Train costs are estimated using the cost of FCH technology, batteries and propulsion technology and compared against current OEM orders that are publicly available. The numbers were sense checked with the Advisory Board of this study. Based on the CAPEX value the sub TCO items were calculated.

The **financing costs** are calculated with the country-specific WACC based on the total investment for the trains. For the **maintenance costs** of the train, values already determined in the individual countries and considering both the acquisition value of the train and the country-specific salary costs are used. At the same time, the maintenance of tractive batteries and fuel cells as well as the potential replacement of tanks are considered. A residual value of approximately 20% for batteries was used. In some countries additional tanks must be kept ready for pressure tests. For this an additional surcharge is considered. In principle, it can also be assumed that an exchange of essential parts is necessary for diesel engines. This has also been considered in the calculations for the diesel drive systems if a retrofit is assumed to take place before the end of life (30 – 35 years) of the train is reached. The **train depreciation** is calculated based on a straight-line depreciation over 30 – 35 years and assuming a residual value of EUR 0 is used.

INFRASTRUCTURE RELATED COSTS

CAPEX and OPEX (maintenance costs) were also considered under infrastructure costs. Financing and depreciation costs are based on the total investment sum for the infrastructure.

The CAPEX for diesel trains was set at a fixed value of approx. 70 – 100 EUR/l diesel daily capacity. For hydrogen trains the calculation was carried out based on the daily required amount of hydrogen. After the dimensioning of HRS and hydrogen on-site or off-site production, the corresponding CAPEX was calculated based on the current costs of the respective technology. The individual CAPEX is listed in the case studies. For catenary applications, the CAPEX for overhead lines, masts and the associated infrastructure were considered.

The **financing costs** are calculated with the country specific WACC based in the total investment sum for the infrastructure for each technology. The **maintenance costs** represent a share of the CAPEX.

In addition, the maintenance costs were supplemented by the costs for the replacement of electrolysis units.[92] The **infrastructure depreciation** is calculated based on a straight-line depreciation over 50 years and assuming a residual value of EUR 0 is used. For overhead lines a straight-line depreciation over 100 years was used. **The rail track fee / Track Access Charges (TAC)** must be considered country specific. Since the parameters and systems in all European systems are very different and the calculation framework seems to change at least every three years, partly driven by EU directives, in this study the minimum access packages for the TAC are assumed. The EU Directive 2012/34/EU defines charges for minimum access package and for access to infrastructure, connecting service facilities shall be set at the cost that is directly incurred as a result of operating the train service.

However, these comparisons and integration of minimum access packages in this study still do not allow a direct comparison. The Independent Regulators Group (IRG) – Rail analysed the main charging units used in the EU Member States. Most of the EU Member States are using train-km, but some of them are also using gross tonne/km, billing period, EUR/minute, path-km/node, etc. The TACs used therefore give more of an indication of the share of infrastructure costs and are related to a non-electrified route. For a more detailed discussion of the Track Access Charges, please refer to the following studies.

In addition, care was taken to ensure that only one basic tariff was used for the track access fee so that possible infrastructure costs were not included twice in the calculation. In the calculations, the capacity utilisation of the respective line was also taken into account by means of a case study of trains. For example, lower CAPEX for electrification have been taken into account if it is to be expected that other trains will also use catenary. The same applies to the maintenance costs, which were calculated in proportion to the CAPEX The country-specific WACC was used for the financing costs of the infrastructure.

FUEL COSTS

For the calculation of fuel costs, different assumptions are used depending on the technology. For diesel trains, only the diesel price is considered. For Catenary, Battery and FCH industrial energy prices of the respective countries are used.

Statistical data for **diesel prices** from different countries was used to calculate the TCO model. The most recently available value was used. Consumption prices including taxes served as the basis for calculating the diesel prices. After the creation of a uniform data basis, the data was further compared with studies on diesel prices for industries and large consumers and adjusted as necessary.[93]

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[92]Paul Noothout et al., 'The Impact of Risks in Renewable Energy Investments and the Role of Smart Policies', DiaCore Report, 2016.
[93]'Europe Prices / Diesel Zone / Indices & Statistics / Comité National Routier - CNR', accessed 5 December 2018, http://www.cnr.fr/en/Indices-Statistics/Diesel-Zone/Europe-Prices.

In the area of **electricity prices**, the individual operators can use very different price models. This also depends on where they buy the electricity for the electrolysers or the supply of the catenary systems. To ensure comparable results, a cross-country database was accessed the electricity prices for large consumers without VAT but with all other taxes and levies is used. Known discounts or other price models of railway operators were taken into account as well as the input from the stakeholder interviews. The specific average electricity prices of the respective operators are strictly confidential.[94] If the high emission values of the respective national energy mix result in a negative emissions balance due to the use of alternative technology, emissions were offset. This compensation is carried out by theoretically increasing the energy price in line with the current price for CO2 certificates. With this compensation, the use of alternative technologies does not represent a deterioration of the environmental balance.

