D1.5 – Hydrogen refuelling and storage requirements for rail vehicles

WP 1 – Generic fuel cell train requirements specifications and concept

Task 1.4 – Hydrogen storage and refuelling station interfaces development

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Contributions table

Partner	Contribution
CNH2	Preparation of the deliverable
ADIF	Information on the refuelling of diesel trains and the need for hydrogen refuelling station locations (ANNEX A). Support and review
CAF	Information on the hydrogen storage capacity for each type of train (Section 6.2, ANNEX C). Support and review. Quality check
DLR	Information on the comparison of vehicle infrastructure interfaces and on-board energy storage options (Sections 5.1.2, 5.1.3, 5.6, 6.1, ANNEX B). Support and review
RENFE	Refuelling operational procedures from the point of view of the vehicle. Support and review

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Executive summary

This document constitutes the Deliverable D1.5: Hydrogen refuelling and storage requirements for rail vehicles, for the project “FCH2RAIL: Fuel cell hybrid power pack for rail applications”, under Grant Agreement No. 101006633 [1].

The results of Deliverable D1.5 will be hydrogen refuelling requirements and an evaluation of different hydrogen on-board storage systems.

In order to establish the requirements that hydrogen refuelling for rail vehicles must accomplish in the future, an analysis of the state-of-the-art diesel refuelling of rail vehicles has been carried out. This analysis shows that there are strict requirements with regard to high volume flows and low refuelling times, large, established diesel refuelling station networks with a high number of daily refuelling operations with sometimes very large diesel delivery volumes. The refuelling capacity and mass flow rates are parameters that must be taken into account in the development of hydrogen refuelling stations (HRSs) for rail vehicles and its refuelling protocols.

Currently, there is a lack of standards regarding hydrogen refuelling protocols for heavy-duty vehicles with high flow (HF) because, although SAE J2601-2 establishes the boundary conditions for refuelling heavy-duty vehicles with > 10 kg of hydrogen storage and/or mass flow rates of up to 7.2 kg/min, SAE J2601-2 lacks the level of practical detail required for a full standard. The capacity for railway applications is planned to be greater than the capacity covered by existing protocols and ISO 19885-3 is a high-flow hydrogen refuelling protocol that is being developed under the supervision of the ISO/TC 197 and could be a valid option for trains.

Based on hydrogen refuelling requirements, an interface analysis between the infrastructure and on-board hydrogen storage was carried out for compressed gas hydrogen (CGH_2), cryo-compressed hydrogen (CcH_2) and liquid hydrogen (LH_2). The result was the identification of components (nozzle, receptacle, hose, breakaway and communication) that are part of these interfaces for different types of refuelling and ensure compatibility between them. At present, no specific nozzles and receptacles have been developed for the refuelling of rail vehicles.

With regard to pressure, the 35 MPa refuelling technology is state of the art for railways and is used for current developments. At the moment, LH_2 and CcH_2 refuelling technologies and matching nozzles are not used in rail vehicles but are under development for lorries and there is no hydrogen refuelling technology that comes close to the refuelling times of diesel trains.

In addition, CGH_2 (35 MPa, 50 MPa, 70 MPa), CcH_2 and LH_2 on-board hydrogen storage options and their possible implementation in trains were analysed. Currently, there are no directly applicable standards and regulations for the use of hydrogen storage systems in rail vehicles, but international standardisation work is underway.

Glossary of terms

Acronyms	Description
APRR	Average pressure ramp rate
CaFCP	California Fuel Cell Partnership
CcH_2	Cryo-compressed hydrogen
CGH_2	Compressed gaseous hydrogen
CHSS	Compressed hydrogen storage system
DMU	Diesel multiple units
FCEV	Fuel cell electric vehicle
FCH2RAIL	Fuel cell hybrid power pack for rail applications
H_2	Hydrogen
HDV	Heavy duty vehicle
HF	High flow
HRS	Hydrogen refuelling station
IrDA	Infrared Data Association
KRRI	Korean Railroad Research Institute
LH_2	Liquid hydrogen
LRV	Light rail vehicle
NWP	Nominal working pressure
sLH_2	Subcooled liquid hydrogen
SOC	State of charge
OTV	On-tank valve
PEM	Proton membrane exchange
PRR	Pressure ramp rate
P&ID	Piping and instrumentation diagram
TRL	Technological readiness level
TRPD	Thermal and pressure relief divide

Contents

ANNEX A – State-of-the-art diesel refuelling

ANNEX B – Type of vessels

ANNEX C – Detailed H_2 storage systems vehicle integration options

1. Background

In Task 1.4, essential information on and understanding of refuelling processes and storage analysis are being developed.

