

Study on use of fuel cell hydrogen in railway environment

Study overview

Shift2Rail Joint Undertaking
FCH 2 Joint Undertaking



Brussels, 17 May 2019



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A. Study overview and key results

Shift2Rail Joint Undertaking
FCH 2 Joint Undertaking



Hydrogen for rail applications is becoming more and more visible publicly – Frist FCH regional train demonstrated in Germany

Recent developments ...

News

"Germany launches world's first hydrogen-powered train"
The Guardian,
17 September 2018



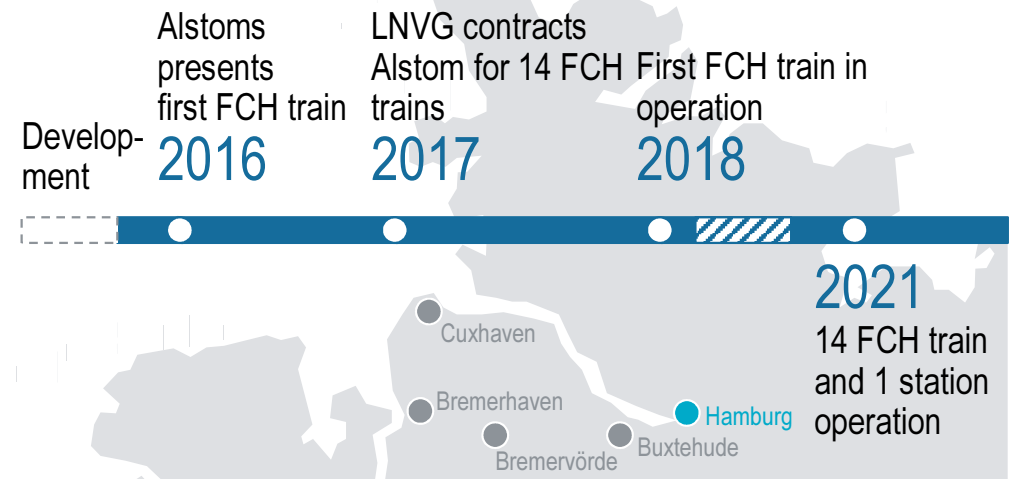
"Hydrogen fuel cell trains herald new steam age"
The Times, 13 May 2018

"French train giant Alstom set to make UK's first hydrogen fleet at British site"
The Telegraph,
14 May 2018

Benefits of FCH rail applications

- > Zero emission
- > Route flexibility
- > Reduced noise
- > Higher range compared to battery solutions
- > Avoidance of electrification cost

Project example: FCH trains in North-West Germany



- > FCH train "Coradia iLint" development by Alstom (with support from German government)
- > Northern German regional rail operator LNVG commissioned Alstom for 14 FCH trains incl. a 30 year maintenance contract
- > Hydrogen is provided by a refuelling station built and operated by Linde (30 year contract)
- > State government of Lower-Saxony is supporting the project

The study sought to analyse the potential of FCH technology in the rail industry and to lay the groundwork for future R&I projects

Study objectives

Main objectives



- 1 Provide a **business case and market potential analysis** per rail application and geographical area for the use of FCH technologies in the railway sector and give an overview about the state of the art as well as existing initiatives
- 2 Provide **case studies by rail application** expressing **potential opportunities** and carry out a **concept design** for each case study compared with other alternative solutions, in a multimodal perspective
- 3 Identify **technical and non-technical barriers** for the implementation of FCH technologies in the rail sector and show needs in terms of research and innovation, regulation and standards
- 4 Produce **recommendations on future activities** with particular focus on short term R&I



As a result we have:

- > Assessed the potential and applicability of fuel cells & hydrogen in rail and performed the **analytical work as basis for future Research & Innovation funding** from EU sources such as S2R and FCH 2 JU

We worked with an Advisory Board consisting of FCH and rail industry stakeholders from four

Advisory Board composition

System integrators / OEMs



Infrastructure/H₂ suppliers



HEXAGON



Operators

FCH technology providers

FCH technology can become a viable alternative to replace diesel engines – First products for passenger service enter market

Shift2Rail and FCH JU study focus applications

- > We analysed the potential of fuel cell and hydrogen technology for rail transport for three application areas
- > Most activity visible in multiple unit application area (products already being launched)
- > First insights suggest attractive use cases and good market potential



Multiple units

	Passenger operation in regional transport
	First FCH trains in operations since September
	up to 1,000 km ¹⁾
	up to 140 km/h
	30 years



Shunters

	Shunting and short distance operation
	?
	200-1,000 km ¹⁾
	up to 50 km/h
	35 years



Mainline Locomotives

	Med. + long distance freight + passenger service
	?
	500-1,100 km ¹⁾
	up to 120 km/h
	30 years

1) Depending e.g. on # cargo/passengers, stops and topography Application Maturity of technology Range Speed Lifetime Market entry

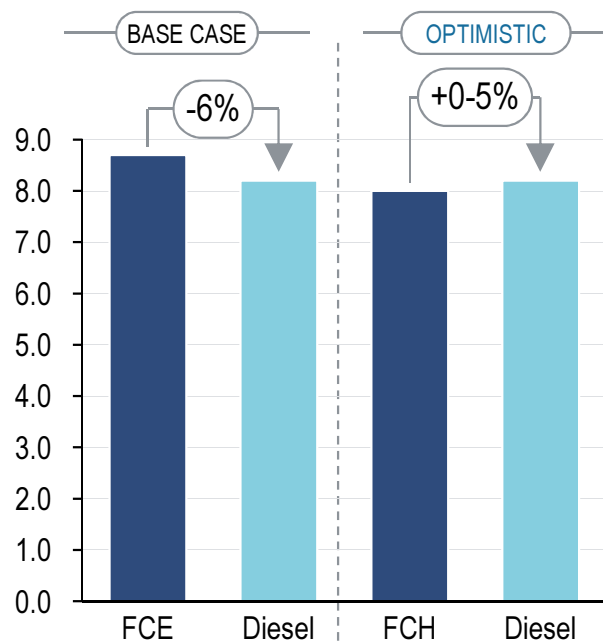
FCH technology has promise in rail sector - Can be competitive with existing technology under certain conditions

Summary results

Economic



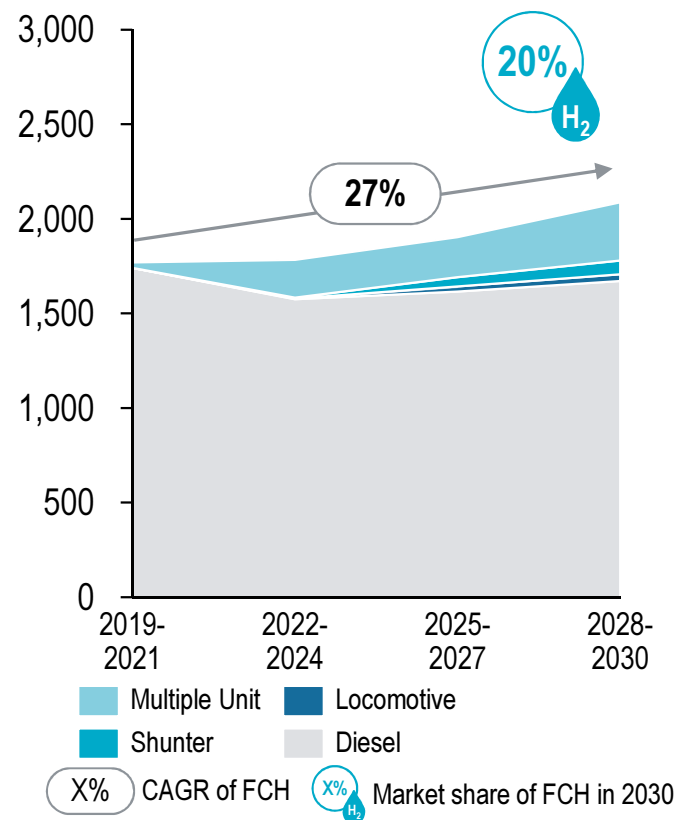
Estimated Multiple Unit Total Cost of Ownership (TCO) [EUR/km], 2022 prices