SALARY

Salaries were determined on the basis of a transnational salary study. In addition, the values were compared with published collective agreements and mirrored with the stakeholders. In all cases, there was no evidence that the technologies differ significantly in terms of personnel deployment.[95]

WEIGHT CALCULATION FOR FCH TRAINS

The weight calculation for FCH trains was based on current industrial standard technology. In addition to a fixed weight of the train body, fuel cells, batteries, hydrogen storage and electronics were taken into account. The electronics also consider DC/DC converters. The trains' weight is a lever in the OPEX section of the TCOs and builds the relation between mass, performance criteria and necessary energy input.

POWER CALCULATIONS

The FCH train specifications include tractive motors, compressor power, auxiliary power, fuel cells and batteries. Super capacitors were not taken into consideration for the calculation. The auxiliary power includes the fuel cell and battery thermal management system power. Power calculations influence the overall OPEX by correlating with the effective fuel cost for train operations.

We noted that a discharge of the FCH train batteries to fully power the tractive motors will result in C values of approximately 6 to 7. This strong discharge will most likely effect the lifetime of the battery. However, it is assumed that this strong discharging will not be needed in standard operations.

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[94] 'Electricity Prices for Non-Household Consumers - Bi-Annual Data (from 2007 Onwards)', accessed 5 December 2018, http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en.
[95] 'Average Annual Wages', accessed 5 December 2018, https://stats.oecd.org/Index.aspx?DataSetCode=AV_AN_WAGE#; 'Average Annual Salaries in EU 2017 | Statistic', Statista, accessed 5 December 2018, https://www.statista.com/statistics/557777/average-yearly-wages-of-full-time-employees-in-eu-countries/.

ANNEX 2: DETAILED EXPLANATION OF BATTERY-POWERED TRAINS

Battery-powered trains are another zero-emission alternative besides FCH trains and catenary-electrified trains. They obtain their entire energy (e.g. traction, hoteling etc.) from rechargeable batteries installed on the train. The train is typically charged via specially built charging stations (e.g. at each train stop or at final destinations depending on the battery capacity) or might be able to recharge its batteries with a pantograph via an existing overhead while driving on an electrified line. Battery-powered trains are not the focus of this study, but they are among potential clean alternatives. Therefore, the potential of batteries for rail transport will be reviewed below in parts.

BATTERY-POWERED TRAINS ARE TESTED AS A CLEAN ALTERNATIVE FOR MULTIPLE UNITS AND SHUNTERS

Today, purely battery-powered trains are considered for Multiple Units and Shunters because of their high energy efficiency and simple systems. First products in the Multiple Unit segment have been presented by industry. These Multiple Units are expected to enter into service in 2019.[96] In the Shunter segment, small battery-powered automatic Shunter systems are already used. Also, battery-powered trains would be suitable for operating in a defined area with small distances and much idling time for charging in between shunting operations. However, battery-powered trains are not considered a viable option for Mainline Locomotives, mainly due to the very large batteries that would be required to achieve a long range without recharging.

UNCERTAINTIES FOR BATTERY-POWERED TRAINS REMAIN

The experience with battery-powered trains is still limited and doubts remain as to whether or not the technology can fulfil the strict performance requirements of the rail segment. Experience with battery-powered buses for public transport suggests a cautious and thorough development program. For example, bus operators report suboptimal performance of some bus products due to their dependence on fixed charging points and relatively long charging times or their real-life range turned out to be lower than specified.

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[96] Keith Barrow, 'Bombardier Unveils Battery-Electric Talent 3', International Railway Journal, 15 September 2018, https://www.railjournal.com/fleet/bombardier-unveils-battery-electric-talent-3/.

Battery-powered vehicles in general and battery-powered trains specifically are subject to complex, interdependent technology design with inherent, required trade-offs. The main sensitivities of a battery-powered train include the battery cycle life (important for recurring investment and charging strategy), battery price (expected low purchasing volumes and advanced cell chemistry suggest higher prices), battery capacity (decisive for range and weight of the system) and required charging infrastructure (CAPEX depends on battery performance, e.g. charging speed). There is clearly no one-size-fits-all solution. Therefore, for each use case, tailor-made solutions must be considered taking into account different characteristics that will be outlined below.

TRAIN TECHNOLOGY AND PERFORMANCE

Train OEMs will have to carefully consider the design of the battery-powered train in order to meet the performance expectations of rail operators while keeping investment and service and maintenance costs competitive.