The FCH2RAIL project is considered to be one of the first in the sector and there is no specific legislation and regulations yet in this regard. As the project progresses, a better understanding of the benefits and limitations of the HRS for trains will emerge.

The requirements for hydrogen refuelling systems and storage for railway vehicles are being developed through an analysis of current refuelling stations, HRS and on-board hydrogen storage options; all relating to rail vehicles. Current regulations and standards for hydrogen refuelling and storage as well as the technology for both need to be taken into account. To achieve this, the following actions will be carried out:

- Analysis of the current state of diesel refuelling stations in Spain from the perspective of an infrastructure manager.
- Review of current HRS technologies, standards and regulations.
- Review of different hydrogen storage options and their integration, supported by the train manufacturer's experience.

2. Objective and methodology

The aim of this deliverable is to show the advantages and disadvantages of the different solutions for on-board energy supply and storage for railway vehicles. First, information on the diesel train refuelling process is used as a knowledge base to determine the logistical requirements for hydrogen refuelling.

An analysis of the current normative, technological and infrastructural requirements is also carried out for several participants in this project, taking into account previous requirements for fuel cell hydrogen trains.

The methodology described above will finally result in an overview of the general requirements for different types of HRS and an assessment of on-board hydrogen storage.

3. State-of-the-art railway diesel refuelling

As explained in D1.3, an analysis of the refuelling requirements for the services currently provided by diesel multiple units (DMU) was prepared by the partners in Task 1.1. Consequently, Tasks 1.1 and 1.2 explain that one of the critical interests of the project is to acquire a deep understanding of how a railway operator can develop hydrogen services in a scalable architecture.

Diesel refuelling stations can serve as a starting point for the design model and the definition of the technical characteristics of HRS in order to introduce hydrogen into the railway sector. However, the differences in installation, operation and safety requirements resulting from the use of hydrogen as a fuel need to be studied in detail. As the project progresses, a new deliverable will be defined with the requirements for the location of HRS.

In Spain, the diesel refuelling process is managed and provided by the National Railways Infrastructure Administrator (ADIF). According to ADIF's Network Statement 2021, diesel refuelling stations are defined as facilities equipped with the appropriate technical means for dispensing diesel for the propulsion of railway vehicles with the appropriate safety measures.

There are two types of diesel refuelling stations: mobile and fixed. Mobile refuelling stations can be used for a limited period of time and have less complex facilities than fixed diesel refuelling stations. Another difference between them is their management, which, in turn, depends of the individual country.

The main functional areas in diesel refuelling station are as follows:

- Storage: The storage system consists of tanks, venting, electronic measurement, charging and propulsion.
- Sanitary system: The sanitary system consists of piping, class I separator, scupper and linear grid.
- Electrical system: The electrical system consists of an electrical panel, an grounding network, a meter and a lighting network.
- Fire protection: The electrical system consists of at least three types of fire extinguisher.
- Security: The security system consists of an emergency alarm system with acoustic signal, emergency lighting, signalling systems, security fencing, a video surveillance system, mechanised access control system and identification card system at the point of supply.

The infrastructure manager of each country has internal operating procedures for the supply of diesel fuel. These procedures can serve as the basis of the future hydrogen supply but will require specific adaptation.

A study of the current railway refuelling situation has been carried out in ANNEX A.

4. Hydrogen refuelling stations and refuelling protocols

An overview of the HRS definition and the current refuelling protocols is provided in this chapter.

4.1 Hydrogen refuelling station

An HRS is a refuelling station that supplies hydrogen to fuel cell electric vehicles (FCEVs). Its operation is similar to conventional refuelling stations. The design and configuration of the HRS depends on many factors, such as the level of demand or the type of vehicle to be refuelled and the availability.

At the end of 2020, 553 HRSs were in operation worldwide, of which 200 were in Europe [2]. In the railway sector, however, hydrogen is mainly supplied by temporary refuelling solutions, especially when the nominal working pressure (NWP) is 35 MPa with no large-scale infrastructure tested yet [3]. The construction of the world's first HRS for trains began in Germany at the end of 2020 and is expected to continue until 2022 [4].

