D6.1 – Report on KPI assessment

WP 6 – WP Demonstration of the Competitiveness

Task 6.1 – KPI Assessment

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Executive Summary

The scope of this Deliverable was to collect, analyse and interpret key performance indicators (KPI) derived during the FCH2Rail project duration. The project's KPIs were benchmarked against the Clean Hydrogen JU target KPIs as defined in the Multi-Annual Work Plan and Strategic Research and Innovation Agenda respectively (reference years 2020 and 2024) as well as against KPIs defined in a 2019 Roland Berger study. We analysed the following KPIs: Fuel cell stack durability, hydrogen consumption, fuel cell system availability, fuel cell module volumetric and gravimetric densities, range before refuelling and refuelling time.

The analysis distinguished between two train types. First, the Bi-mode H2 Demonstrator train developed and retrofitted within the FCH2Rail project and, second, a generic so called Bi-mode H2 Future train which encompasses several technical improvements over the Demonstrator train. Another goal was to compare technical and operational KPIs of the hydrogen trains investigated against diesel train KPIs.

<u>FC stack lifetime</u>: Each track together with its operational schedule results in a different overall energy demand which is delivered by the FCHPP. The energy can come from 3 different sources (catenary, hydrogen & battery), managed through the Energy Management System. Hence, the fuel cell load profile is specific to each track. Since the load profile is an important parameter influencing the FC stack lifetime, each track (and FCHPP configuration) will result in a different stack lifetime. Based on simulation of 10 different tracks, the lifetime ranges from 30,000 hours to 40,000 hours. These values are based on the Bi-mode H2 Future train configuration, which is today's state of the art.

As a Bi-mode H2 train will use the FCHPP only under non-catenary sections, the replacement interval of the FC stack as expressed in train operational hours will therefore be higher when there is a high coverage by catenary.

<u>Hydrogen Consumption:</u> For the EN 50591 regional profile the hydrogen consumption of the Demonstrator train in pure hydrogen mode is 0.135 kg H2/100 ton-km and 0.126 kg H2/100 ton-km for the Future bi-mode H2 train respectively. It is only slightly higher than the SRIA targets for 2020 (0.12 kg H2/100 ton-km) and 2024 (0.11 kg H2/100 ton-km). But for a range of simulated real tracks with part electrification, the hydrogen demand of both Demonstrator and Future train is substantially lower than the SRIA targets.

<u>Range before refueling (autonomy)</u>: Autonomies achieved by diesel trains are typically 2 to 2.5 times larger than those of Bi-mode H2 trains. However, the autonomy targets of 650 to 1,000 km defined by operator Renfe can be reached by the Bi-mode H2 Future train configuration for all tracks investigated in this deliverable.

<u>Refueling downtime:</u> Diesel refueling is unsurpassed in terms of refueling speed. Hydrogen refueling is still much slower with a range of 0.69 to 1.17 kg H2/min measured in this project with the transportable HRS. But with improving HRS technology yielding refueling speeds of 4 kg H2/minute on average and parallel refueling the operational downtime to refuel hydrogen trains can be reduced drastically down to 20 minutes.

Generally, we demonstrated in the FCH2Rail project that the hydrogen fuel cell technology as part of a bi-mode powertrain brings together the best of two worlds: high autonomies on non-electrified track sections and high efficiency and excellent power characteristics of the overhead catenary powertrain.

Glossary of Terms

Abbreviations/Acronyms	Description
Absorption AC	Absorption air conditioning system
BoL	Begin of life
CA	Consortium Agreement
DMU	Diesel multiple unit
DX.X	Deliverable X.X
EMU	Electric multiple unit
EOL	End of life
FC	Fuel cell
FCH2Rail	Fuel Cell Hybrid PowerPack for Rail Applications
FCHJU	Fuel Cell Hydrogen Joint Undertaking
FCHPP	Fuel cell hydrogen power-pack
GA	Grant Agreement
H2	Hydrogen (H_2)
HRS	Hydrogen refueling station
HVAC	Heating ventilation air-conditioning
HyPAC	Hydrogen Powered Air Conditioning
KPI	Key performance indicator
MAWP	Multi-Annual Work Plan
MoL	Middle of life
OESS	Onboard energy storage system
SoC	State of charge
SRIA	Strategic Research and Innovation Agenda
VCRS	Vapor compression refrigeration system

Contents

1. Introduction

1.1 Objective

The objective of this Deliverable is to formulate and quantify the key performance indicators (KPIs) derived within the FCH2Rail project and to analyze whether the fuel cell hydrogen powerpack applied in this project is competitive in technical and operational aspects to diesel trains, specifically in terms of autonomy and refueling time.

We benchmark the project's KPIs against the FCHJU MAWP (Multi-Annual Work Plan) KPIs and its update, the Clean Hydrogen Joint Undertakings 2021-2027 SRIA (Strategic Research and Innovation Agenda) KPIs as well as against a 2019 study of a management consultancy (Roland Berger) as requested in the FCHJU call.

The quantified KPIs in this Deliverable are

- Fuel cell stack durability
- Hydrogen consumption
- Fuel cell system availability
- Fuel cell module volumetric density
- Fuel cell module gravimetric density
- Range before refueling (autonomy)
- Refueling time

1.2 KPI benchmarks

The FCH2Rail consortium committed to challenge the project against the then valid FCH JU Multi-Annual Work Plan (MAWP) 2014-2020 KPI targets for fuel cell electric trains (Figure 1).

No.	Parameter	Unit	State of the art		FCH 2 JU target		
			2012	International SoA 2017*	2020	2024	2030
1	Fuel cell system durability	h	N/A	12,000	20,000	25,000	30,000
2	Hydrogen consumption	kg/100 km	N/A	24 - 34	22 - 32	21 - 30	20 - 28
3	Availability	%	N/A	87	94	97	>99

Notes:
No possibility at this time to estimate train cost, including fuel cell system cost and yearly operation costs targets.

1) *Durability of the fuel cell system subject to EoL criterion output voltage at maximum power*
2) *Hydrogen consumption for 100 km driven under operations using exclusively hydrogen feed*
3) *Percent amount of time that the train is able to operate versus the overall time that it is intended to operate*

Figure 1: MAWP 2014-2020 KPI targets for fuel cell electric trains (FUEL CELLS and HYDROGEN 2 JOINT UNDERTAKING 2018)

For hydrogen consumption we use the newer and more representative SRIA target, which is given in kg /ton-km.

The Clean Hydrogen Partnership requested in its call for proposal also to compare its KPI against the KPI issued by a series of studies prepared by Roland Berger in 2019. (Europe's Rail Joint Undertaking 2019). This benchmark will be done in Chapter 3.8.

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Table 1 lists the applicable benchmark KPI categories and the two FCH2Rail project related KPI dimensions (Demonstrator train and Future train) and the applicable reference years. In addition to the FCH2Rail Demonstrator train, which, by its nature cannot meet all KPI targets, we also include a virtual 'Future train' which encompasses improved fuel cell and battery technologies. The Future train is a dedicated bi-mode-optimized train as opposed to the EMU retrofit used for the FCH2Rail Demonstrator train.

Benchmark KPI categories	KPI target years
FCH JU MAWP KPI 2014-2020	SoA 2012, targets 2020/2024/2030
Roland Berger Study 2019	/
FCH2Rail KPI dimensions	**KPI target years**
FCH2Rail – Demonstrator train	2020 - actual/measured in the project 2021-2024 [in effect: 2020 technological status]
FCH2Rail – Future train / Generic BiMode H2 train	2024 - new FC generation and new battery

Table 1 KPI reference years

Table 2 displays the MAWP-related KPI addressed in this Deliverable (Chapters 3.1 to 3.2.6) and further KPI assessed independent of the MAWP KPI (Chapters 3.4 to 3.2.6).

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	Parameter		MAWP 2014-2020 fuel cell train KPI			FCH2Rail designation	Unit
Chapter	**MAWP 2014-2020 fuel cell train KPI**	**Unit**	**SoA 2020**	**Target 2024**	**Target 2030**		
3.1	FC stack durability	h	20,000	25,000	30,000	Lifetime (Durability)	h
3.2	Hydrogen consumption sys	kg / 100km / ton	0.12[1]	0.11[1]	0.08[1]	Hydrogen consumption	kg H2 / 100km / ton
3.2	Hydrogen consumption sys	kg / 100km	22-32	21-30	20-28	Only SRIA target will be used, because MAWP is not mass-dependent and therefore not comparable	
3.2.6	HyPac and Absorption AC	Reduction of energy demand (MWh/a)					
3.3	Availability	%	94	97	>99	FC system availability	%
3.4	FC module volumetric density	kW/m³	n/a[1]	53[1]	>60[1]	FC module volumetric density	kW/m³
3.5	FC module gravimetric density	kW/ton	n/a[1]	135[1]	>160[1]	FC module gravimetric density	kW/ton
3.6	Range before refueling (autonomy)	km					
3.7	Refueling time	Minutes					

Table 2: KPI targets based on MAWP 2014-2020 fuel cell train KPI
[1] Based on SRIA 2021-2027 fuel cell train KPI instead of MAWP 2014-2020 target

2. Train and operational profiles

2.1 Bi-mode H2 train and FCHPP configuration

In this KPI report, we derive KPI from the FCH2Rail Demonstrator train which is a Bi-mode FC hybrid train converted from a EMU train. But since technology evolves we also include a so called future train that incorporates the then (compare Table 1) available powertrain technologies. The Future train is a generic bi-mode fuel cell hydrogen multiple unit optimized for integration of a bi-mode fuel cell powertrain whereas the Demonstrator train is a not-optimized multiple unit that was retrofitted from a conventional EMU and which involves some compromises concerning the component arrangement in and on the train. The generic Future train configuration is applicable to all tracks in the in this report investigated countries Spain, Portugal, Germany. The specifications of the Future train follow the requirements outlined in Deliverable 1.3 of FCH2Rail (Munoz Vicent and Fernandez Del Rey 2024).

The auxiliary demand of the Demonstrator train follows real conditions experienced during track tests, without passengers. The Future train's auxiliary demand follows CAF's experience in normal operating conditions taking into account annual average HVAC power demands. The Future train is 50 % seated according to EN50591. Up to date energy efficient driving modes have been applied, coherent with CAF's current driving assistance system DAS being used in the Demonstrator.

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2.2 Operational profiles

To quantify the KPIs, new simulations of operational profiles from Spain, Portugal and Germany were required (input from non-public FCH2Rail Deliverable 1.4 – Generic requirements for Fuel Cell Hybrid PowerPack). Table 3 lists the tracks used in this deliverable. Track and electrification data of these tracks were taken from FCH2Rail Deliverable D1.1 and D1.4. All distances are given for a complete round-trip. Some tracks are operated in pure (exclusive) hydrogen mode, whereas other tracks are operated in bi-mode operation. Table 3 displays the total lengths and the lengths of the non-electrified sections.

Track	Distance [km]	Distance Non catenary [km]
1 Zaragoza – Canfranc – Zaragoza [Bi-mode Operation]	441.8	327.2
2 Madrid – Soria – Madrid [Bi-mode Operation]	491.8	202.2
3 Madrid – Talavera – Madrid [Bi-mode Operation]	273.9	230.8
4 Valencia – Alcoi – Valencia [Bi-mode Operation]	240.0	128.4
5 Valencia – Zaragoza – Valencia [Bi-mode Operation]	731.1	654.7
6 A Coruña – Ferrol – A Coruña [H2 Operation]	137.4	137.4
7 Monforte – A Coruña – Monforte [H2 Operation]	377.7	377.6
8 Madrid – Sevilla – Madrid [Bi-mode Operation]	1312.1	1211.6
9 Murcia – Alicante – Murcia [H2 Operation]	155.8	155.8
10 Porto – Vigo – Porto [Bi-mode Operation]	344.0	293.4
11 Stuttgart - Aulendorf - Stuttgart [Bi-mode Operation]	405.642	261.9

Table 3: Real tracks (round trip lengths)

Detailed data (elevation profiles, allowed speed profiles, stations and timetable data) of theses tracks can be found in the FCH2Rail Deliverable 1.1 (Herwartz and Kühlkamp 2022b).