Market potential



EU Market potential FCH trains – Base scenario [standard units]



Case and barrier analysis



- > 10 case studies demonstrated that FCH technology can be competitive highly dependent on specific case conditions
 - FCH technology competitive on non-electrified routes ~100 km
 - FCH attractive for routes with low utilisation
 - Low energy prices driver of competitiveness (e.g. by-product hydrogen)
- > No show-stopping barriers for FCH in rail exists but still optimization potential
- > Three research and innovation topics have been identified to tackle these barriers

B. State of the art and high-level TCO

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More than 15 years of trials and demonstrations resulted in first promising commercial prototypes being created and tested

Key conclusions from state of the art review

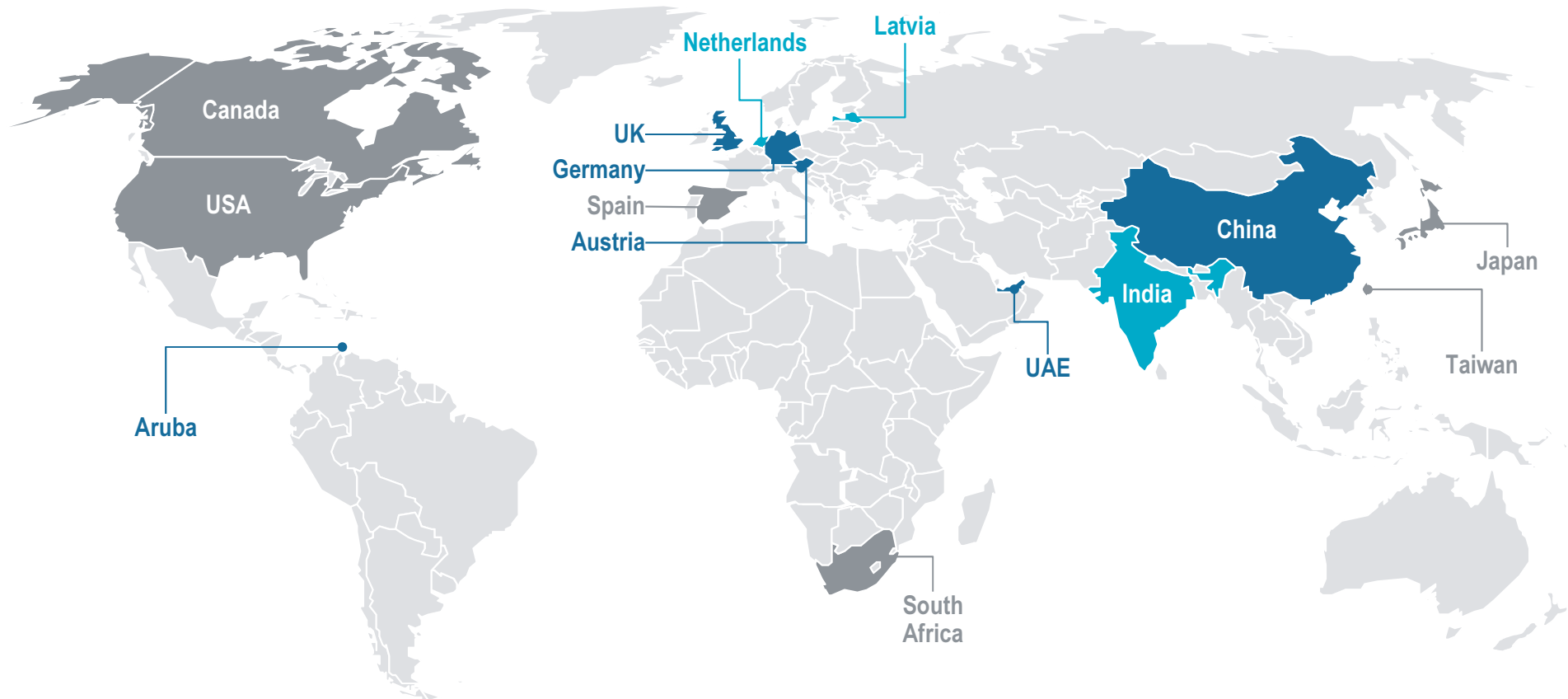
- 1 By now, **trials and demonstrations for fuel cell hydrogen trains are limited** – Currently, about 20 known trials and demonstrations
However, **continued interest in FCH trains** from different countries all around the world indicates relevance of FC application in railway

- 2 Increased commercial interest towards FCH trains during last years resulted in **first promising train prototypes being developed and tested**; commercial operations planned

- 3 Some coalitions between train manufacturers and fuel cell technology suppliers have been established offering first commercial prototypes, however the **amount of commercial product available to the market** needs to increase

Currently, hydrogen rail vehicles are operating for example in Germany and China – More deployments to come