In general, an HRS consists of the following elements as shown in Figure 1:

- Hydrogen generation and supply.
- Compression and storage.
- Dispensing system.

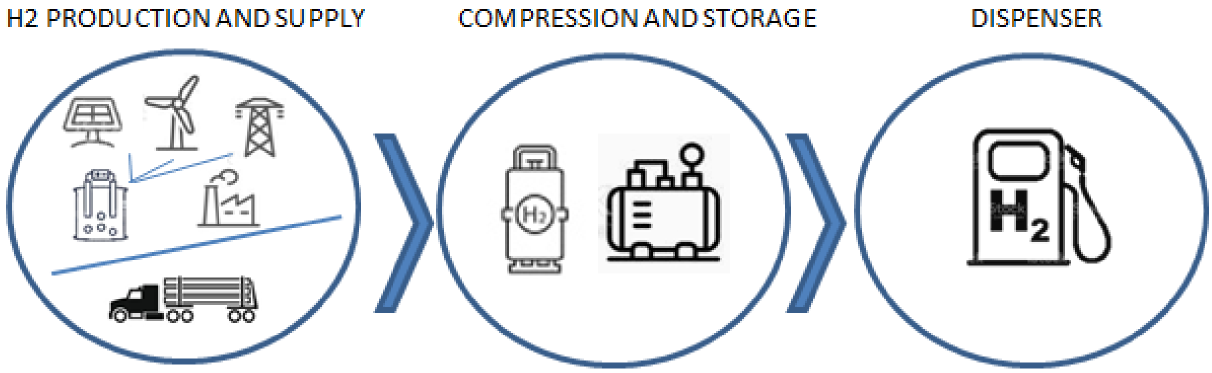


Figure 1: Basic components of HRS. Source: CNH2

There are also different types of HRSs. They can be classified according to the origin of the hydrogen as shown in Figure 2.