Battery capacity: Battery-powered trains will likely be developed with a view to the specific route that they will be operated on. For example, battery-powered Multiple Units that should have operational independence without recharging for more than 100 km will require a total battery capacity of more than 950 kWh with assumed consumption of 5.6 kWh/km. The battery systems on the trains would be designed with overcapacity in order to allow operation within a window of 10 - 20% and 80 - 90% state of charge in terms of the maximum battery capacity in order to maximise the battery's lifetime.

Battery cycle life: Batteries typically have a specified cycle life that defines the number of full charges a battery can withstand before the battery capacity drops by more than 20% of the initial capacity. For heavy-duty applications like trains a cycle life of more than 15,000 cycles will be required to keep recurring investments in replacement batteries reasonable. Depending on usage, 15,000 cycles would require a battery replacement every 10 years (assuming 5 charging stops per day, 290 days per year).

Battery charging speed: The charging speed of batteries will have an impact on battery lifetime and operational flexibility of the train service. Fast charging is typically expected to degrade batteries faster than slow charging. Thermal management of the battery needs to be designed appropriately. Depending on the train service, and even with fast charging, adequate time for charging must be allowed for, either at each stop or at the end of line. This additional time for charging could reduce the time the train is available for operation. This could require additional trains to be purchased and put into service, especially for more frequently used routes.

Temperature control: Electro-chemical systems like batteries typically show sensitivity to sub-zero and hot ambient temperatures. Therefore, the battery-powered trains require an adequate temperature management system that will control the battery's temperature during operation (discharge), charging and even while the train is not in operation. Separate infrastructure will be required at the depots to supply the trains with power while they are on hold.

Charging infrastructure and transmission grid: From an infrastructure perspective, battery-powered trains require access to multiple charging points at the end or along the serviced route. The anticipated costs for these charging stations vary widely today and will depend on the required charging speed for the trains and whether or not already existing infrastructure can be used. Quoted costs currently range from EUR 0.5 m to EUR 2.0 m per charging station. Depending on the battery capacity installed on the train, the number of charging stations required will vary. For intermediary charging at stations, powerful fast charging equipment will be required to keep the duration of the train's stop within the usual service schedule. This will likely come at a higher cost than charging stations where the train can be charged overnight. Additional aspects that will have to be considered are related to potential necessary upgrades of the transmission and distribution grid. These costs can vary significantly depending on the location. It can be expected that currently non-electrified routes which are often servicing less densely populated areas also have less dense and powerful electricity grids. The above has to be closely investigated when considering battery-powered trains to service parts of network. Also, for overhead lines the local electricity off-take is critical and the grid has to be carefully adjusted to the needs of the rolling stock operated in a certain area and during a certain time.

Train operations: From a cost and performance perspective, the battery-powered train should be designed for a specific use case in order to dimension the battery system efficiently, i.e. without oversizing. However, some of the rail operators participating in the study raised concerns that these tailor-made designs reduce the route flexibility of trains. A train with higher fuel independence, i.e. longer range without refuelling or recharging, can be operated flexibly on multiple routes in the area of a central depot or even across the network. This could limit the attractiveness of battery-powered train for wider applications besides dedicated routes.

In contrast to the above, in the right rail network environment, batteries could become a useful add-on to design bi-mode trains. These could be used in networks that are already to a large extent equipped with catenary electrification. Shorter non-electrified routes could be serviced using the train's battery system. The batteries would be charged while the train operates on the electrified parts of the routes. The trains will potentially be constrained to certain parts of the network.

COMMERCIAL READINESS AND PERFORMANCE TO BE PROVEN

Battery-powered trains are in a very early stage of market introduction with little experience in real-life operation. While the technology is potentially feasible in some specific use cases, the broader commercial readiness and performance have yet to be proven. A key factor will be the availability of durable, long-life, easy to maintain batteries with an adjusted cell chemistry that can cater for the heavy-duty use case of rail operations. Furthermore, heavy and large batteries will be required to give trains enough range for operational flexibility. There will also be a trade-off in terms of how many charging stations should be installed and how long trains can stop for charging.

Nevertheless, batteries are an important technology, also as part of hybridised powertrains like FCH trains. Therefore, research and innovation activities are an important instrument to optimise battery technology for trains.

For further, more technical information on battery-powered trains, Germany's Association of Electric Engineers (VDE) has published a research paper that highlights the technological parameters. While the battery systems tend to have a simple design and low service and maintenance costs, the required flexibility and performance as well as recurring cost for battery replacement could constrain the commercial potential of the technology in the rail segment.

[97] Wolfgang Klebsch et al., 'Batteriesysteme Für Schienentriebzüge: Emissionsfreier Antrieb Mit Lithium-Ionen-Zellen' (VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V., n.d.).

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"*

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