Geography of hydrail projects

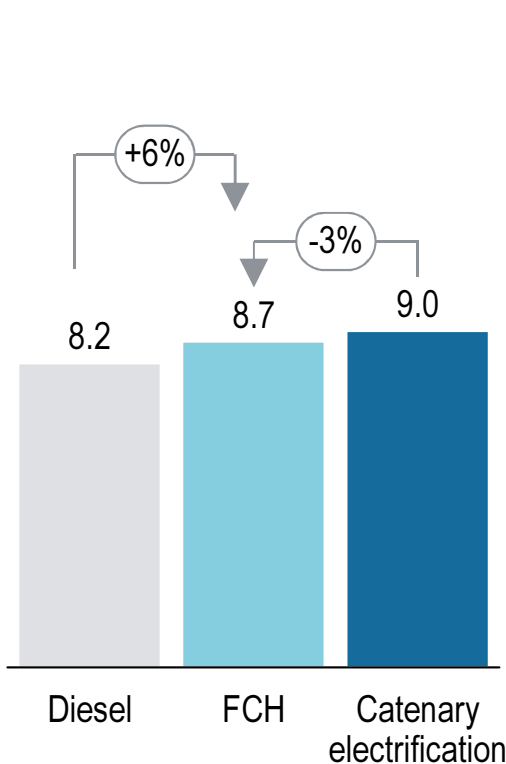


Ongoing projects Projects planned Projects in the past

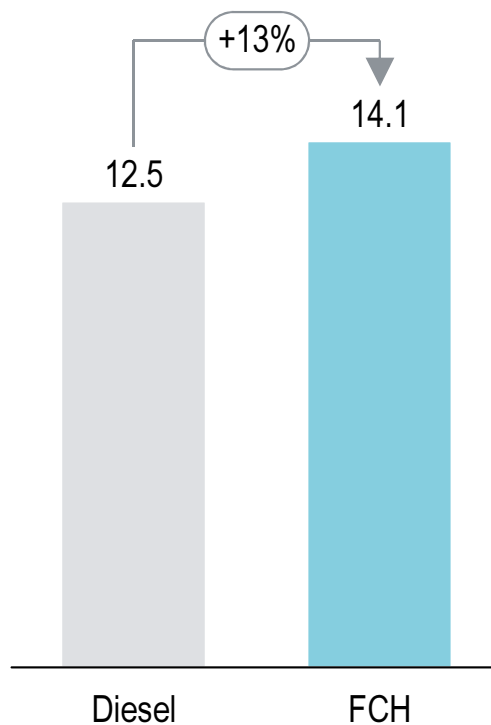
Under base case assumptions, FCH trains assume a cost premium of up to 14% over a diesel train

High-level TCO assessment – Base case in 2022 [EUR/km]

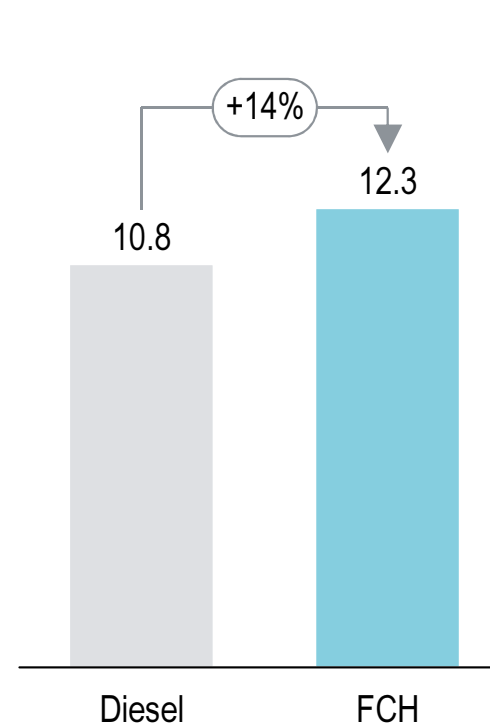
1 Multiple Unit



2 Shunter



3 Locomotive



Comments

- > FCH Multiple Units are competitive with a catenary electrified MU and assume a **cost premium of EUR 0.5 per km** over a diesel
- > FCH Shunters and Locomotives assume a **cost premium of EUR 1.5-1.6 per km**
- > Actual TCO will differ based on regional differences

+X% FCH TCO difference versus alternatives

Optimistic assumptions suggest competitiveness of the FCH train in all three applications with a TCO advantage up to 10%

High-level TCO assessment – Optimistic case in 2022 [EUR/km]

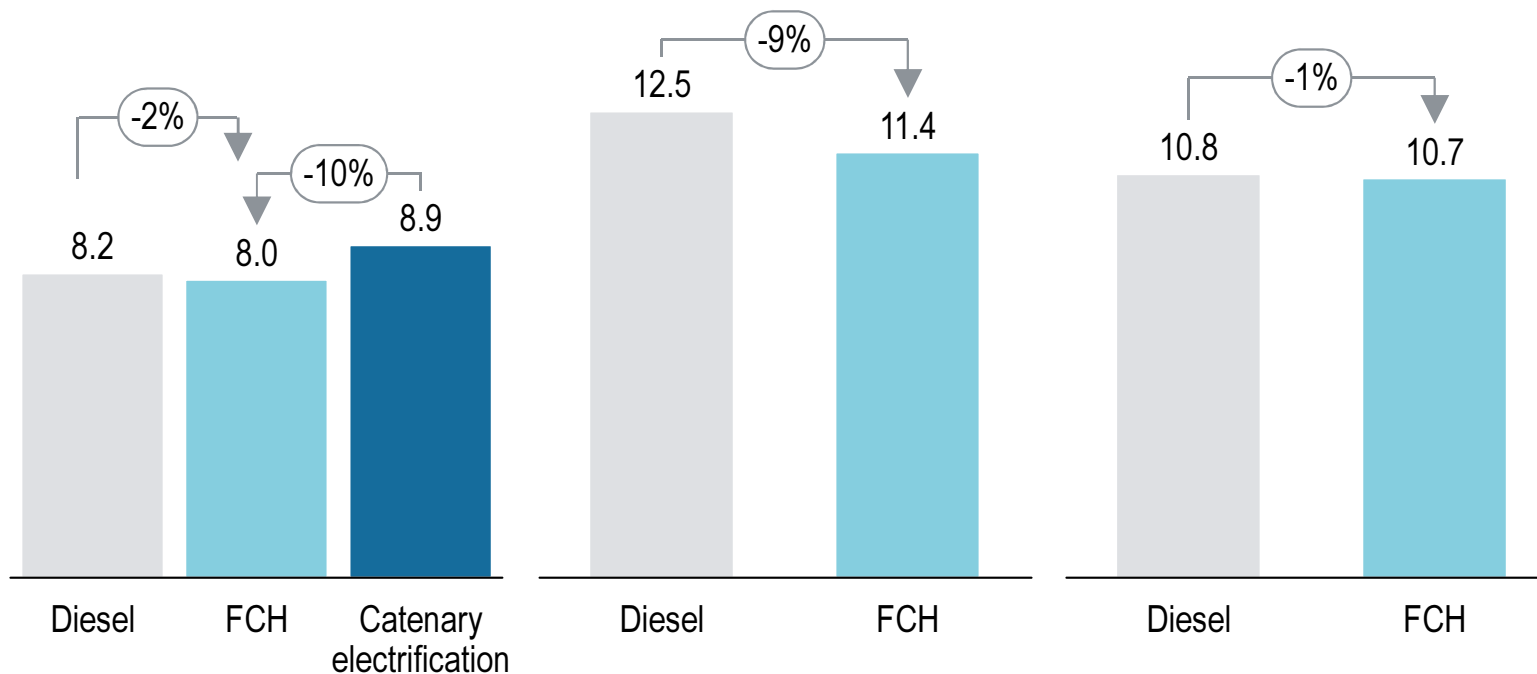
1 Multiple Unit



2 Shunter



3 Locomotive



Comments

- > TCO assessment in a optimistic case is based on a potential for:
 - Electricity price reduction for H₂ production
 - Diesel price increase
 - Reduced H₂ consumption
 - FCH train CAPEX reduction
- > TCO modelling suggests that FCH trains can be competitive given **high annual utilisation** and **low energy sourcing cost**

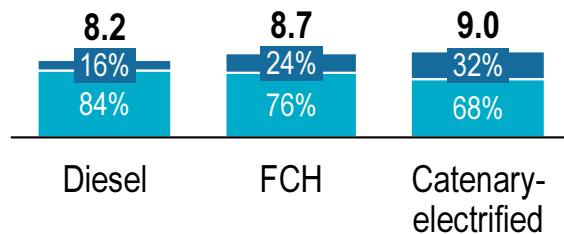
+X% FCH TCO difference versus alternatives