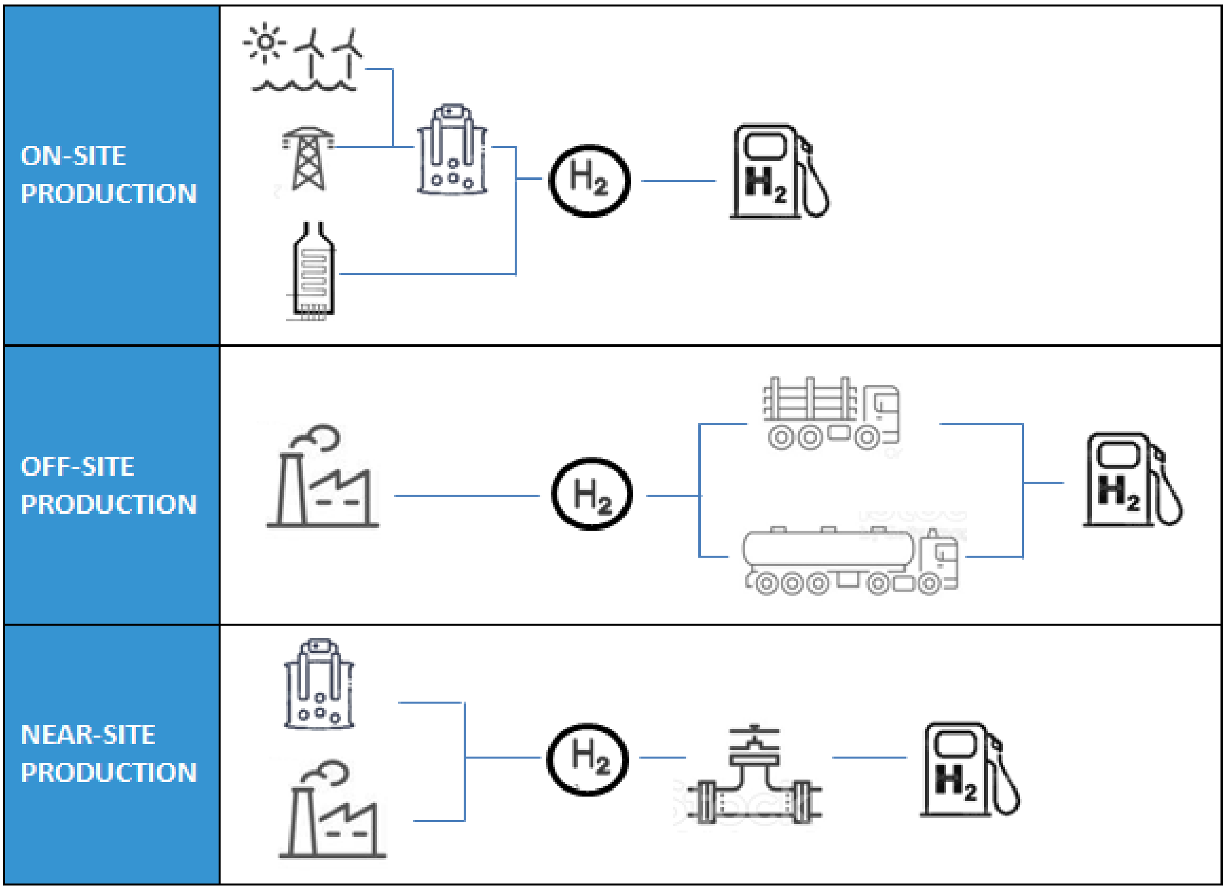


Figure 2: Origin of the hydrogen supplied. Source: CNH2

- On-site production: Hydrogen can be produced in different ways, by electrolysis or steam reforming. In electrolysis, water is split into hydrogen and oxygen by electricity in an electrolyser. If the source of this electricity is renewable, usually solar or wind energy, the hydrogen produced is called 'green hydrogen'. Another possibility is to produce hydrogen with electricity directly from the grid. Nowadays, there are several electrolyser technologies on market, with alkaline and proton membrane exchange (PEM) technologies the most mature.
  Another option for hydrogen production is steam reforming that uses natural gas or biogas in a catalytic reaction. In contrast to electrolysers, this technology produces environmentally harmful emissions.

- Off-site production: The hydrogen is delivered to the HRS from a production facility, which can be a large-scale hydrogen production plant or a facility where the hydrogen is produced as a by-product. Chlorine production and thermal cracking of hydrocarbons are two examples of facilities that produce hydrogen as a by-product. Transport to the HRS can be realised in different ways, depending on the quantity or pressure:

  - Gaseous hydrogen in lorries. Hydrogen is compressed at different pressure levels into long, stacked cylinders. Until now, gas operators supplied hydrogen at a pressure of 20 MPa, but recently the demand for higher pressures (50 MPa) has been growing.
  - If a large amount of hydrogen is required, the best type of supply is LH_2 (Figure 3). Hydrogen liquefaction requires conditions to be maintained inside the trailer (-253 °C at ambient pressure, ~0.2 MPa). LH_2 is delivered in highly insulated trailer tanks and although they are insulated, LH_2 can warm up and vaporise during delivery, increasing the pressure in the storage tanks. As a safety measure, the gaseous hydrogen must be vented when the pressure exceeds the maximum pressure of the tank. This phenomenon is called 'boil-off losses' as explained in section 6.1.2.

Figure 3: Tube trailer for GH_2 and LH_2 trailer [5]

- Near-site: The hydrogen is not produced on site, but close to the HRS. Due to the high construction costs , a pipeline can only be used to supply hydrogen over short distances. The pressure range over which hydrogen can be transported in a pipeline is large.

The design of HRSs (see Figure 4) depends on the H_2 production, the type of delivery and the operational concept (e.g. number of trains, parallel refuelling), and the most common refuelling pressure is 35 MPa (similar to fuel cell buses).