Some of the tracks in Table 3 will be electrified completely or partly according to recent plans (e.g. Track 5: Electrification works on the section Zaragoza-Teruel and on Track 7: Electrification on the section Monforte-Lugo). These electrification plans where not known at the time the Deliverable 1.1 was finalized in February 2022. In order to have a coherent Deliverable sequence we used the same electrification patterns known in 2022 throughout the whole project. As a consequence of additional track electrification, the tracks become more prone to bi-mode operation in general which supports the general idea of the FCH2Rail project in implementing a bi-mode train. Figure 2 displays the EN 50591 regional profile (passenger service) used as demanded in the MAWP.

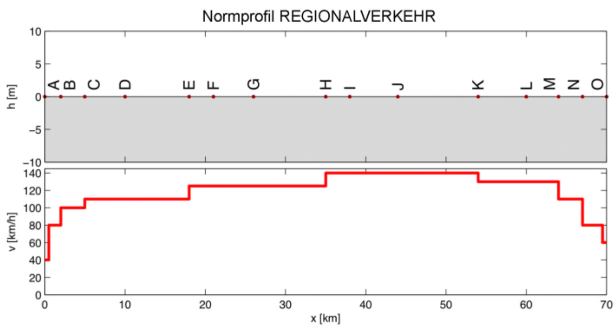

Figure 2: EN 50591 – Regional profile (passenger service)

3. KPI analysis – FCH2Rail

3.1 FC stack durability

The following table displays the applicable Clean Hydrogen Partnership KPI targets on fuel cell stack durability.

	Parameter						
No	**SRIA 2021-2027 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
1	FC stack durability	h	15,000	20,000	30,000	Lifetime (Durability)	h
No	**MAWP 2014-2020 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
1	FC stack durability	h	20,000	25,000	30,000	Lifetime (Durability)	h

3.1.1 Methodology

The durability of a FC stack is an estimation of the total available operational time during which the stack is meeting the customer performance requirements. As such, there are several factors the customer can influence to extend the FC stack durability, like the maximum power request from the FC stack, the available cooling system heat rejection capacity and/or maximum allowed deterioration in FC stack efficiency.

When these factors are not yet known, the FC stack manufacturer can use a more standard definition of the durability which is a certain voltage drop for a given operation point. For the bi-mode H2 future train a -20% voltage drop is used as definition to determine End of Life (EOL) timing.

Measurement methodology

The cell voltage remained constant during the whole testing and demonstration period of the bi-mode H2 Demonstration train. As such, it was not possible to estimate the End of Life timing based on field data obtained over the course of the FCH2RAIL project. Therefore, simulation tools were used to estimate the EOL timing of the FC stack in function of a given load profile. These tools are developed inhouse based on a combination of physical and empirical models of the fuel cells as used in the Future train configuration (see Chapter 1.2).

3.1.2 Results

Figure 3 shows the simulated End of Life timing after which the fuel cell module will have to be replaced. The replacement interval can be expressed in fuel cell operational hours or train operational hours (both being equal when the bi-mode train is constantly used in H2 mode).

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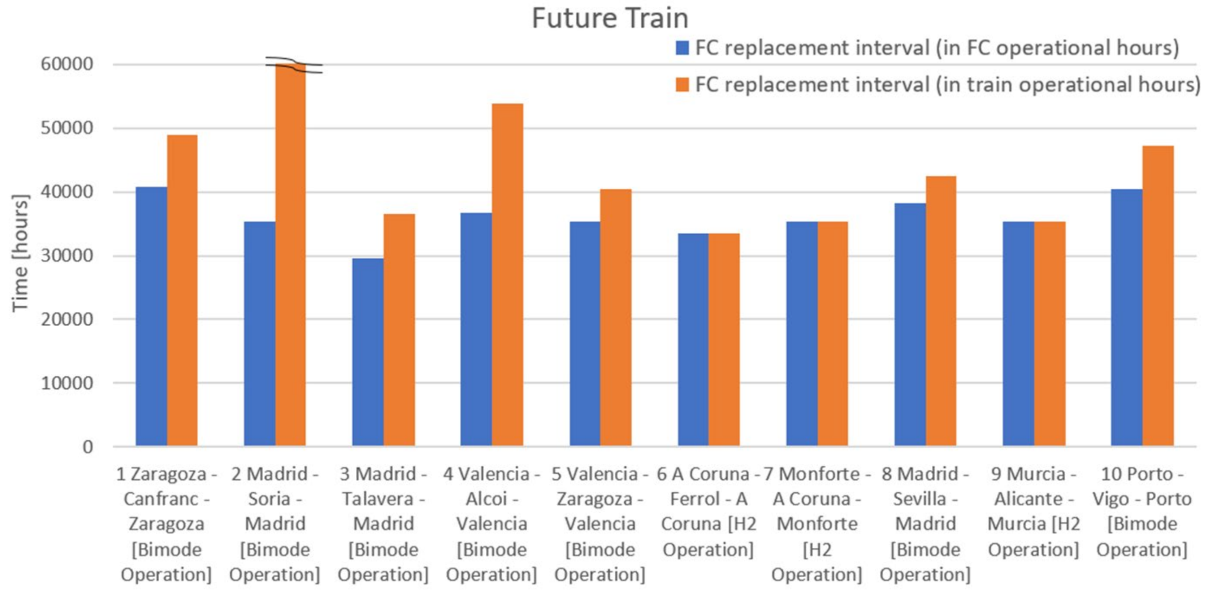

Figure 3: Fuel cell stack lifetime (blue) and exchange interval in train operational hours (orange): Future train

3.1.3 Interpretation

Each usage condition is different in terms of

- Load requested from the fuel cell module (min, average and max power)
- Load transients and the associated thermal dynamics
- Number of on/off cycles.

Since the stack durability will be affected by above factors, the lifetime is changing from one usage condition to another. Extending the durability is therefore possible by making system optimization at the start of the project in order to meet the durability targets. Of course, other project constrains might limit the optimization possibilities. The simulation results predict a FC stack operational lifetime in the range of 30,000 to 40,000 h. What is more relevant for the railway manufacturer is the FC stack operational time in function of the train operational time. Since the bi-mode train is not using the FC module 100% of the time when catenary operation is available, the actual replacement interval for the FC stack will depend on the usage ratio across the track.

3.2 Hydrogen Consumption

The following table displays the applicable Clean Hydrogen Partnership KPI targets. Here, only the SRIA targets are relevant.

	Parameter						
No	**SRIA 2021-2027 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
7	Hydrogen consumption sys	Kg / 100km / ton	0.12	0.11	0.08	Hydrogen consumption	kg H2 / 100km / ton
No	**MAWP 2014-2020 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
2	Hydrogen consumption sys	Kg / 100km	22-32	21-30	20-28	Only SRIA target will be used, because MAWP is not mass-dependent and therefore not comparable	

3.2.1 Methodology

We used simulated values to reflect real world timetable operation. The methodology is as follows:

1. Measurement of Demonstrator train real track test hydrogen demand (using data of FCH2Rail Task 5.2 and 5.3) and of test bench hydrogen demand (input from FCH2Rail WP 4: Implementation and Test of FC Hybrid PowerPack),
2. Validation of CAF simulation tool using the measured values derived in FCH2Rail Task 5.2 and Task 5.3,
3. With the validated simulation tool, hydrogen demand was derived for all real Spanish and Portuguese tracks defined in FCH2Rail Task 1.3, both for the Demonstrator train and for the Future train (see Chapter 2.1).

The lines selected for the tests in Task 5.3 were considered as representative by the project partners. Some of them are the same as considered in Task 1.3, but not all. That is why simulation was performed in all cases, to provide comparable results for all lines, both those with test records and those without.

3.2.2 Simulation set up and tracks

We used real tracks from Spain, Portugal and Germany and the generic EN 50591 rail standard which is applied industry-wide for calculating energy demand of railways (see Chapter 2.2). The simulation parameters are summarized in Table 4.

Track	Remarks	Train configurations
Real tracks	- Speed profile according to commercial timetable and track speed limits - Auxiliary demand with HVAC - Demonstrator train: without passengers - Future train: with passengers (50 % seated)	- Demonstrator train - Future train
EN 50591, standard service profile regional (passenger service)	- 70 km track, max velocity 140 km/h, 13 intermediate stops, no elevations - Speed profile according to timetable - Auxiliary demand without HVAC (according to MAWP/SRIA) - Three cases had been simulated (see Chapter 3.2.4)	- Demonstrator train - Future train

Table 4: Simulated tracks

We used the total lengths (distances) and the lengths of the non-electrified catenary sections of the *real tracks* as shown in Table 3 and the EN 50591 regional profile (passenger service) shown in Figure 2.

3.2.3 Simulation results – Real tracks

The simulation was performed for the Demonstrator and for the Future train configuration. Table 5 summarizes the results which are described in more detail in the subsequent chapters.

Train	Operational Mode	Tracks (see Table 3)	Hydrogen consumption range (kg H2/100 ton-km)	
			total distance (non-electrified sections and catenary sections)	only non-electrified section distance
Demonstrator train	BiMode	1, 2, 3, 4, 5, 8, 10	0.06 … 0.19	0.14 … 0.22 (BoL)
	Pure H2	6, 7, 9	/	0.18 … 0.25 (BoL)
Future train	BiMode	1, 2, 3, 4, 5, 8, 10, 11	0.04 … 0.16 (BoL) *0.05 … 0.18 (EoL)*	0.10 … 0.18 (BoL) *0.12 … 0.22 (EoL)*
	Pure H2	6, 7, 9	/	0.15 … 0.22 (BoL) *0.18 … 0.26 (EoL)*

Table 5: Simulation results – real tracks. Data of Future train include both BoL and EoL conditions of fuel cell and battery mode.

3.2.3.1 Demonstrator train

Hydrogen consumption of the Demonstrator train in bi-mode operation (tracks 1, 2, 3, 4, 5, 8, 10) shows *Figure 4*. It is:

- 0.06 to 0.19 kg/100 ton-km for the *total distance* (non-electrified sections and electrified sections where the train draws its power from the catenary) and
- 0.14 to 0.22 kg/100 ton-km if *only the non-electrified sections* are looked at.

In pure H2 operation (tracks 6, 7, 9) the H2 consumption varies between 0.18 and 0.25 kg/100 ton-km.

The data show that there is some variability in hydrogen consumption results among the routes. Routes with the highest specific hydrogen consumption are those that do not include any electrified sections. In these cases 100% of the energy demand has to be covered by the FCHPP, whether directly from the FC to the traction equipment or through the OESS, in which case the OESS losses are added to the hydrogen consumption.

Furthermore, significant differences in consumption are also observed due to the variety among routes in terms of elevation profile, target journey time between stations, and maximum circulation speeds. For example, routes with short running times and a short stopping interval will have higher consumption, as the energy demand will be greater. Evidence of this can be seen in the routes from Madrid to Soria and Madrid to Talavera. Both are partially electrified routes, but in the case of Madrid-Talavera, the train must run almost the entire journey at the maximum train velocity of 120 km/h to meet the timetable. In the case of Madrid-Soria the timetable is less demanding, and the train can travel at a lower speed, applying a more energy efficient driving pattern.