The TCO is mainly driven by high OPEX costs, economies of scale on the infrastructure side and asset utilisation rate

Key TCO drivers

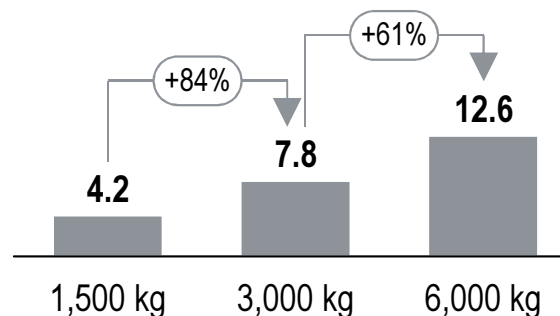
CAPEX and OPEX costs

- > TCO is mainly driven by energy OPEX, i.e. the electricity price for on-site production or the external purchasing cost of trucked-in hydrogen
- > CAPEX for the train is still important for a competitive TCO



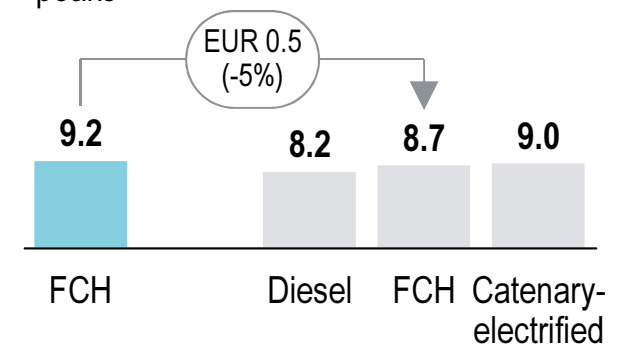
Economics of scale

- > Larger and high performing HRS and H₂ production facilities have a positive impact on the TCO
- > Lower power purchasing cost on the FCH train side can be expected with a larger batch purchase orders
- > Specific train components (e.g. FC stacks) show a significant cost reduction potential



Asset utilisation

- > A heavier utilisation of fuel cell system can decrease the service and maintenance intervals leading to higher costs (improvement potential)
- > In contrast, a hydrogen refuelling and production infrastructure can be optimized with a higher utilisation rate due without significant hourly, daily and seasonal peaks



■ CAPEX¹⁾ in the base case [EUR/km]
 ■ OPEX¹⁾ in the base case [EUR/km]
 ■ Daily kg capacity of HRS and its CAPEX [EUR m]
 ■ TCO¹⁾ given 50% utilisation of HRS and H₂ production facility²⁾ [EUR/km]
 ■ TCO¹⁾ given 100% utilisation of HRS and H₂ production facility²⁾ [EUR/km]

1) For a Multiple Unit 2) Based on a 6,000 kilogram per day station capacity

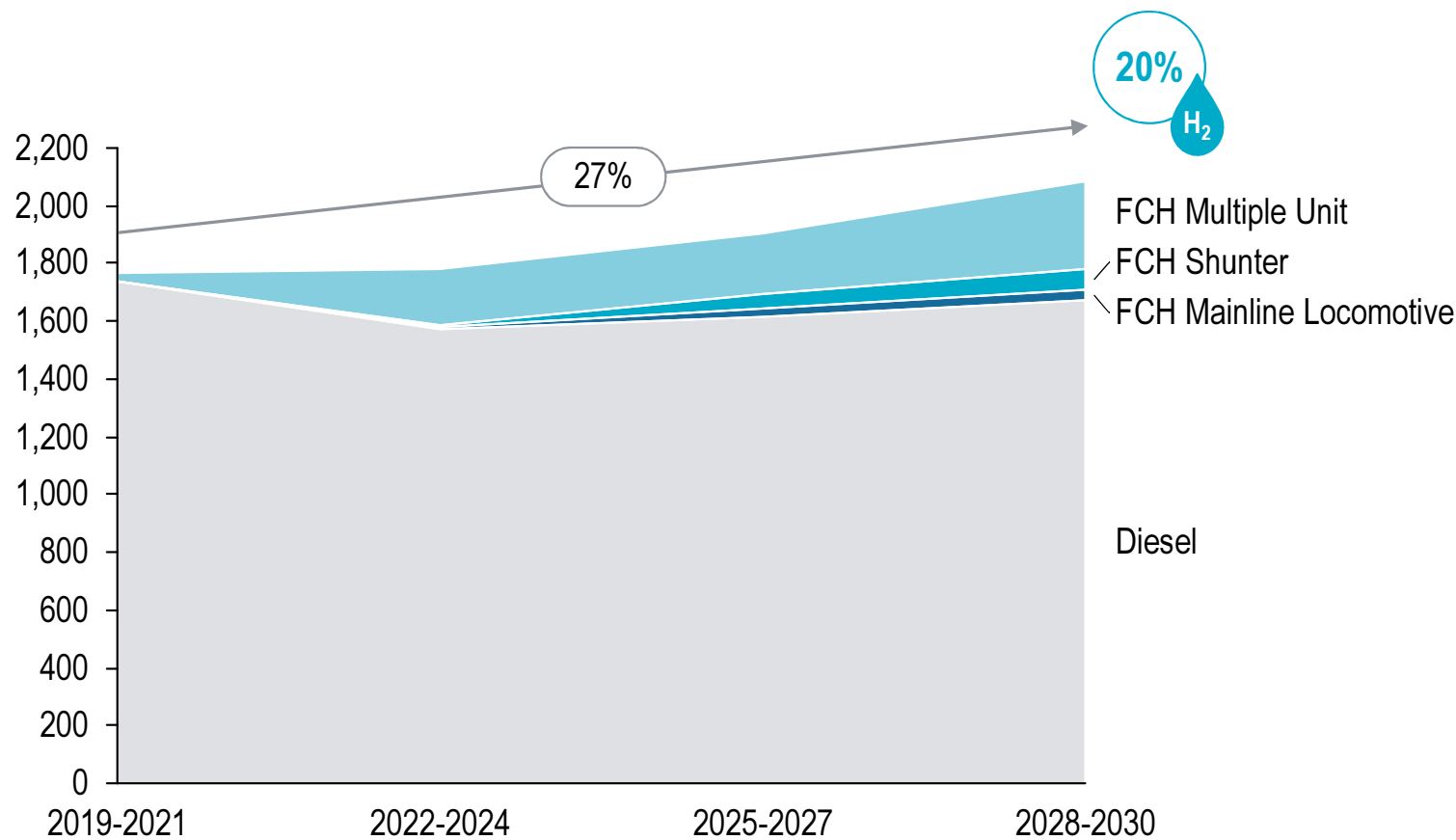
C. Market potential

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In the base scenario, the Market potential for FCH trains reaches 20% by 2030

EU Market potential FCH trains – Base scenario [standard units¹⁾]



Comments

- > As of 2021, the market uptake of Multiple Units starts with 30 SU
- > Starting 2023, it will be followed by FCH Shunters and Locomotives
- > By 2030, the market will accumulate 944 SU in all rail segments – Multiple Units taking the largest part out of FCH applications (749 SU constituting 15% of the total accumulated market uptake)