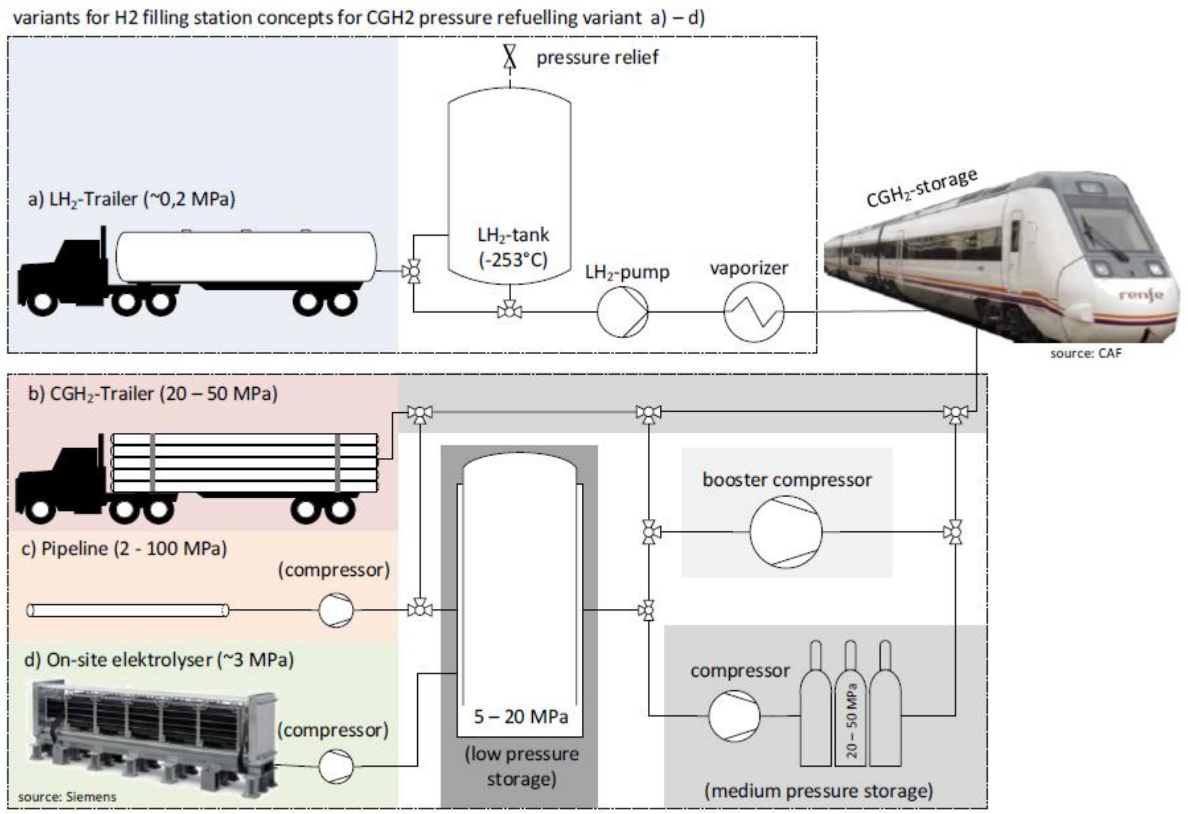


Figure 4: Different HRS layouts. Source: DLR

4.1.1 Compression and storage

The hydrogen must be compressed to the required vehicle pressure. A compressor is not required if the hydrogen supplied is at a higher pressure level than that required by the train. In this case, the vehicle is refuelled by the difference in pressure.

There are different types of compressors for gaseous hydrogen depending on the required flow rate and pressure. The most common are boosters and diaphragm compressors. The booster is driven by compressed air and is used for low mass flow rates, whereas the diaphragm compressor (see Figure 5) is electrically driven and is recommended for high mass flow rates.

Figure 5: Diaphragm compressor [6]

In the case of LH_2, it is common to use a reciprocating cryo-pump (see Figure 6) to increase the pressure, but it is not the only type. A cryo-pump is usually more compact than a compressor and its minimum design requirements are specified in ISO 24490.

Figure 6: Reciprocating cryo-pump [7]

Another very important HRS component is the storage system. Hydrogen should be stored to balance the supply and, as described in chapter 6.1, there are four different types of hydrogen tanks (I-IV).

As shown in Figure 4 and Figure 9, there are two general types of gaseous hydrogen refuelling [8]:

- Cascade refuelling: This type of refuelling consists of one or more compressors and different pressure storage banks. To explain how cascade refuelling works, three storage banks are assumed with different (high, medium and low) pressure levels. When a vehicle connects to the station, the station starts refuelling from the low-pressure bank until the pressure in both storage systems is similar or the pressure reaches a target value, so the medium-pressure bank is now in charge of filling the tank. When the pressure reaches the equilibrium pressure or a limit value, refuelling begins from the high-pressure bank instead of the medium-pressure bank. The procedure ends when the vehicle tank pressure reaches the target pressure (35 MPa in heavy-duty vehicles). This procedure is also known as ‘refuelling by pressure difference’. The procedure for filling the vessels is in reverse order. The compressor first fills the high-pressure vessel, then the medium-pressure vessel and, finally, the low-pressure vessel.
- Booster compressor refuelling: This is composed of a low-pressure vessel and a high-flow booster. After compression, the hydrogen is refuelled directly into the vehicle tank. The advantages of this system are that high-pressure storage is not necessary, so the process is less complex than the other refuelling system and the compressor only runs until the target pressure in the vehicle is obtained, so it is not oversized.