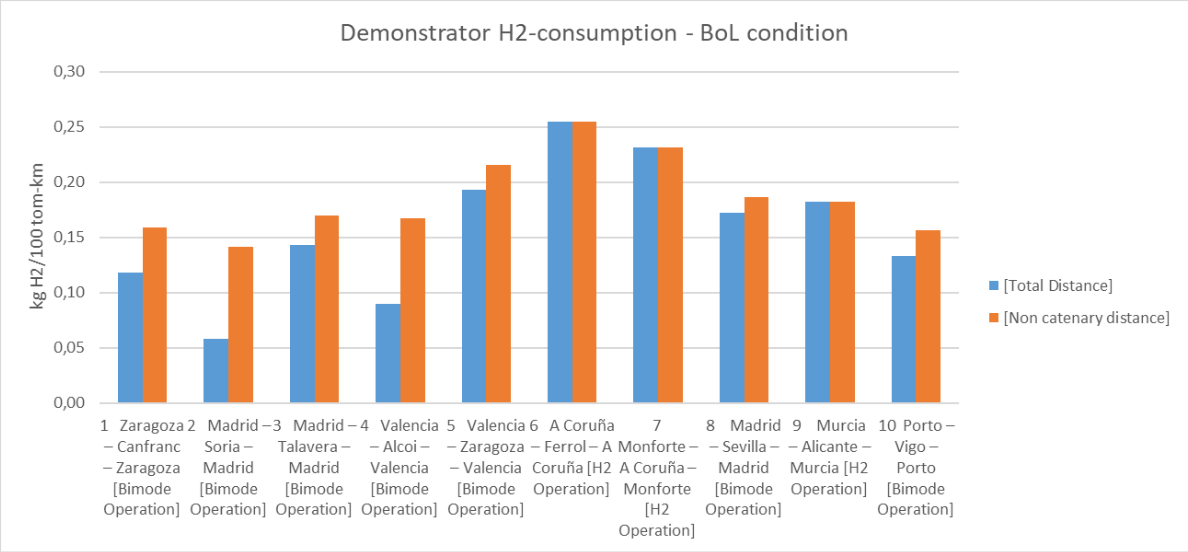

Figure 4: *Simulation results for real tracks – Demonstrator train. BoL condition of battery and fuel cell.*

3.2.3.2 Future train

For the Future train we distinguished between FC BoL and EoL conditions with varying hydrogen and catenary (electricity) demand. As expected the lowest hydrogen consumption occurs during BoL condition. However, it is essential to asses the EoL condition to validate the feasibility of the configuration to fufil the timetable.

BoL conditions

Hydrogen consumption in bi-mode operation (tracks 1, 2, 3, 4, 5, 8, 10, 11) varies between 0.04 and 0.16 kg / 100 ton-km for the total distance (including electrified and non-electrified sections - the train draws its power from the catenary under electrified sections) and 0.10 and 0.18 kg / 100 ton-km if only the non-electrified sections are looked at. In pure H2 operation (tracks 6, 7, 9) the H2 consumption spans between 0.15 and 0.22 kg / 100 ton-km.

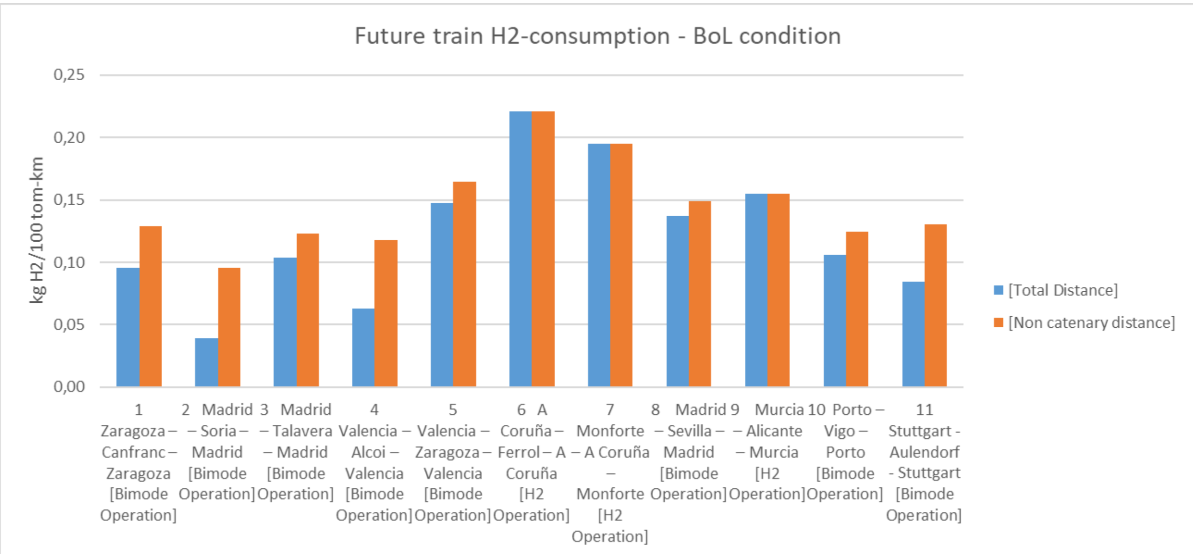

Figure 5: *Simulation results for real tracks – Future train. BoL condition of battery and fuel cell.*

<u>EoL conditions</u>

At EoL condition of the FCHPP (FC and OESS), the hydrogen and electricity demands are higher than in the BoL case.

Hydrogen consumption in bi-mode operation (tracks 1, 2, 3, 4, 5, 8, 10, 11) varies between 0.05 and 0.18 kg / 100 ton-km for the total distance (including electrified and non-electrified sections - the train draws its power from the catenary under electrified sections) and 0.12 and 0.22 kg / 100 ton-km if only the non-electrified sections are looked at. In pure H2 operation (tracks 6, 7, 9) the H2 consumption spans between 0.18 and 0.26 kg / 100 ton-km.

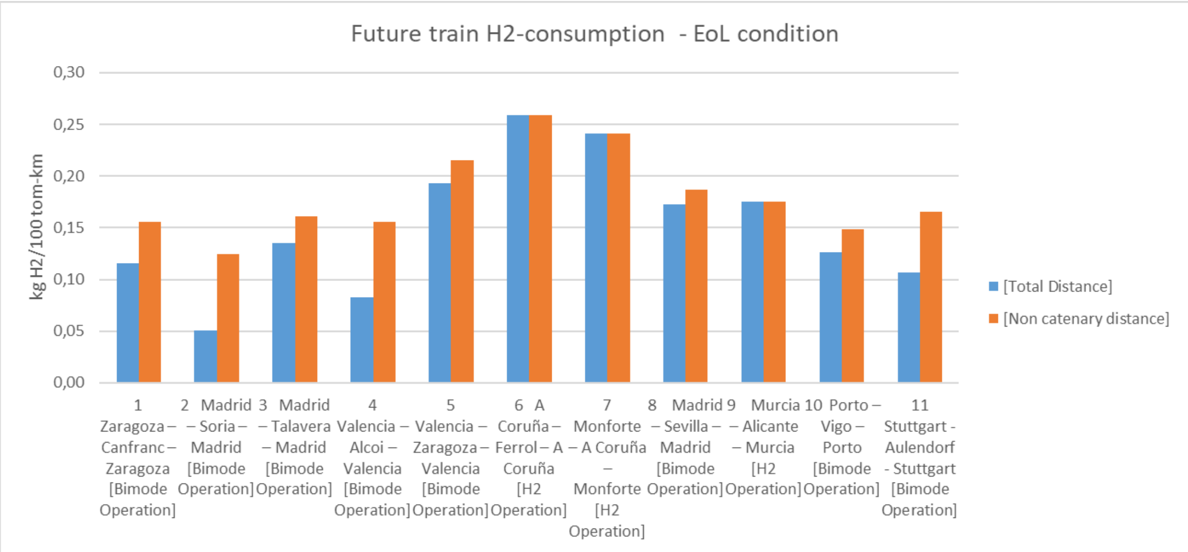

Figure 6: *Simulation results for real tracks – Future train. EoL condition of battery and fuel cell.*

The power and energy requirements of the Future train are more ambitious than those of the Demonstrator train due to its increased weight (longer trainset due to additional passenger car), higher design speed (160 km/h vs 120 km/h), and because it is a commercial service vehicle, thus it has been simulated with passengers and HVAC (the Demonstrator train was simulated also with HVAC but without passengers). Despite this a significant reduction in specific hydrogen consumption was observed for the Future train against the Demonstrator train, ranging from 13% to 32% depending on the track and at BoL condition.

This reduction is primarily due to the improved efficiency of the traction chain and a more precise sizing of the FCHPP has been carried out, considering the battery and FC technology available in 2024. The batteries in question have a notably higher energy density than those of the Demonstrator, increasing the kWh/train ton ratio by 25% in the Future train.

The factors that lead to the H2 consumption reductions seen in Figure 7 are

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- improved efficiency of the traction chain
- more precise sizing of the FCHPP using the battery and FC technology available in 2024
- more battery capacity installed in the Future train than in the Demonstrator train increasing the kWh installed battery capacity / train ton ratio by 25% in the Future train

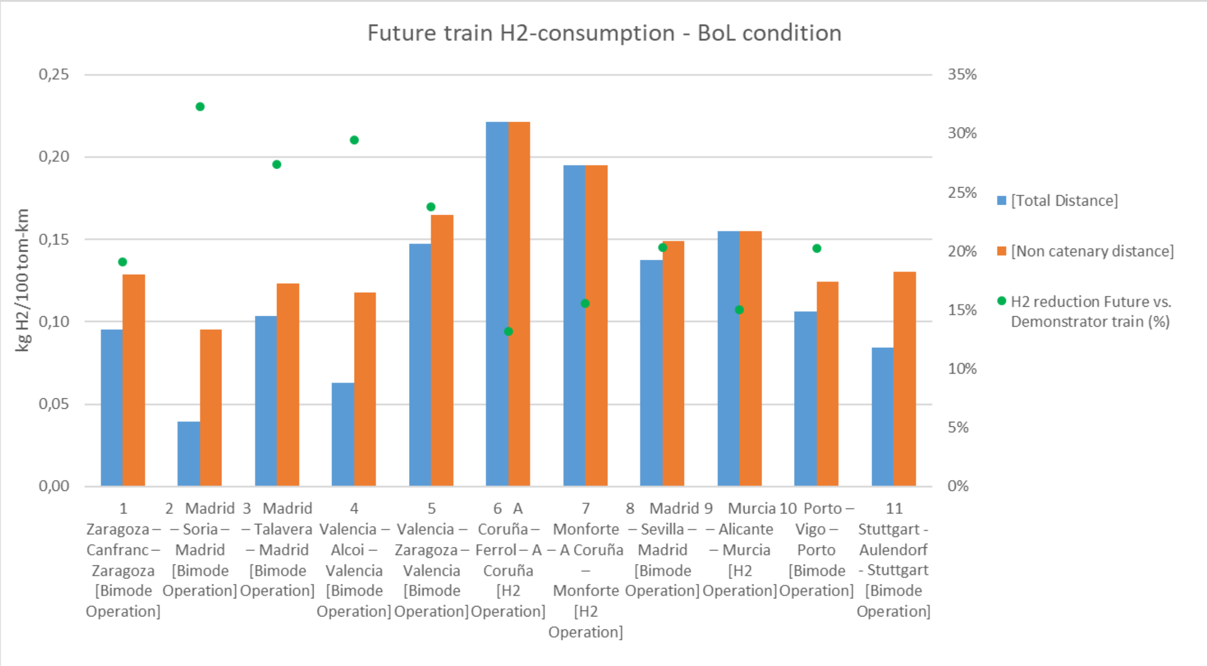

Figure 7: Relative H2 demand reduction of Future train vs. Demonstrator train, simulated for real tracks. BoL conditions.