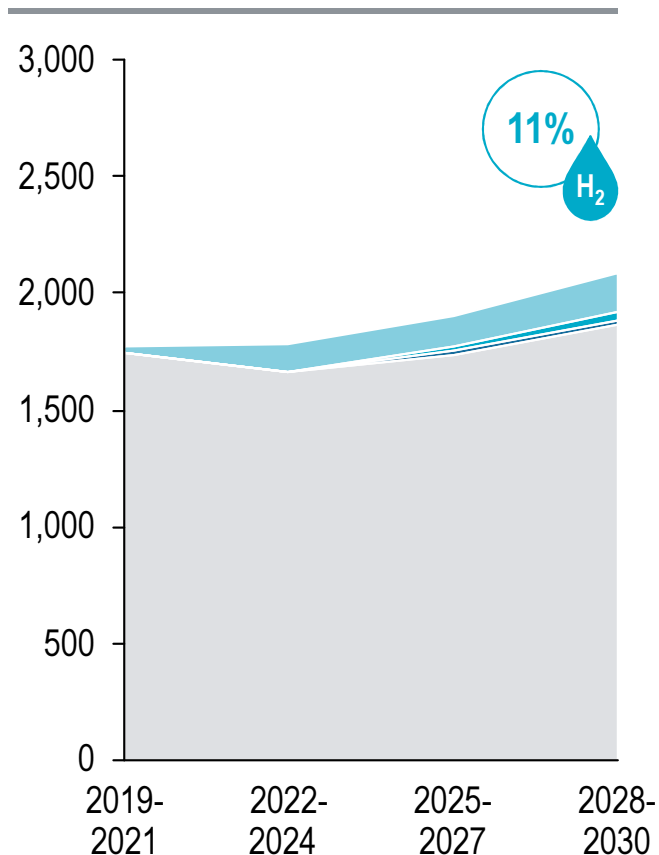
X% CAGR of FCH X% Market share of FCH of new purchases in 2030

1) According to definition of UNIFE World Rail Market Report
Source: Market research, Expert interviews, Roland Berger

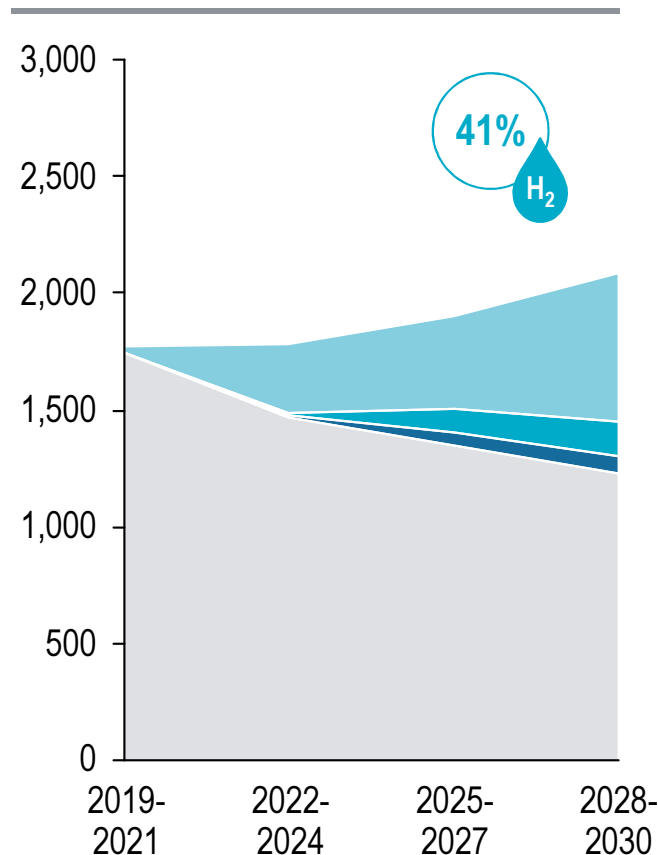
Even at this early stage of market development, market feedback suggests significant potential for FCH trains in Europe

Market potential for FCH trains in Europe [standard units¹⁾]

Low scenario



High scenario



Additional market potential exists

Market potential for FCH trains could further increase by addressing/considering, e.g.:

- > Existing green image of the rail segment and lack of awareness for the business case of FCH trains
- > Long lifetime of diesel trains and short-term purchasing decisions
- > Uncertainty about alternatives to FCH technology
- > Market potential from export opportunities to other geographies

Multiple Units Shunter Mainline Locomotive Diesel

X% CAGR of FCH share



X% Market share of FCH of new purchases in 2030

1) According to definition of UNIFE World Rail Market Report
Source: Market research, Expert interviews, Roland Berger

A Market potential in the base scenario is driven by FCH Multiple Units in the Frontrunner markets; by Shunters – in other markets

Overview of FCH train markets outlook for 2030 [standard units¹⁾]

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

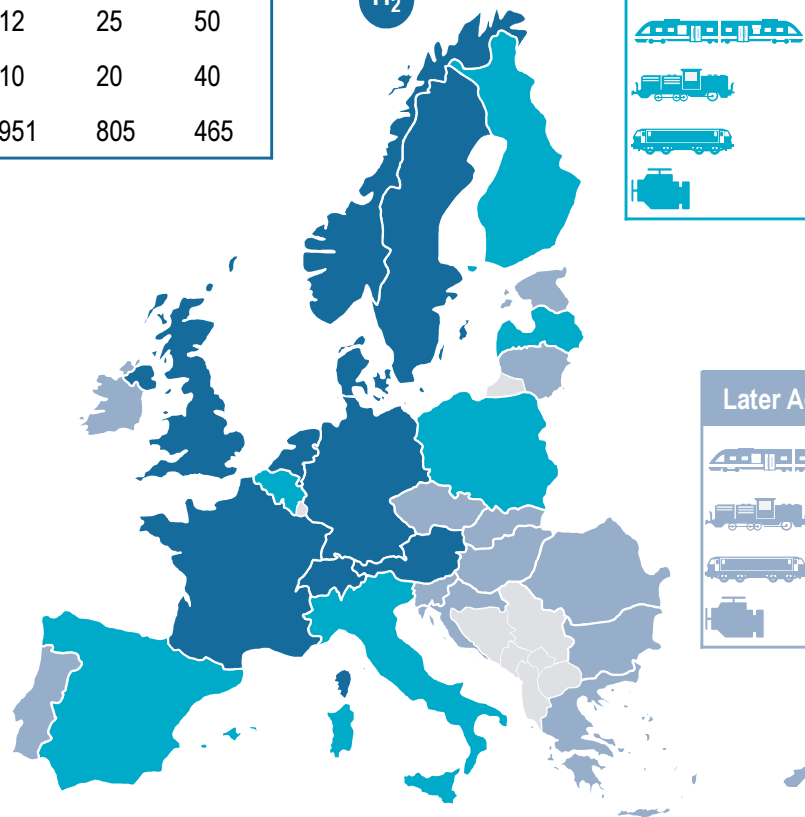
Base 2030
28%
H₂

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

Base 2030
11%
H₂

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

Base 2030
9%
H₂



Comments

- > The Market potential will depend on the projected diesel purchasing volumes
- > Substitution of diesel trains is driven by the Multiple Units in the Frontrunner markets
- > On the other hand, Shunters drive the substitution in the Newcomer and Later Adopter markets