In both cases, a pre-cooler could be installed before the fuel dispenser to lower the fuel temperature, thereby ensuring that the refuelling process is within its operating limits. SAE J2601 for light duty vehicles and SAE J2601-2 for heavy duty vehicles (HDVs) establish the boundary conditions of the refuelling process. Also, EN 17127 defines the general requirements for the refuelling protocol. The temperature in the vehicle’s fuel system should be less than or equal to 85 °C. The pressure difference between the storage and the vehicle tank and the expansion that occurs with a temperature rise due to the Joule-Thompson effect must be taken into account. For example, when refuelling light duty vehicles at 70 MPa and when refuelling HDVs with HF nozzles, a pre-cooler is necessary to reduce the temperature below 85 °C. In the other cases, where the temperature limits of the compressed hydrogen storage system (CHSS) are not exceeded, the pre-cooler is not required, resulting in a significant cost reduction.

An analysis was carried out to investigate whether a pre-cooling stage is required before the fuel dispenser in order to confirm the mass flow rate, temperature and pressure. If the temperature rises above the allowed temperature, the mass flow rate will drop to reduce the temperature in the tank and the refuelling time could take longer than expected. This increase in the refuelling time would have to be monitored, otherwise the HRS would lose its appeal since other emission-free alternatives would become more interesting.

LH_2 refuelling, on the other hand, requires a highly insulated storage tank, a cryo-pump and an evaporator (Figure 13). The LH_2 must pass through an evaporator before it reaches the dispenser.

Figure 7: Liquid hydrogen refuelling station [9]

Liquid HRSs are generally the most appropriate for refuelling large quantities of hydrogen.

4.1.2 Dispenser

The hydrogen dispenser is used to supply hydrogen to heavy-duty vehicles. It consists of a nozzle, a filling hose, sensors, a breakaway system, a PLC control system and filters, and its design is similar to a petrol or diesel dispenser (Figure 8).

Figure 8: Compressed hydrogen refuelling station. Source: CNH2

According to ISO 19880-1, the dispenser can be a stand-alone device on the forecourt of the refuelling station or integrated as part of a hydrogen production/compression tank unit. Physical guards should be implemented to protect the dispenser from any impact by vehicles.

The structural foundation of the dispenser and refuelling area should be adequate to support all components including vehicles to be refuelled. It should be noted that fuel dispensers should not be located beneath a canopy unless the canopy has been designed to prevent hydrogen accumulation.

Filters should be included as part of the fuel dispenser in order to prevent contamination of the hydrogen that could affect the FCEV system. For example, ISO 19880-1 specifies that the filters should prevent particles with a maximum size of 5 µm and a minimum removal efficiency of 99 % under the expected process conditions, or alternatively a 5 µm filter. The filter should be installed upstream of, and as close as possible to, the hose breakaway device. This should filter out the particulate concentration in the hydrogen according to EN 17124.

Summarising the information given in this chapter, different HRS configurations can be considered, as shown in Figure 9, and should be considered for train refuelling.