3.2.4 Simulation results – EN 50591 tracks

SRIA KPI targets (Chapter 1.2) for trains defines the EN 50591 as reference standard under the condition of exclusive hydrogen feed with low demanding power and no HVAC. The SRIA, however, does not mention the specific driving profile to be applied. Further, the specific conditions for calculating SRIA targets are unclear, which complicates a controlled comparison. As will be shown in the following, the hydrogen consumption is highly dependent on boundary conditions. We used the regional profile since it best reflects target application of both the FCH2Rail Demonstrator and the Future train.

The targets set in the SRIA are

- 0.12 kg H2 / 100 ton-km for 2020 (Demonstrator train target)
- 0.11 kg H2 / 100 ton-km for 2024 (Future train target)
- 0.08 kg H2 / 100 ton-km for 2030

Three cases (Case 1, 2, 3) had been simulated for the EN50591 standard, each reflecting the regional profile with coasting (Annex B2, low demand option, without HVAC), applicable to both the Demonstrator and the Future train. These cases were selected because EN50591 standardizes electrification exclusively for electrical multiple units (100% electrification scenarios). Consequently, considering the FCH2Rail project's emphasis on a bi-mode train, it was considered reasonable to simulate scenarios including both non-electrified and partially electrified conditions.

- Case 1: Hydrogen operation while driving, recharging of the batteries at the end station via catenary / charging station (2 minutes of dwell time for recharging– compliant to timetable)
- Case 2: Hydrogen operation while driving, recharging of the batteries at the end station via catenary / charging station (15 minutes of dwell time to fully recharge the batteries)
- Case 3: Exclusive hydrogen mode

Main results

The simulation was performed for the Demonstrator and for the Future train configuration. Table 6 summarizes the results which are described in more detail below. Figure 8 visualizes the results.

Train	Operational Mode	Hydrogen consumption (kg H2/100 ton-km)			SRIA 2021-2027 fuel cell train KPI target (kg H2/100 ton-km)	
		<u>Case 1:</u> H2 operation while driving, 2 min recharging of the batteries at end station	<u>Case 2:</u> BiMode operation with 15 min full recharging of the batteries at end station	<u>Case 3:</u> Exclusive hydrogen mode	2020	2024
Demonstrator train	BiMode	0.11 (BoL)	0.052 (BoL)		0.12	
	Pure H2			0.135 (BoL)	0.12	
Future train	BiMode	0.116 (BoL)	0.039 (BoL)			0.11
	Pure H2			0.126 (BoL)		0.11

Table 6: Simulation results – EN 50591

Pure hydrogen mode

The <u>Demonstrator train</u> has a hydrogen demand of 0.135 kg / 100 ton-km (BoL condition) in pure hydrogen mode.

A comparison of this result against the MAWP targets is not possible because the MAWP target is not mass-dependent and no mass data is given by the MAWP. Therefore we benchmark the simulation data against the SRIA 2021-2027 fuell cell train KPI target.

The hydrogen demand of the Demonstrator train is higher than the SRIA target of 0.12 kg /100 ton-km for 2020.

The <u>Future train</u> configuration yields a reduced hydrogen consumption of 0.126 kg / 100 ton-km (BoL condition) which is near the SRIA 2024 target of 0.11 kg / 100 ton-km.

Bi-mode operation

The Bi-mode FCHPP configuration enables the reduction of the hydrogen demand compared to a pure hydrogen mode through recharging of the batteries when the train is under catenary. This is a major advantage of bi-mode compared to hydrogen-only trains.

Case 1 (hydrogen operation and recharge of the batteries at end station for two minutes) reduces the hydrogen demand of the Demonstrator train slightly to 0.11 kg / 100 ton-km (0.116 kg / 100 ton-km of the Future train respectively) while Case 2 reduces the hydrogen demand of the Demonstrator train further down to 0.052 kg / 100 ton-km (0.039 kg / 100 ton-km of the Future train respectively). The values are given for BoL conditions.

The lower hydrogen consumption in Cases 2 and 3, however, goes hand in hand with a higher electricity consumption drawn from the catenary. But in any case the autonomy can be largely increased in bi-mode operation which is a large benefit. Figure 8 summarizes the simulated consumption values and puts them into perspective to the SRIA KPI hydrogen consumption targets.

To summarize, the Future train has a slightly higher hydrogen demand than the very ambitious 2024 SRIA target for exclusive H2 feed. If the benefit of additional bi-mode operation is considered, the hydrogen SRIA targets for 2024 and 2030 can both be met by the Demonstrator and the Future train easily. This applies to the 15 minute recharging.

However, it is important to note that the SRIA does not clearly specify the boundary conditions associated with the target KPIs. While it refers to the EN50591, it does not specify which track is used as a reference, which timetable is considered (some tracks have two reference timetables), which auxiliaries are included, etc. Another crucial aspect that remains unclear is the hybridization conditions, particularly whether the OESS starts and ends at the same SoC. All these factors significantly influence H2 consumption. Therefore, as long as these conditions remain unclear, it will not be possible to conduct a precise and controlled evaluation of the targets.

Additionally, the EN50591 profile does not reflect real-world conditions which leads to very low and unrealistic hydrogen consumption values. The purpose of the EN50591 is to have an universal standardized benchmark scenario to make trains' energy consumption comparable among each other. In our KPI analysis though, we wanted to discover the autonomy of the FCH2Rail Demonstrator and Future train configurations in real world conditions. Therefore we included real tracks in order to have more representative use cases and service conditions.

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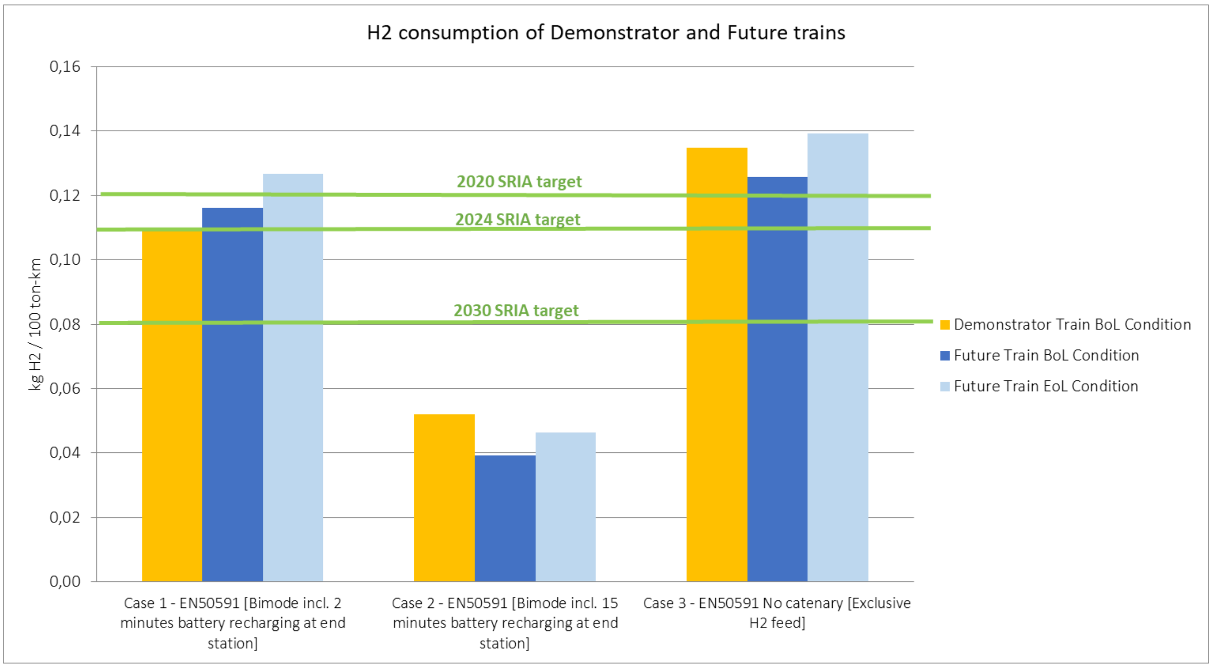

Figure 8: H2 consumption - EN 50591 simulation results versus SRIA targets

3.2.5 SRIA targets against optimized Bi-mode H2 Future train hydrogen consumption

Although the SRIA targets are related to the EN50591 track, Figure 9 provides an informative overview of the consumption of the Future train with respect to these targets. As shown, even though these simulations include HVAC consumption and are based on actual service profiles and topography, consumption in bi-mode (blue bars, considering total distance) generally meets the 2020 and 2024 targets (tracks 1–4 and 10–11). Furthermore, under these same criteria, two of these routes even meet the 2030 target (tracks 2, 3).

The routes that do not meet the targets are those with zero electrification (pure H2 operation) or particularly demanding routes, such as Madrid–Sevilla, which correspond to a high-speed service, and Valencia–Zaragoza–Valencia, which is not only the second-longest route after Madrid–Sevilla but also the most challenging in terms of topography (highest accumulated elevation gain).

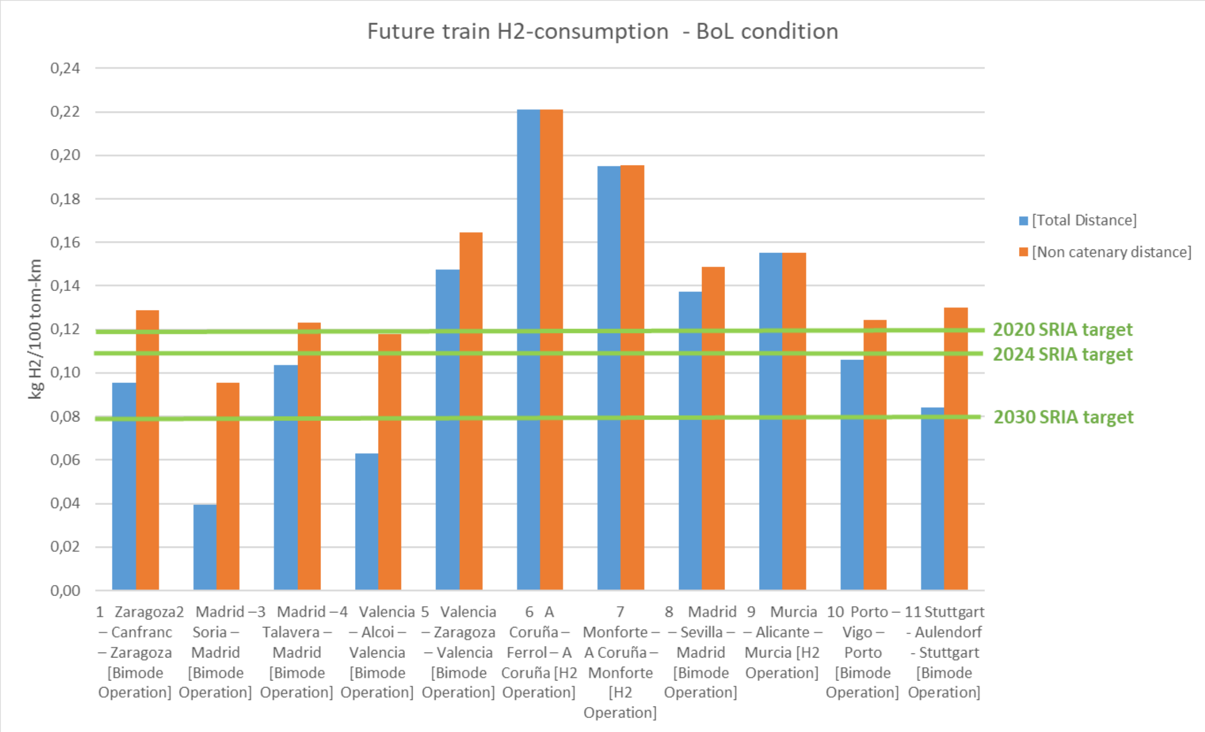

Figure 9: H2 consumption – Real tracks hydrogen consumption simulation results versus SRIA targets (Bi-mode H2 Future train)

3.2.6 HyPac and Absorption AC - Reduction of electric HVAC energy per year and standard carbody (acc. to FINE2)

The Hydrogen Powered Air Conditioning (HyPAC) and the absorption refrigerator (Absorption AC) are both technologies to utilize waste energy from the train to increase system efficiency. The HyPAC uses the pressure energy between the compressed gaseous hydrogen tank and the fuel cell to store it in a metal hydride material, which heats up when hydrogen is absorbed and cools down when hydrogen is desorbed. The absorption refrigerator uses the waste heat of the fuel cell system to drive a thermal compressor with a lithium-bromide and water material pair. Both technologies aim for supporting the passenger compartment HVAC system through reduction of electric energy usage.