Market share of FCH of new purchases in 2030

1) According to definition of UNIFE World Rail Market Report
Source: Market research, Expert interviews, Roland Berger

D. Case studies

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Detailed analysis was conducted on ten case studies selected based on balanced technological and geographical perspectives

Overview of selected case studies

	Location	Application	Country
1	Groningen & Friesland		NL
2	Aragon region		ES
3	Montréjeau – Luchon		FR
4	Brasov – Sibiu (Theoretical)		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



FCH MUs present a clean, economically sensible alternative to existing technology in dense networks with many unelectrified lines

Multiple Unit case study results [EUR/km_{train}]

Overview

Montréjeau – Luchon, France



Aragon, Spain



Groningen & Friesland, Netherlands



Track length	
Rolling stock	
H ₂ consumption	
Characteristics	
Diesel	
FCH	
Catenary	
Battery	
CO ₂ saving potential in one year	

140 km
3x 4 car trains (bi-mode)
0.36 kg/km
Partly electrified route with a low utilisation on 36 km
18.5
21.2
27.5
19.9
1,334 t

165 km
2x 4 car trains (bi-mode)
0.31 kg/km
Cross border connectivity and long route without electrification
9.3
12.4
22.5
13.7
767 t

300 km
70x 3 car trains
0.22 kg/km
Fast trains for intercity connections
4.8
4.9
4.4
5.2
56,389 t

FCH technology is more competitive in use cases where Shunters have larger loads, idle less and travel longer distances

Shunter case study results [EUR/km_{train}]

Overview

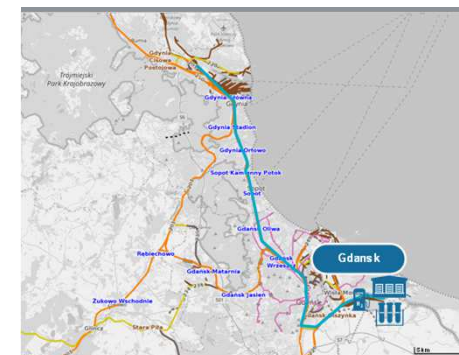
Hamburg-Billwerder, Germany



Riga Node, Latvia



Gdansk, Poland



Track length	
Rolling stock	
H ₂ consumption	
Characteristics	
Diesel	
FCH	
Catenary	
Battery	
CO ₂ saving potential in one year	

10 km
15 Shunters
0.39 kg/km
Shunting yard in a large urban area and next to Hamburg port
10.1
12.7
11.6
1,969 t

100 km
15 Shunters
0.49 kg/km
Shunting operation between several port terminals
20.9
20.4
21.8
3,350 t

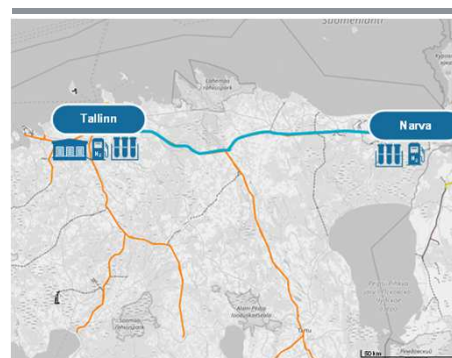
35 km
10 Shunters
0.72 kg/km
Marshalling yard in collocation of the refinery supplying hydrogen
32.1
36.7
36.9
339 t

FCH Mainline Locomotives could be competitive in cases where route interoperability is limited, but still face barriers to market entry

Mainline Locomotive case study results [EUR/km_{train}]