In the non-public FCH2Rail deliverable D6.2 which covers the HyPac and Absorption AC in detail simulation studies were conducted. These studies yielded results on the electricity reduction potential of both technologies. Various climatic testcases were defined and simulated for two Spanish tracks (Zaragoza-Canfranc-Zaragoza and Madrid-Talavera-Madrid).

Between 0.6 and 8.07 MWh/year can be saved per standard car body. The autonomy on non-electrified sections can be increased by 48 – 125 km.

Parameter	Unit	Madrid -Talavera	Zaragoza - Canfranc
Electric energy demand of a standard vapor compression refrigeration system (VCRS)	MWh/y	20.74 – 43.88	20.74 – 43.88
HyPac - **Reduction** of electric HVAC energy per year and standard car body (acc. to project FINE2)	MWh/y	2.29 – 8.07	2.11 – 7.64
HyPac – Increase of Autonomy	km	48.48- 75.14	100.83 – 125.82
Absorption AC - **Reduction** of electric HVAC energy per year and standard car body (acc. to FINE2)	MWh/y	1.28 – 6.10	0.60 – 2.99
Absorption AC – Increase of Autonomy	km	57.12 – 63.89	50.23 – 65.71
Waste Heat Utilization – Reduction of electrical energy	MWh/y	12.44 – 25.69	12.30 – 24.11

Table 7: Electric energy demand savings and autonomy increase of HyPAC and Absorption AC systems per car body

Table 7 summarizes the results for the tracks Zaragoza - Canfranc and Madrid - Talavera for one standard car body.

The climate zones 1 – 2 according to EN 50591 have been considered for both tracks and the range within one KPI is explainable with different cooling capacities, as the standard system shows. There is no difference between the tracks in the standard system, as a vapor compression refrigeration system (VCRS) is independent from the traction power and powertrain system of the train. However, the HyPAC system's and the Absorption AC systems results vary in`between the tracks, as they are coupled with the hydrogen tanks and fuel cell. An annual milage cannot be stated here as the methodology described in the EN50591 standard consideres a typical annual consumption with 7,300 hours of commercial, non-commercial and parking operation. As of now the state-of-the-art HVAC systems were independent from the annual mileage, therefore a relation to this is not suitable. Besides considerable energy saving potentials, also range increases are foreseen. The increase of autonomy is calculated with *ITINER*, which is CAF Group's in-house simulation tool for optimizing energy use and hybridizing on-board energy systems, based on vehicle, track and operational characteristics, among other functionalities (speed profile calculation/optimization, power train sizing, etc). Here, the auxiliary load was reduced by the value of potential energy reduction of both technologies for two testcases. These testcases have the highest cooling capacity and show the maximum range increases with the use of these systems. Here we show the potential increase of autonomy for the climatic use cases with the highest cooling capacity (Testcase 7 in Climate Zone 1 and 2 EN50591). However, there is no simulation data for the EN50591 regional track available, as the authors decided that the Madrid – Talavera and Zaragoza – Canfranc lines give a more realistic picture of the potential energy savings.

The last line of the table shows the potential energy savings by using the waste heat from the cooling circuit of the fuel cell system. An electric heater with an efficiency of 1 has been assumed as the conventional reference system.[1] The figures show that it is recommended to use the waste heat from

[1] An efficiency of 1 is a conservative assumption to calculate the potential energy savings by using the fuel cell's waste heat. In reality the efficiency is below 1 and the savings will be even higher.

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the fuel cell as this has even a higher reduction impact than the cooling cases (HyPac and Absorption AC) against the conventional VCRS (vapor compression refrigeration system).

3.3 FC system availability (Uptime)

	Parameter						
No	**SRIA 2021-2027 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
14	FC system availability (Uptime)	%	94	97	>99	FC system availability	%
No	**MAWP 2014-2020 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
1	Availability	%	94	97	>99	FC system availability	%

The SRIA target for train availability related to the FC system for 2024 is 97 %. Generally, the availability target of a FC train fleet is the same as for a EMU fleet. In the FCH2Rail project the demonstrator train has so far proven a 100 % availability and so has the fuel cell system. A test program with a single train is obviously not comparable to a day-to-day service of a whole commercial fleet.

The conclusion that can be drawn from the testing experience is that the fuel cell and battery systems are sufficiently mature to meet all the test milestones. It should be noted that it has on no occasion been necessary to cancel the tests for reasons due to the Demonstrator. Consequently, in terms of reliability and availability, the hybrid technology implemented in the FCHPP is promising, pending testing of its performance in a fleet as a whole.

3.4 FC module volumetric density

	Parameter						
No	**SRIA 2021-2027 fuel cell train KPI**	Unit	SoA 2020	Target 2024	Target 2030	**FCH2Rail designation**	**Unit**
8	FC module volumetric density	kW/m³	n/a	53	>60	FC module volumetric density	kW/m³

The Fuel Cell Module used for the FCH2Rail demonstration train has a volumetric density of 243 kW/m^3 (with Fuel Cell Module definition as shown in Figure 10).

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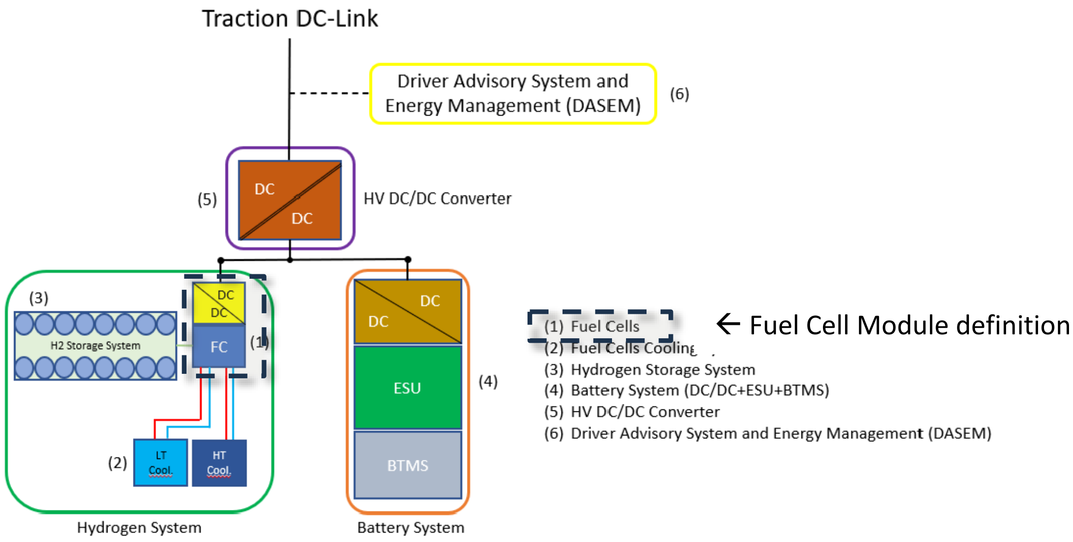

Figure 10: Fuel Cell Module within FCHPP

3.5 FC module gravimetric density

	Parameter						
No	SRIA 2021-2027 fuel cell train KPI	Unit	SoA 2020	Target 2024	Target 2030	FCH2Rail designation	Unit
9	FC module gravimetric density	kW/ton	n/a	135	>160		kW/ton

The Fuel Cell Module used for the FCH2Rail demonstration train has a gravimetric density of 320kW/ton (with Fuel Cell Module definition as shown in Figure 10).

3.6 Range before refueling (autonomy)

Figure 11 shows that in pure H2 operation (tracks 6, 7, 9), the Demonstrator train has a maximum autonomy, or range before refueling, of 496 to 692 km and in bi-mode operation (tracks 1-5, 8, 10) the autonomy is 585 km to 896 km, calculated for the useable hydrogen storage amounts.

In pure H2 operation, the Future train's maximum autonomy is 642 km to 914 km and in bi-mode operation between 862 km to 1485 km.

The values are given for BoL conditions both for the Demonstrator and the Future train.

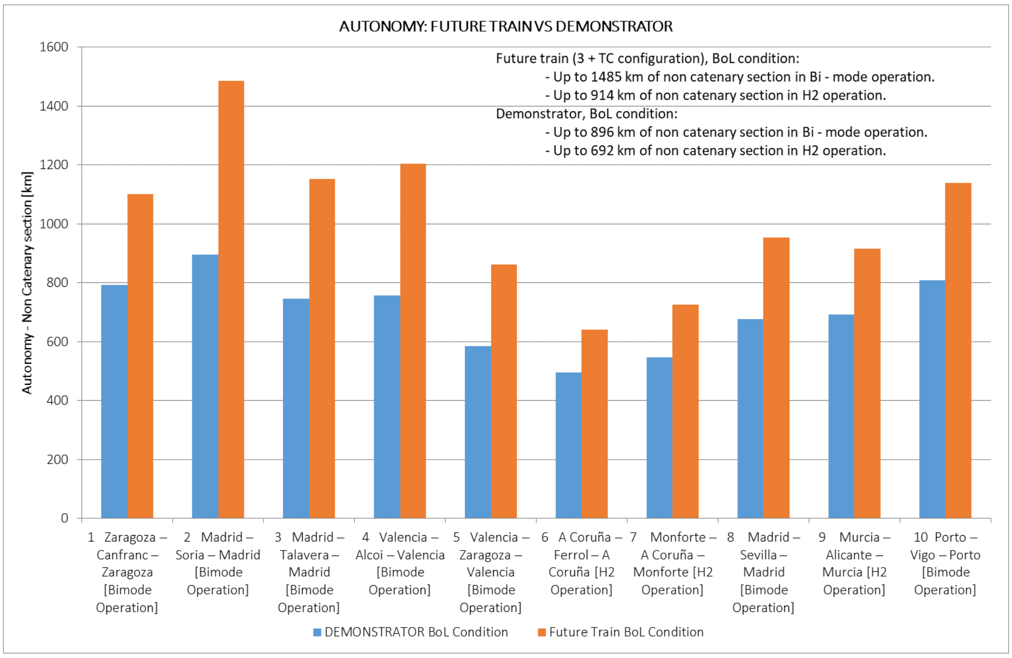

Figure 11: Autonomy of Future train on real life tracks

For the EN50591, the maximum autonomy of the Demonstrator train in BoL conditions is 1,151 km (Case 1), 2,425 km (Case 2) and 938 km (Case 3), see Figure 12. Autonomies of the Future train in BoL conditions are 1,221 km (Case 1), 3,616 km (Case 2) and 1,127 km (Case 3). The Future train with its larger battery capacity, compared to that of the Demonstrator train, proves advantageous in Case 2 with a recharging time of 15 minutes.

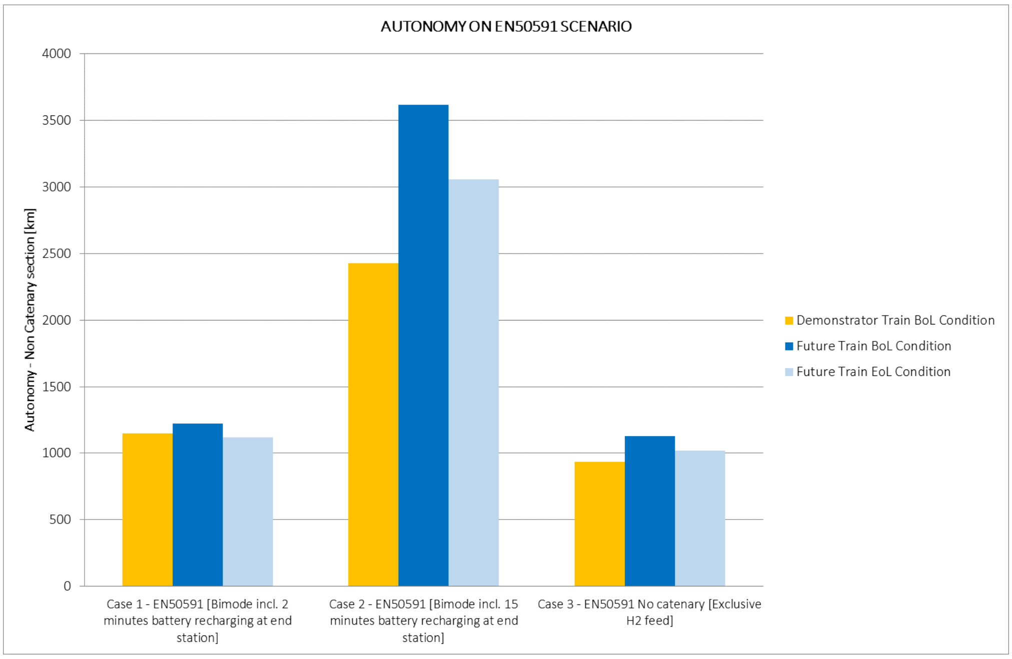

Figure 12: EN 50591 simulation results – Demonstrator and Future train

A comparison of the FCH2Rail Demonstrator and of the Future train's autonomies against DMU values is done in Chapter 4.

3.7 Refueling time

In the FCH2Rail project the aim was to develop a transportable HRS to refuel the Demonstrator train. In the following the resulting refuelling downtimes are displayed.

3.7.1 Demonstrator train's refuelling times

Refueling tests have been performed with two on-board hydrogen storage modules installed on the Demonstrator train. Each hydrogen storage module consists of 16 cylinders type III of 205 L each (80 kg of hydrogen at 350 bar per hydrogen storage module). The hydrogen storage modules can be isolated / divided in two other smaller submodules of 40 Kg of hydrogen at 350 bar each (8 cylinders). Refuelings are independent of each other; the refueling of both hydrogen storage modules must be done successively. Refuelings had been carried out from a 300 bar tube trailer storage without a chiller and a 10 meter hose.

The HRS was operated in three different locations around Spain (Zaragoza, El Goloso near Madrid and Vigo, Pontevedra). During refueling, the flow rates achieved in dispensation varied depending on the initial ambient temperature, the initial pressure of the train storage at the beginning of the refueling as well as of the HRS operational mode (manual or automatic). Besides, as a regular rule, flow rates reached in second dispensing processes were lower than the preceding ones, due to the then lower hydrogen pressure on the tube trailer.

Throughout the dispensing process the flow rate is not constant. The average flow rate has been calculated by using the means among all the flow rate values registered (each 5 or 10 s). Flow rates ranged between 11.54 to 19.44 g H_2/s.

For a particular refueling, for instance on first of October (Zaragoza), with an initial ambient temperature of 8º C, an initial pressure on the train storage around 10 bar, and automatic working mode, the average flow rates for the first and second dispensation were 18.34 and 13.87 g H_2/s respectively.

From the flow rate range of the refuelling tests carried out in the framework of the FCH2Rail project, it can be stated that the average refueling speed was 0.69 to 1.17 kg H2/minute. If these values were extrapolated, a full refueling of the Demonstrator train containing 160 kg of hydrogen would last between 137 and 231 minutes.[2] That extrapolation is, however, only a theoretical value to illustrate the general performance of the research HRS applied in the FCH2Rail project. In practice, the refueling time could be even longer.

The HRS used for the Demonstrator train tests is a modular and transportable prototype, capable of refuelling light- and heavy-duty vehicles. It has not been exclusively and specifically developed for train refuelling and is not a high-performance HRS for operational timetable operation, which explains the relatively low refuelling speed. Nevertheless, it fulfilled the operational requirements of the project.

[2] The minimum and maximum values related to the time [min] needed to refuel 1 Kg of hydrogen are 0.69 and 1.17 (at a feeding pressure of 300 bar). Multiplied by the total hydrogen storage mass of 160 kg this translates 137 and 231 min. No train maneuvering times are included in these refuelling times.

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The refuelling time shown so far in this section has been obtained from an experimental point of view. However, it has been considered interesting to complete it with the results of simulations after optimization of the HRS.

3.7.2 Achievable Generic bi-mode refueling speed according to market observation and standards

This chapter aims to complement the above results derived by testing in the FCH2Rail project by state-of-the-art 35 MPa refueling speeds observed in commercial or industrial settings given the limited data that is disclosed by relevant stakeholders so far.

The HRS is responsible to ensure a safe refueling, which means that pressure and temperature in the hydrogen storages have to be kept within specific boundaries. Relevant parameters to ensure this safety are the ambient temperature, the refueling speed, the end pressure and potentially a hydrogen pre-cooling. Refueling protocols define these parameters.

The concrete refueling speed depends on parameters such as the vehicles' vessel specification and the refueling protocols. The refueling speed is usually confined in order to prevent the permeability of the liner over a long period of time. Another parameter is the refueling temperature. A pre-cooling of the hydrogen (e.g. to -40°C) enables a reduction of refueling times. Rail vehicle 35 MPa refueling is orientated towards the SAE J2601-2 (SAE International 2023) which defines for fast refueling a maximum of 120 g/s (7.2 kg/min). The need for refueling protocols for rail vehicles was identified in the German standardization roadmap (Projektpartner Normungsroadmap Wasserstofftechnologien 2024).

The TIR J2601-5 (SAE International 2024) are directed towards the refueling of medium- and heavy-duty vehicles and define peak flow rates from 60 g/s (3.6 kg/min) to 120 g/s (7.2 kg/min) for 35 MPa and up to 300 g/s (18 kg/min) for 70 MPa CGH2. It is not yet clear, however, whether this TIR and later SAE norm will be applied to rail vehicles.

These peak flow rates cannot be reached continuously during the refuelling as the mass flow increases slowly with the beginning of a refuelling process. Consequently, the average mass flow needs to be lower than the presented peak values. If on average a refuelling speed of 4 kg H2/min for 35 MPa CGH2 could be achieved, the refuelling of 2 x 80 kg of hydrogen at parallel refuelling with two dispensers would take 20 minutes. But this remains a theoretical value unless being proven in operational practice.

Hydrogen refuelling time targets of 15 minutes have repeatedly been reported in the railway sector. However, there is no transparent or comparable data available to the authors of this report under what conditions and for which hydrogen amounts these 15 minutes apply specifically.

Although HRS operators and rolling stock system integrators are generally hesitant to report achieved refueling times there is evidence to suggest that as of today the achievable average refueling speed seems to be usually substantially below 120 g/s, especially if there is no pre-cooling foreseen. However, taking into account technological progress and experience building in hydrogen refueling during commercial operation, a maximum refueling speed of 7.2 kg H2 / min is within reach.

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3.7.3 Achievable Refueling times of Demonstrator Train and Future Generic Bi-mode H2 train

To sum up this chapter:

1) Demonstrator train H2 refueling:

    - The refueling speed achieved in the FCH2Rail project with the transportable HRS was 0.91 to 1.44 min / kg H2 (or 0.69 to 1.1 kg H2 / min) refueled which would translate to 145.6 to 230.4 minutes to refuel 160 kg of hydrogen.

2) Future Generic Bi-mode H2 train:

    - If an average refuelling speed of 4 kg H2/min (35 MPa CGH2) could be achieved, the refuelling of 2 x 80 kg of hydrogen at parallel refueling with two dispensers would take 20 minutes.

3.8 KPI comparison of FCH2Rail project against Roland Berger Fuel Cell study

The call for proposal of the funding program demanded that the then FCH2Rail project must benchmark its KPI also against a Roland Berger study on fuel cell trains. In 2019 Roland Berger had produced three reports of which Report 1 and Report 2 are relevant in the context of this comparison (Europe's Rail Joint Undertaking 2019). The following table lists technical parameters issued in these two reports. By its nature these parameters are mostly not KPI but technical specifications instead. The data issued by Roland Berger is a compilation of OEM specifications, calculations and assumptions and were derived for specific use cases. Some data are, however, confined in its comparability, for instance the Roland Berger data is not related to the train mass.

KPI / Technical Specification in Roland Berger reports	Unit (Roland Berger reports)	Roland Berger Report 1	Roland Berger Report 2	FCH2Rail Demonstrator Train
Type of train		FC hybrid train	BiMode H2 train	BiMode H2 train
Track		General	Zaragoza-Canfranc	Zaragoza-Canfranc
Configuration		2 cars	4 cars	3 cars (incl. 1 technical car)
Power rating	kW	800-1000	1450	1190 (in FCHPP mode)
Tractive effort	kN	90	147	No data available
Max. speed	Km/h	140	110	120 in FC mode
Pass. capacity	Seats	120	270	No passenger operation
Acceleration	m/s^2	0.8-1.0		0.7 (0-100 km/h)
Hydrogen tank	kg	250	350	160
H2 consumption	kg/km	0.25-0.3	0.31	0.2 (only in catenary-free section)
Max. range	km	1000	550	800
Lifetime	Years	30	30	No data available
Tractive motors	kW		925	1400
Compressor	kW		97	No data available

Battery capacity	kWh	270	238.48 (installed, BoL)
Auxiliary and hotel power	kW	463	76 (average power)
Fuel cell size	kW	410	480 (6 fuel cell modules)
Space	m³	19	No data available
Weight	t	75	No data available

Table 8: KPI / Technical Specification of Roland Berger 2019 study compared to FCH2Rail Demonstrator Train

4. Comparison Bi-mode H2 train vs. DMU (overall competiveness)

This chapter aims to assess the bi-mode H2 train competitiveness against diesel multiple units (DMU).[3] The analysis is confined to technical and operational KPI which can be used for a direct comparison. Economic KPI are out of scope of this Deliverable and are subject to the non-public FCH2Rail Deliverable 6.3. The most relevant KPI which are directly comparable are the range before refueling (autonomy) and the refueling downtime. Results and detailed explanations are given in the subsequent subchapters.

4.1 Range (autonomy)

For the derivation of the range of a DMU the average diesel consumption and the diesel storage tank capacity is required.

4.1.1 DMU autonomy

Spanish DMU:

As a general orientation, the range of Renfe DMUs dedicated for Iberian gauge (S 594, S 596, S 598, S 599) is 1,000 km according to D1.1 of the FCH2Rail project (Herwartz and Kühlkamp 2022b). But there are more detailed data available on a per-route-level available (Table 9). The autonomies are between 805 km and 1,485 km depending on the route and the DMU series operated on these routes.

[3] The reason why we used conventional DMU instead of bi-mode diesel trains as comparison base is that in Spain no bi-mode diesel trains are in operation that are comparable in terms of service profile and tracks operated on or in terms of technical parameters. In fact, the existing Renfe class S 730 is a 9 coach plus 2 locomotive plus technical car high-speed bi-mode train composition dedicated to high-speed train operation mainly and closer to middle range train operation (Madrid-Extramadura).