Overview

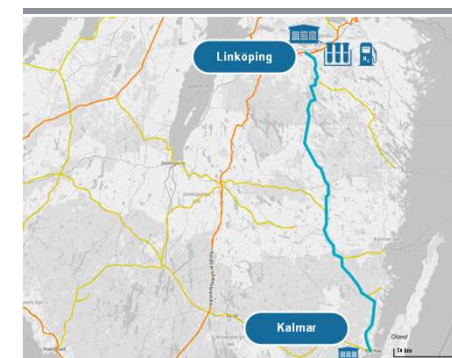
Tallinn – Narva, Estonia



Frankfurt (Oder) – Hamburg, Germany



Kalmar – Linköping, Sweden



Track length

210 km

720 km

230 km

Rolling stock

2 Locomotives

5 Locomotives

5 Locomotives

H₂ consumption

0.67 kg/km

0.82 kg/km

0.48 kg/km

Characteristics

Cross-border operation between Russia and Estonia

Shunting operation between several port terminals

Passenger and freight transport between two cities

Diesel



22.6

9.2

5.7

FCH



22.8

11.9

6.7

Catenary



24.4

6.4

22.0

Battery



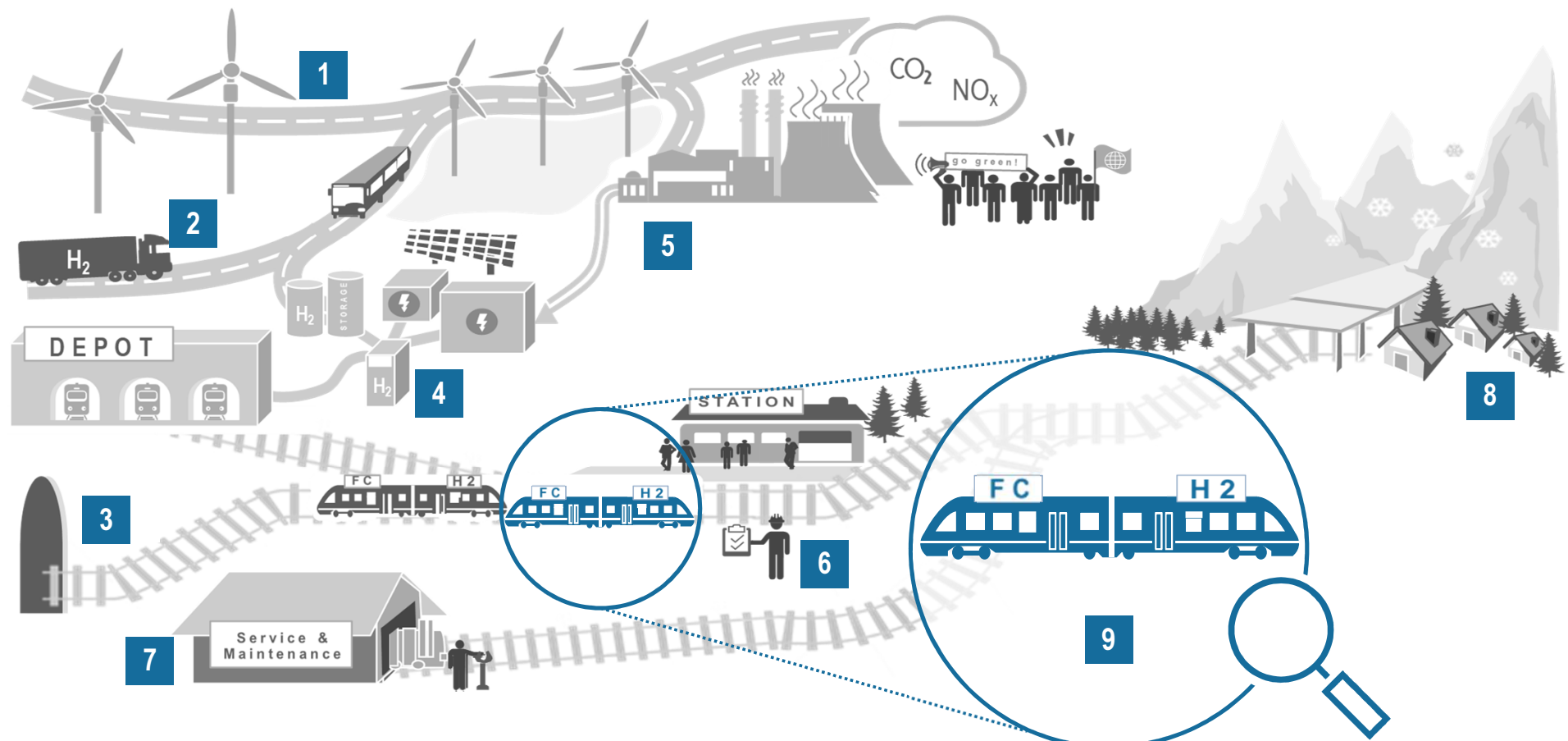
CO₂ saving potential in one year

2,556 t

12,874 t

4,980 t

Analysis of the FCH train eco-system included several selected focus topics – One focus topic was developed in each case study



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

E. Barriers and recommendations

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No barriers are show-stoppers for FCH rail technology, but R&I projects are required to realise a broader commercial potential

Task 4: Conclusions

Barriers for FCH trains

- > **No principle show-stoppers** to the deployment of FCH technology in the rail environment exist
- > **High priority barriers** are related to **financing** FCH train deployment, **lack of standard scalable design** and **H₂ storage optimisation**



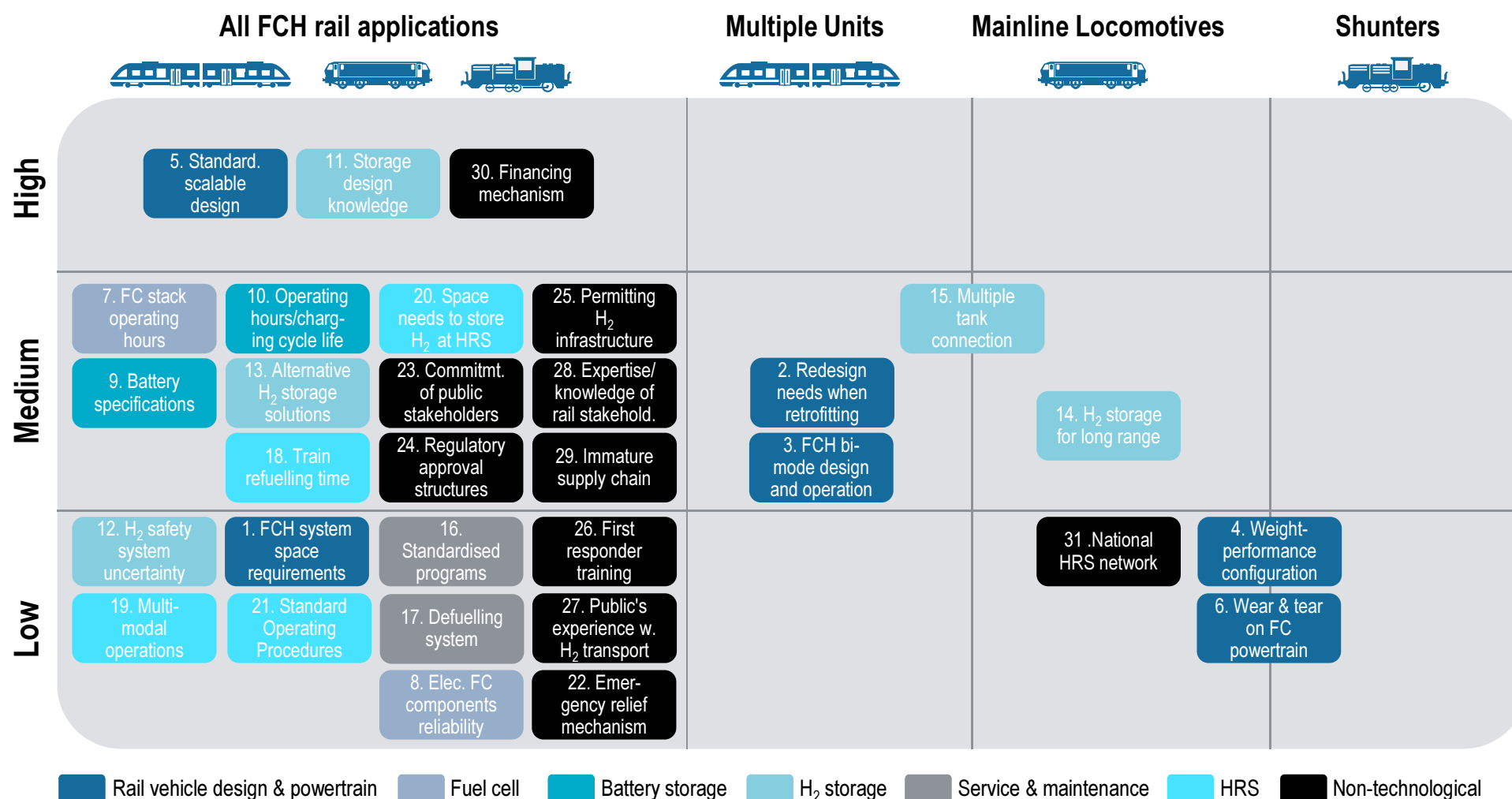
Suggested Research and Innovation (R&I)

- > **R&I projects** can bring FCH technology significantly closer to commercialisation by **addressing high priority barriers**
- > Three key project topics
 - **Large-scale demonstration** of Multiple Units fleets
 - **Prototype level.** and testing of Shunters or Mainline Locomotives
 - Research and **tech. dev.** of **optimised H₂ storage** system
- > **Medium, low priority barriers can integrated** in the same R&I project



Analysis identified 31 barriers in total, with most applying to all FCH train applications and other specific to certain use cases

Overview of barriers for FCH trains



Rail vehicle design & powertrain
Fuel cell
Battery storage
H₂ storage
Service & maintenance
HRS
Non-technological

Barriers mostly related to the trains but also to related infrastructure and social, legal and economic factors in the ecosystem

Design & Engineering a

1. Additional space required by FCH system in new designs
2. Potential structural changes and redesign requirements in retrofits
3. No available designs and safety concerns for FCH bi-mode operation
4. Reduced train performance due weight characteristics changes
5. Limited experience with designing standardised, scalable, customisable powertrain
6. Wear and tear on FCH powertrain fom rail operations