DMU Series	Route	Train mass (t)	Diesel tank capacity (L)	Diesel consumption (mean) (L/km)	diesel storage capacity (l)	autonomy (km)
S596	Zaragoza-Canfranc	51	900	0,873	900	1031
S599	Madrid-Talavera-Extramadura	157	2 x 1400[1]	1,886	2800	1485
S594	Madrid-Talavera-Extramadura	97	2 x 1000	1,628	2000	1229
S599	Zaragoza-Teruel	157	2 x 1400[1]	2,307	2800	1214
S594	Ourense-Santiago	97	2 x 1000	2,483	2000	805
S599	Madrid-Soria	157	2 x 1400[1]	2,114	2800	1325
S594	Madrid-Soria	97	2 x 1000	1,568	2000	1276

[1] Series S599 has 2 tanks dedicated for the traction engines and 1 tank dedicated for the auxiliary engines. Diesel consumption values (mean) of the S599 encompasses only diesel consumption of the traction engines.

Table 9: Renfe diesel train consumption and autonomies

German DMU:

Based on German field data, the consumption of DMU ranges from 1.08 to 1.57 l/100 ton-km (Bombardier Talent, Stadler RegioShuttle, Alstom Coradia Lint41, Siemens Desiro Classic), which translates to an autonomy of 1,290 km to 2,100 km (diesel storage capacities are usually 1,000-1,600 l per train). Daily operational mileages of DMU in Germany usually span from 300 to 1,200 km which is considerably below the train autonomies (Pagenkopf et al. 2018). DMU are usually refueled every 1-3 days, typically during the night-time operating break.

4.1.2 Bi-mode H2 train autonomy

The maximum autonomy of the Demonstrator train in exclusive hydrogen mode is between 496 and 896 km depending on the service profile and track while the Future train reaches autonomies of 642 up to 1,485 km (see Chapter 3.6).

4.1.3 Autonomy comparison

Table 10 and Figure 13 summarize the autonomy ranges of Spanish and German DMU and the achievable autonomy of the FCH2Rail Bi-mode H2 train configurations against the targets set by operator Renfe.

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Powertrain	Min autonomy (km)	Max autonomy (km)	Renfe autonomy H2 train target range (km)
DMU Spain	805	1485	
DMU Germany	1290	2100	
Bi-mode H2 Demonstrator train	496[a)]	896[b)]	650 … 1000[c)]
Bi-mode H2 Future train	642[a)]	1485[b)]	650 … 1000[c)]

Table 10: DMU vs. Bi-mode H2 train autonomy,
a) A Coruna – Ferrol (Pure H2 operation), b) Madrid-Soria (Bi-mode operation),
c) Renfe autonomy targets (catenary + non-catenary sections) for Iberian gauge and for long and medium distances according to (Munoz Vicent and Fernandez Del Rey 2024)

The data show that typical autonomies of DMUs are still larger compared to the autonomies of Bi-mode H2 trains by a factor of about 2 to 2.5 depending on the specific type of train and applications. The data shows, though, that the autonomy targets on hydrogen multiple units (both fuel cell hybrid and Bi-mode configurations) defined by the Spanish railway undertaking Renfe in FCH2Rail D1.3 (Munoz Vicent and Fernandez Del Rey 2024)) is fulfilled by the Demonstrator train partly and by the Future train entirely. It must be noted that the cases where the Demonstrator train does not reach the Renfe H2 train autonomy targets are pure H2 operation tracks.

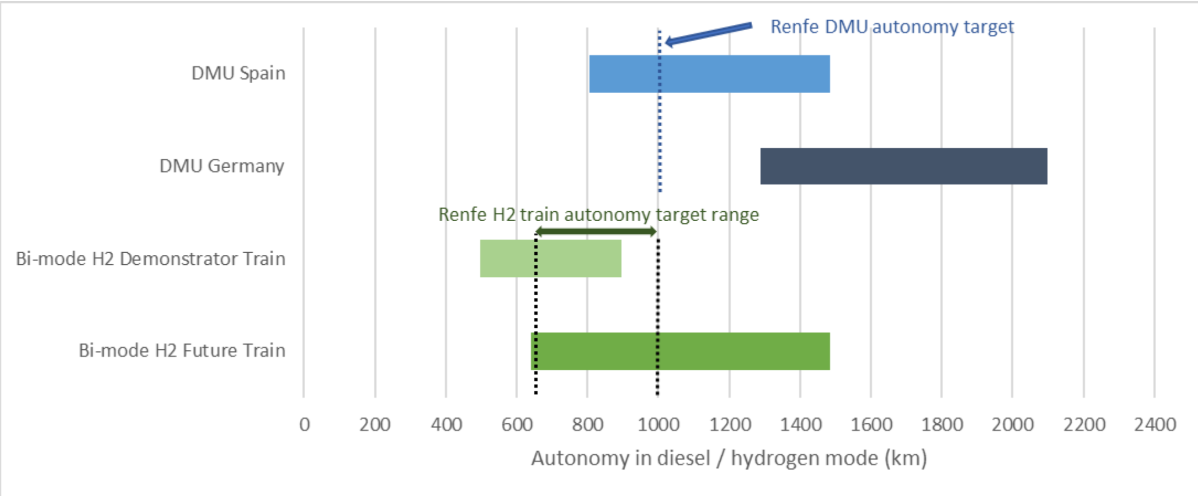

Figure 13: *Autonomy ranges of DMU and Bi-Mode H2 multiple units in diesel / hydrogen mode vs. autonomy targets (catenary + non-catenary sections)*

While the former comparison can give only a general and not normalized comparison, the comparison gets more precise when comparing autonomies for specific lines where measured DMU data (Table 9) and simulated Bi-mode H2 train data is available. Line-specific data both for DMU and H2 train is available for the routes Zaragoza-Canfranc and Madrid-Soria (see Table 11). For Zaragoza-Canfranc there is data for the DMU class S596 while for Madrid-Soria autonomy data is available for two DMU classes (S594 and S599).

	Distance round trip (km)		**DMU autonomy (km)**			**Bi-mode H2 autonomy (km)** (non-catenary sections only)		**Trackside electrificat ion degree**
Route	catenary + non-catenary	non-catenary only	S594	S596	S599	Demons-trator BoL	Future Train MoL	
Zaragoza-Canfranc-Zaragoza	442	327		1031		794	1005	26%
Madrid-Soria-Madrid	492	202	1276		1325	896	1302	59%

BoL : Begin-of-life conditions of fuel cell and battery, MoL : End-of-life conditions

Table 11: Train autonomies of specific lines. DMU: measured. Bi-mode H2: simulated

Autonomy of the Bi-mode Demonstrator train on the Zaragoza-Canfranc route is lower than that of the incumbent DMU series S596. But the Bi-mode H2 Future train is on par with the DMU. On the Madrid-Soria route only the Bi-mode H2 Future train (and not the Bi-mode H2 Demonstrator) is on par with both the S594 and with the S599 in terms of autonomy (Figure 14).

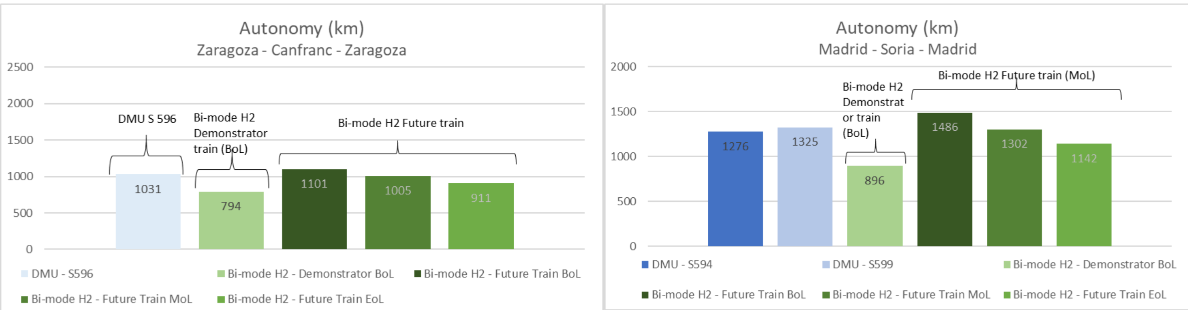

Figure 14: *Autonomy of DMU (blue) and Bi-Mode H2 multiple units (green) on lines Zaragoza – Canfranc and Madrid - Soria*

The picture is shifting clearly in favour of the Bi-mode H2 train configurations when the number of round-trips before refueling is looked at. While running under overhead catenary, hydrogen resources remain unused which increases the autonomy accordingly. Zaragoza-Canfranc has a 26 % electrification degree of the track length and in the case of the track Madrid-Soria it is 59 % (Figure 15).

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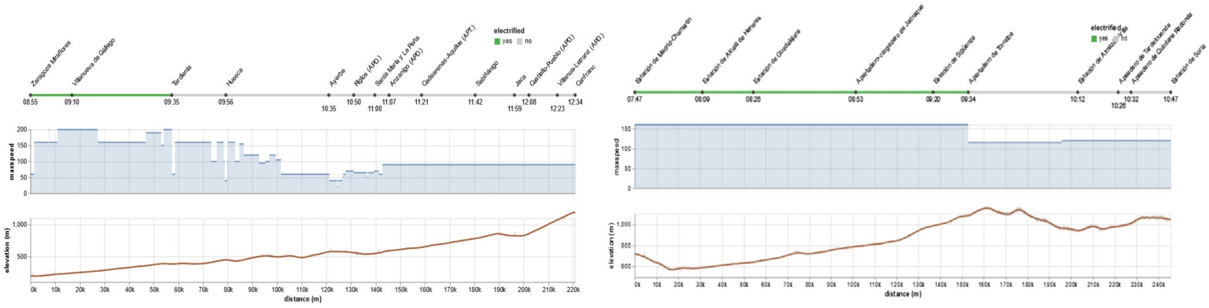

Figure 15: Route profile Zaragoza-Canfranc (left) and Madrid-Soria (right). Electrification section in green. Source: (Herwartz and Kühlkamp 2022a)

Consequently, the number of achievable Bi-mode H2 train round trips is higher both for the Demonstrator and the Future train than the achievable round trips of the DMUs in both lines as Figure 16 demonstrates. That results in the same or even better operational autonomy of Bi-mode H2 trains than those of the incumbent DMUs, even in EoL conditions of fuel cells and batteries.

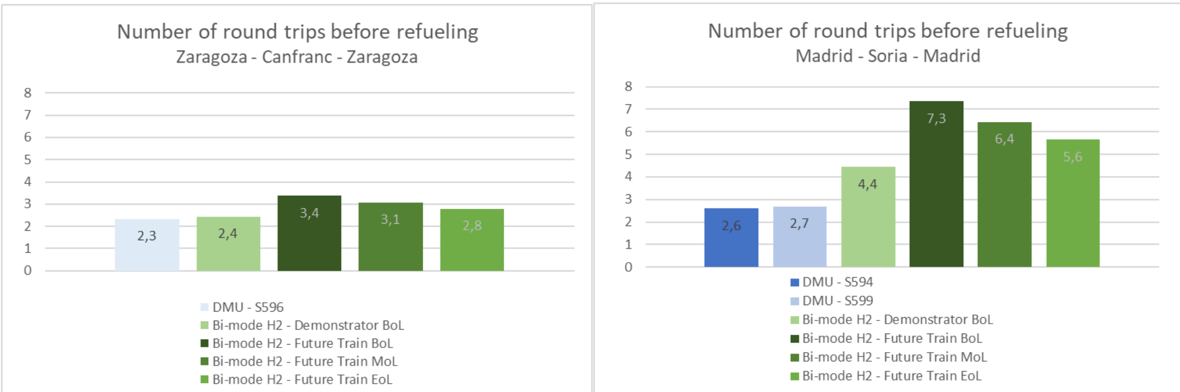

Figure 16: Achievable round trips before refueling of DMU (blue) and Bi-Mode H2 multiple units (green) on lines Zaragoza – Canfranc and Madrid - Soria

Interpretation of the results

The autonomy of the Bi-mode H2 Demonstrator train is lower than today's DMU trains, while in certain situations the Bi-mode Future train's autonomy surpasses that of some DMU's. But the autonomy is competitive to DMU trains for day-to-day operation in any case because,

a) the Demonstrator train is not optimized in terms of H2 storage capacity compared to the Future train and
b) Bi-mode trains by concept have a limited H2 storage compared to pure fuel cell hybrid trains because of the dual-powertrain technical equipment needs. But Bi-mode trains have the advantage of reducing the hydrogen demand through their ability to power the train by

drawing electricity from the wire in electrified sections. Thus, Bi-mode H2 trains yield a larger number of achievable round trips before refueling than DMU do.[4]

4.2 Refueling time

4.2.1 DMU refueling downtime

A typical refueling mass flow for diesel trains is 150 l/min per refueling nozzle (DB refuelling standard BN 411 013-02 from 2001). With parallel refueling and a combined DMU tank capacity of 2 x 750 l, this translates to 5 minutes minimum refueling time. Renfe confirmed that 15 minutes is a typical refueling time of a diesel multiple unit. This figure includes both the pure refueling process and the time needed for preparatory measures (e.g. driver leaving the driver's cabin, moving the train etc.).

4.2.2 Bi-mode H2 train refueling downtime

To refuel the Future Generic Bi-mode H2 train and assuming a parallel refueling using two dispensers at a time, 2 x 80 kg of hydrogen could be refueled in 20 minutes if an average refueling flow rate of 4 kg H2/min which is below the maximum value of 7.2 kg H2/min of the SAE 2601-2 HD is assumed. These times do include only the pure refueling process. If an additional 10 minutes is assumed for refueling preparatory measures, the refueling times would be 30 minutes respectively.

4.2.3 Autonomy gained in km per minute of refueling comparison

The last two colums in Table 12 display the time required for full refueling and the autonomy gained in km for each minute of refueling for Renfe DMU trains on different tracks. The results show that for each minute of refueling between 120.8 and 191.3 km of autonomy can be refueled.

[4] However, that does not necessarily mean that Bi-mode H2 trains would yield larger number of achievable round-trips than Bi-mode DMU trains would. On the contrary, since hydrogen storage systems are inferior to diesel storage systems in terms of energy density, Bi-mode DMU trains will likely surpass Bi-mode H2 trains in terms of range.

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DMU Series	Route	Diesel tank capacity (L)	Diesel consumption (mean) (L/km)	autonomy (km)	**Time to complete refuelling (min) at 150 l/min**	**Autonomy gained in km per minute of refuelling**
S596	Zaragoza-Canfranc	900	0.873	1031	6	171.8
S599	Madrid-Talavera-Extramadura	2 x 1400[1]	1.886	1485	9.3	159.1
S594	Madrid-Talavera-Extramadura	2 x 1000	1.628	1229	6.7	184.3
S599	Zaragoza-Teruel	2 x 1400[1]	2.307	1214	9.3	130.0
S594	Ourense-Santiago	2 x 1000	2.483	805	6.7	120.8
S599	Madrid-Soria	2 x 1400[1]	2.114	1325	9.3	141.9
S594	Madrid-Soria	2 x 1000	1.568	1276	6.7	191.3

[1] Series S599 has 2 tanks dedicated for the traction engines and 1 tank dedicated for the auxiliary engines. Diesel consumption values (mean) of the S599 encompasses only diesel consumption of the traction engines.

Table 12: Renfe DMU train achievable refuelling times and autonomy gained in km per minute of refueling

An important KPI to compare is the refueling downtime. Energy demand and refueling characteristics differ from DMU to H2 trains and also among the rolling stock types and the services the trains are serving which is why the operational comparibility is limited here.

Therefore we transferred the data to a normalized KPI which is *Autonomy gained in km per minute of refueling* (see Table 13). The results show that a Bi-mode H2 Future train with an average refueling speed of 4 kg H2/minute reaches 32.1 to 74.3 km of autonomy gained per minute of refuelling which is still considerably lower than that of DMU trains (120.8 to 191.3 km autonomy per minute of refuelling). This lower autonomy to refueling time relation compared to DMU trains becomes less relevant, however, if refueling is done at operation breaks during nights. Also, Bi-mode trains do not require greater autonomies than non-bi-mode trains.

	unit	DMU	Bi-mode H2 – Demonstrator train	Bi-mode H2 – Future train
type of refuelling station		conventional diesel refuelling station	Transportable FCH2RAIL demonstrator HRS	HRS with 4 kg H2/min on average
refuelling speed	l Diesel or kg H2/minute	150	0.69…1.17 *(measured in project)*	4 *(assumption)*
refuelling amount	l Diesel or kg H2	2x1000 … 2x1400 (parallel refuelling)	2 x 80 *(successive refuelling)*	2 x 80 *(parallel refueling)*
Refuelling downtime (only refuelling process)	minutes	6…9.3	184 (137…231) *(extrapolated)*	20
Autonomy at full refuelling	km	805…1485	496[a)] …896[b)]	642[a)]…1485[b)]
Autonomy gained in km per minute of refuelling	km autonomy / minute refuelling	120.8…191.3	2.7[a)] …4.9[b)] *(extrapolated)*	32.1[a)]…74.3[b)]

a) A Coruna – Ferrol (Pure H2 operation), b) Madrid-Soria (Bi-mode operation)

Table 13: Autonomy gained in km per minute of refueling (calculated)

5. Conclusions

One of the initial goals at the start of the project was to demonstrate that the hydrogen fuel cell technology works in trains in the Spanish and Portuguese rail network. During the course of the project this could be verified. Beyond that we were able to demonstrate that the FCH2Rail and FCHPP technology can also compete with diesel trains for several technical and operational KPI investigated in this Deliverable.

With regard to the KPIs analysed in this report the results can be summarized and interpreted as follows.

FC stack lifetime:

The assessment of the fuel cell stack lifetime is based on the Future Bi-mode train configuration according to targets defined by the FCH2Rail consortium: it should be possible to keep the existing train maintenance intervals. For that purpose a minimum of 25,000 operational hours must be achieved before any repair, with the ideal target being 40,000h. Based on simulations results the FC stack lifetime varies from 30,000 to 40,000h, demonstrating that the minimum target can be reached for all tracks and `that with todays generation of fuel cells the ideal target is already within reach.

It should be noted that the fuel cell module is just one component of the FCHPP. Besides the train operational profile, the configuration of the FCHPP will also impact the fuel cell module lifetime. Hence, it is important at the start of a commercial project to understand all requirements from the operator point of view to make various FCHPP iterations considering the trade-off between packaging area, CAPEX and OPEX.

Assessing the fuel cell lifetime according to the SRIA target does not make sense without a pre-defined fuel cell load pattern.

Hydrogen Consumption:

The SRIA 2021-2027 targets are 0.12 (0.11, 0.08) kg H2/100 ton-km for the years 2020 (2024, 2030 respectively). Using validated simulation data for real tracks, both the Demonstrator train and the Future train have higher specific hydrogen demands than those determined in the SRIA targets if only the non-electrified sections are looked at (0.10 to 0.26 kg H2/100 ton-km). However, when looking at the complete (electrified and non-electrified) tracks investigated, the hydrogen demand is often lower than the SRIA targets (0.04 to 0.19 kg H2/100 ton-km) because of the bi-mode powertrain configuration. The specific hydrogen demand therefore depends on the tracks and their specific electrification profile.

For the EN 50591 stipulated in the SRIA 2021-2027 targets hydrogen demand in pure hydrogen feed is 0.135 kg H2/100 ton-km for the Demonstrator train and 0.126 kg H2/100 ton-km for the Future train, which is more in the range of the SRIA targets. It must be noted though, that a bi-mode hydrogen train configuration is less efficient than a pure fuel cell hybrid unit in pure H2 operation due to the added component weight and the inability to take advantage of catenary based battery recharging.

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Range before refueling (autonomy)

We found that DMU autonomies are typically 2 to 2.5 times larger than those of Bi-mode H2 trains. However autonomy targets set by operator Renfe (650 to 1,000 km) can be reached by the Bi-mode H2 Future train configuration for all tracks investigated in this deliverable.

As of 2024 some lines are subject to electrifcation which was not clear at the time the D1.1 was prepared (which was the input for D6.1 and D6.3) back in 2021. However, with more tracks being electrified, but considerable track sections still remaining non-electrified at the same time, the case for Bi-mode H2 trains is even stronger compared to using fuel cell hydrogen hybrid trains or diesel trains. The reason is that Bi-mode trains can make use of the very efficient catenary more often than with less catenary available.

In this context the FCHPP concept is versatile enough to make use also of a battery only solution specifically for tracks that have only short electrification sections.

Refueling downtime

For an assumed refueling speed of 4 kg H2/min and parallel refuelling, Bi-mode hydrogen trains will reach refueling downtimes competitive to DMUs whereas they do not keep up with diesel trains for the KPI 'autonomy gained in km per minute of refuelling'.

In summary, the Bi-mode H2 train has its big advantages when it comes to partly electrified tracks and it will meet or even surpass many KPI targets.

A.1 List of Figures

A.2 List of Tables

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6. Publication bibliography

2019: EN 50591:2019: Railway Applications - Rolling Stock - Specification and verification of energy consumption.

Europe's Rail Joint Undertaking (2019): Study on the use of Fuel Cells and Hydrogen in the Railway Environment. Available online at https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/, checked on 6/18/2024.

FUEL CELLS and HYDROGEN 2 JOINT UNDERTAKING (2018): Addendum to the Multi - Annual Work Plan 2014 - 2020. Available online at https://www.clean-hydrogen.europa.eu/system/files/2018-06/MAWP%2520final%2520version_endorsed%2520GB%252015062018%2520%2528ID%25203712421%2529.pdf, checked on 6/18/2024.

Herwartz, Sebastian; Kühlkamp, Florian (2022a): FCH2RAIL D1.1 - Report concerning line and use-case based requirements. Available online at https://fch2rail.eu/wp-content/uploads/2024/03/FCH2RAIL_Deliverable_1.1_submitted.pdf, checked on 7/4/2024.

Herwartz, Sebastian; Kühlkamp, Florian (2022b): FCH2RAIL deliverable D1.1 - Report concerning line and usecase based. Available online at https://fch2rail.eu/wp-content/uploads/2024/03/FCH2RAIL_Deliverable_1.1_submitted.pdf, checked on 7/30/2024.

Munoz Vicent, Alvaro; Fernandez Del Rey, Abraham (2024): FCH2RAIL deliverable D1.3 Report on generic requirements for bi-mode fuel cell hybrid trains. Available online at https://fch2rail.eu/wp-content/uploads/2024/03/FCH2RAIL-D1.3-.pdf, checked on 7/3/2024.

Pagenkopf, Johannes; Böhm, Mathias; Haas, Jan Lucas; Friedrich, Horst E. (2018): Analysis of German diesel operated regional railway lines' patterns with regard to the application of battery and fuel cell electric trains. 2018-09-03 - 2018-09-07,. Sitges, Spain, 2018. Available online at https://elib.dlr.de/121661/, checked on 6/18/2024.

Projektpartner Normungsroadmap Wasserstofftechnologien (2024): Normungsroadmap Wasserstofftechnologien 2024. Available online at https://www.din.de/de/forschung-und-innovation/themen/wasserstoff/normungsroadmap-wasserstoff/veroeffentlichung, checked on 10/23/2024.

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SAE International (2023): Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles. J2601/2_202307. SAE International. Available online at https://www.sae.org/standards/content/j2601/2_202307/, checked on 10/23/2024.

SAE International (2024): High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles. J2601/5_202402. Edited by SAE International. Available online at https://www.sae.org/standards/content/j2601/5_202402/, checked on 10/23/2024.

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