Fuel cell b

7. Fuel cell stack operating hours
8. Reliability of electronic FCH components in rail applications

Battery storage c

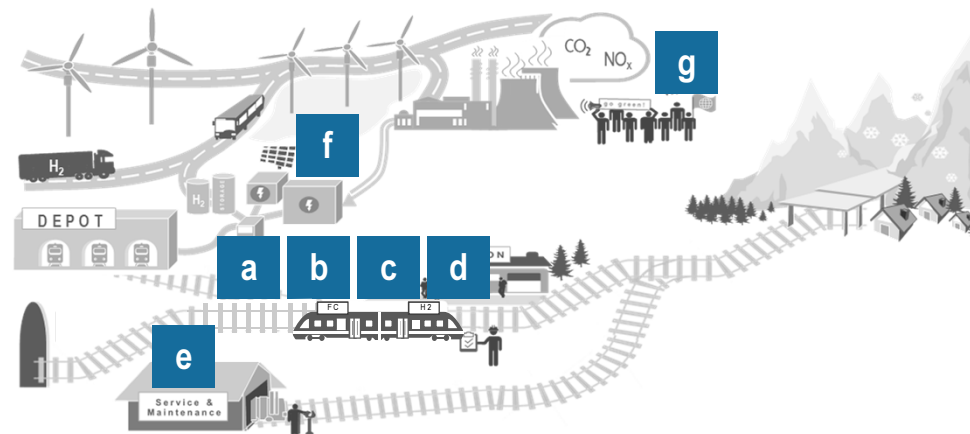
9. Limited expertise in battery specifications
10. Battery sufficiency (oper. hours / cycle life)

Maintenance e

16. FCH rail and maintenance programs
17. Rail H₂ maintenance defuelling system

Non-technological g

23. Commitment of public stakeholders
24. No efficient / appropriate regulatory structures
25. Lack of permitting process for rail H₂ infrastructure
26. Lack of first responder training for FCH rail accidents
27. Limited public experience with H₂ technologies in transport
28. Limited rail stakeholder knowledge about FCH technologies
29. Immature FCH rail supply chain
30. Insufficient financing mechanisms supporting FCH trains
31. Complex build-up of hydrogen refuelling infrastructure



Hydrogen storage d






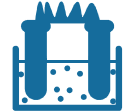


11. Lack of knowledge designing onboard H₂ storage systems
12. Uncertainty on effective vehicle H₂ safety system
13. Optimisation potential via alternative H₂ storage solutions
14. Missing solutions for H₂ storage in Mainline Locomotives
15. Lack of solutions to connect tank systems across train cars

Hydrogen refuelling station f

18. Refuelling time requirements for large amounts of hydrogen
19. Limited experience with Multi-modal operation of HRS in the rail environment
20. Large space and storage requirements of HRS
21. Missing FCH infrastructure Standard Operating Procedures
22. Lack of experience with emergency relief mechanisms of FCH system

Three priority R&I topics should be addressed to unlock the full market potential of FCH trains

Overview of recommended R&I projects

	A Large-scale demonstration of Multiple Unit train fleets	B Development, engineering and prototype operation of Shunters or Mainline Locomotives	C Technology development for optimised hydrogen storage system for FCH rail applications
High-level project scope	 10 - 15  1 - 2	 5 - 10  1 - 2	   
Objectives of project	> Large scale demonstration project of 15 or more Multiple Units could enable the first fleet sized FCH train deployment	> Development and implementation of five new FCH Shunters or Mainline Locomotives (or ten retrofits), including concept design, engineering, and prototype	> Integrated technology development project for optimised hydrogen storage including analysing; filling pressure, tank location, cross-car connections, etc
Est. budget before funding	EUR 80 – 100 m	EUR 15 – 20 m	EUR 4 – 7 m

F. Project summary and closing

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FCH technology is a promising pathway to further improve the environmental friendliness of rail transportation

Conclusion

Numerous exciting developments have taken place during the project ...

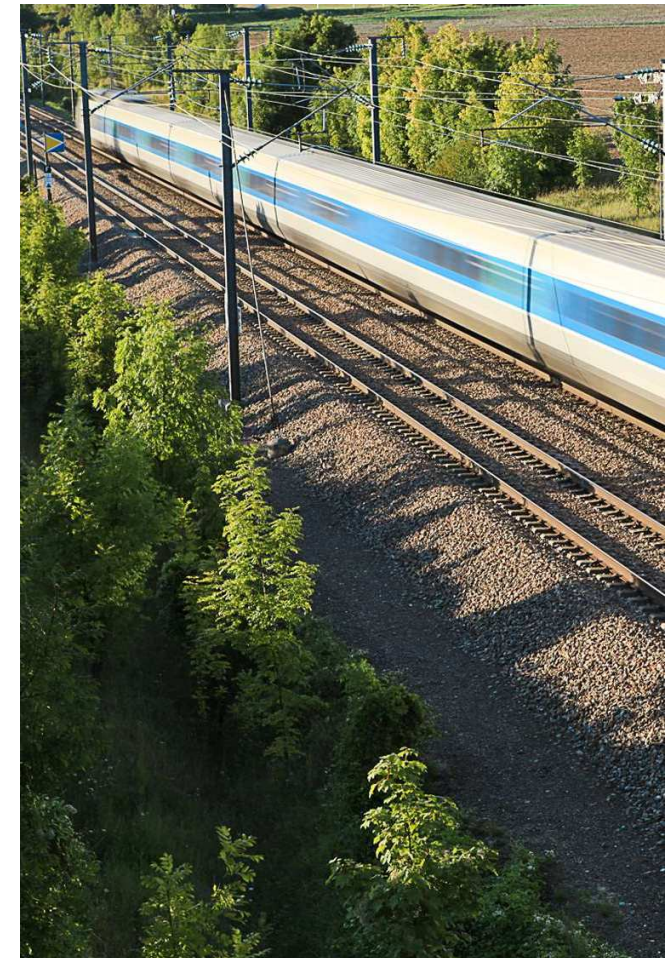
"Germany launches world's first hydrogen-powered train" The Guardian, 17 September 2018

"SNCF to run fuel cell trains in 2022" Railway Gazette, 10 December 2018

... and the future could hold more potential

"First European hydrogen Shunters go to work in new trial" Breaking News, 2020

"1,000th FCH train enters service, as Europe targets diesel rail emissions" Breaking News, 2030



Consider the deployment of FCH trains as attractive way to integrate renewables and synergize with existing initiatives

Collaboration of all stakeholders required



- | | |
|--|--|
| Government | <ul style="list-style-type: none"> > Consider integrating FCH trains in public transport strategy > Support development and deployment of FCH trains |
| Rail operator | <ul style="list-style-type: none"> > Investigate opportunities for the deployment of FCH trains (e.g. most suitable lines, multi-modal refuelling terminals) > Consider retro-fitting existing platforms with FCH technology (long train lifetime) |
| Energy and fuel provider | <ul style="list-style-type: none"> > Assess large-scale hydrogen refuelling stations as alternative to transmission grid expansion for renewables > Consider possibilities to combine FCH train refuelling (baseload) with other modes of transport (multi-modal transport, flexible load) |
| Industry/ technology developers | <ul style="list-style-type: none"> > Adapt existing FCH train technology to local requirement > Market available commercial products actively |
| Associations and Opinion Makers | <ul style="list-style-type: none"> > Raise awareness of technology and include FCH train in the overall FCH and rail strategy |

Our Roland Berger team for today is happy to answer your questions

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