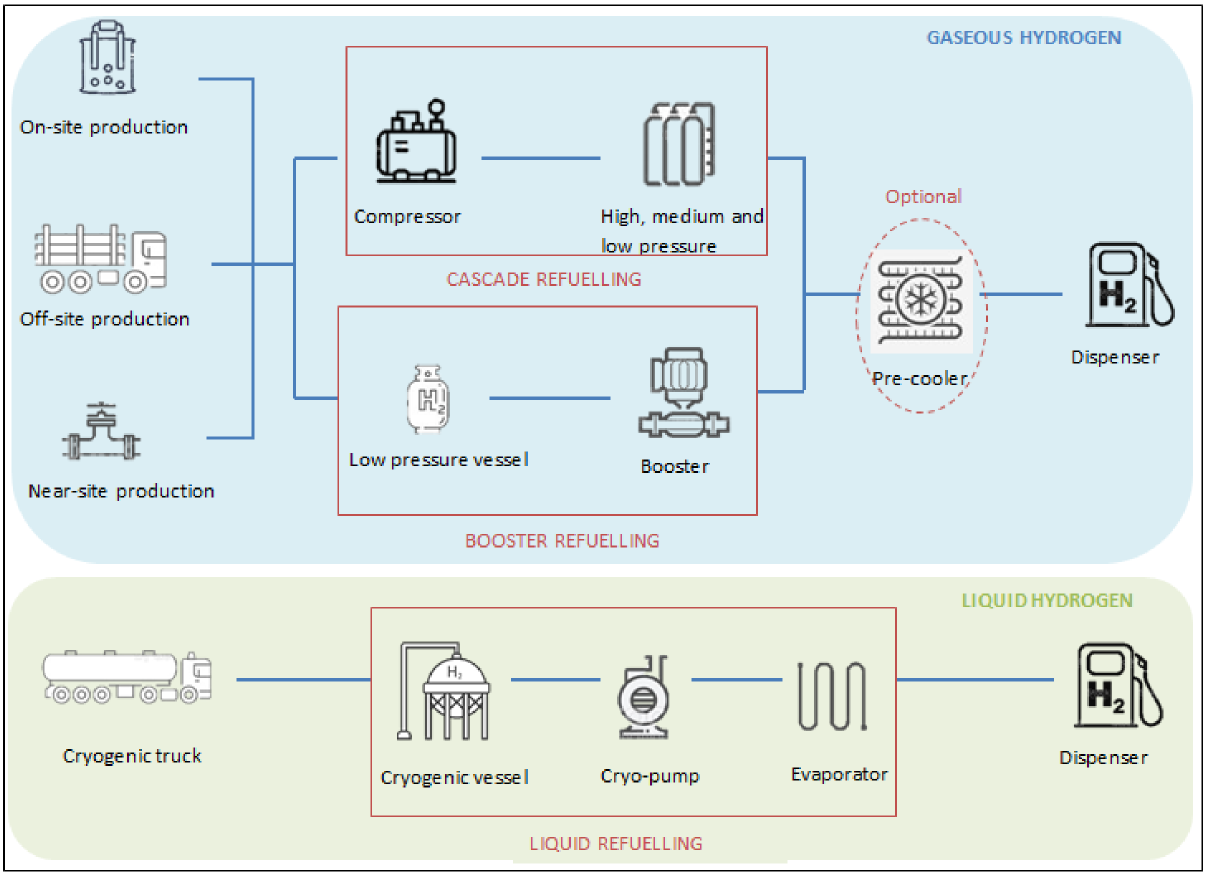


Figure 9: Typical HRS configurations. Source: CNH2

4.2 Refuelling protocol

The refuelling protocol indicates the procedure to be followed when refuelling the vehicle in order to avoid damage to the vehicle's tanks. The aim of the protocol is to avoid overpressure, overheating and overfilling. Therefore, the protocol restricts the conditions under which the refuelling process is feasible, and it is developed in the following standards.

4.2.1 SAE J2601 – H_2 refuelling protocols for light duty vehicles

SAE J2601 establishes the protocol and process limits for the hydrogen refuelling of light duty vehicles. This standard limits the value of the tank temperature, the charging state, the maximum mass flow rate and end pressure. There are also other parameters that affect the refuelling process, such as the initial pressure in the vehicle's CHSS, the ambient conditions and the fuel temperature and pressure at the dispenser.

The goal of refuelling is to achieve a state of charge (SOC) of 100% without exceeding the following limits [10]:

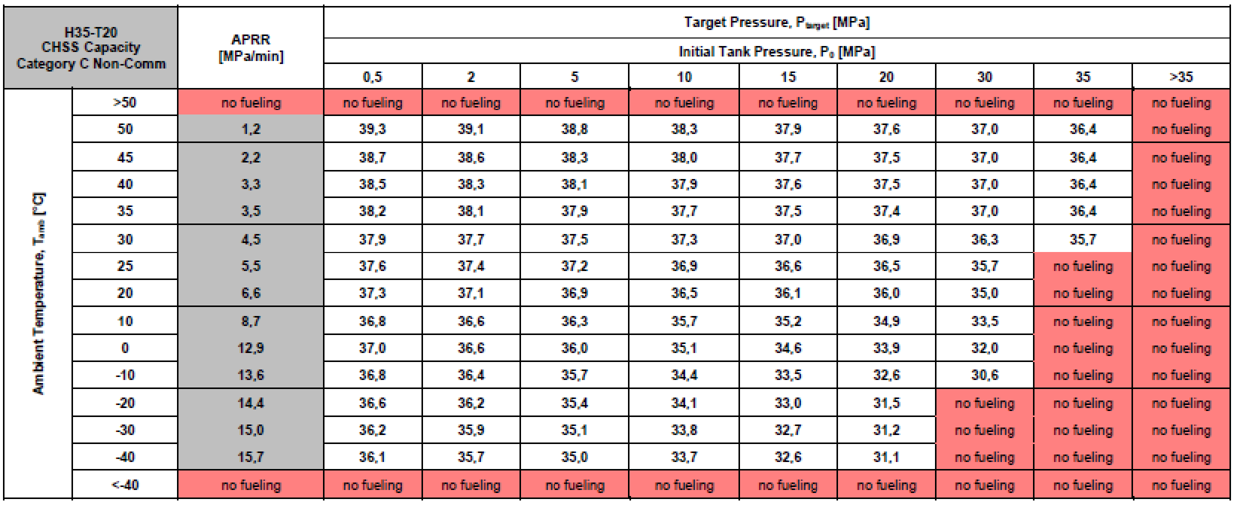
- Temperature in the vehicle's tank: -40 °C < T < 85 °C
- Maximum pressure in the vehicle tank: 125% NWP (87.5 MPa for a 70 MPa NWP vehicle and 43.75 MPa for a 35 NWP vehicle)
- Maximum mass flow rate at the dispenser nozzle: 3.6 kg/min

SAE J2601 establishes how to perform refuelling in two different ways: (i) static (table-based protocol) or (ii) dynamic (MC formula-based protocol) refuelling control. The refuelling process is fully automated by a PLC control system.

For both protocols, the first step is to determine the initial CHSS pressure and the tank mass capacity. When a vehicle is connected to the HRS, the station measures the initial CHSS pressure. That measurement is made with the pressure sensor integrated in the dispenser for a non-communication procedure or with the pressure sensor integrated in the vehicle tank for a communication procedure. The station then used a pressure pulse together with flow measurements to determine the tank volume and hence the mass capacity of the vehicle tank.

4.2.1.1 Table-based protocol

The table-based protocol uses static control. SAE J2601 shows the standard look-up tables used in this refuelling protocol (Figure 10).



H35-T20 CHSS Capacity Category C Non-Comm		APRR [MPa/min]	Target Pressure, P_{target} [MPa]								
			Initial Tank Pressure, P_0 [MPa]								
			0,5	2	5	10	15	20	30	35	>35
Ambient Temperature, T_{amb} [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	1,2	39,3	39,1	38,8	38,3	37,9	37,6	37,0	36,4	no fueling
	45	2,2	38,7	38,6	38,3	38,0	37,7	37,5	37,0	36,4	no fueling
	40	3,3	38,5	38,3	38,1	37,9	37,6	37,5	37,0	36,4	no fueling
	35	3,5	38,2	38,1	37,9	37,7	37,5	37,4	37,0	36,4	no fueling
	30	4,5	37,9	37,7	37,5	37,3	37,0	36,9	36,3	35,7	no fueling
	25	5,5	37,6	37,4	37,2	36,9	36,6	36,5	35,7	no fueling	no fueling
	20	6,6	37,3	37,1	36,9	36,5	36,1	36,0	35,0	no fueling	no fueling
	10	8,7	36,8	36,6	36,3	35,7	35,2	34,9	33,5	no fueling	no fueling
	0	12,9	37,0	36,6	36,0	35,1	34,6	33,9	32,0	no fueling	no fueling
	-10	13,6	36,8	36,4	35,7	34,4	33,5	32,6	30,6	no fueling	no fueling
	-20	14,4	36,6	36,2	35,4	34,1	33,0	31,5	no fueling	no fueling	no fueling
	-30	15,0	36,2	35,9	35,1	33,8	32,7	31,2	no fueling	no fueling	no fueling
	-40	15,7	36,1	35,7	35,0	33,7	32,6	31,1	no fueling	no fueling	no fueling
	<-40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Figure 10: Example of the standard 'look-up table' for non-communication hydrogen refuelling [10]

The station complies with the stated standard and selects the correct look-up table based on the pressure class (H35, H70), fuel delivery temperature, CHSS capacity (2–4 kg, 4–7 kg, 7–10 kg) and the presence or absence of a communication signal from the vehicle. Once the correct table is selected, the inputs are the ambient temperature (measured with the temperature sensor) and the initial CHSS pressure (measured in the first step of the protocol). In the look-up table, the inputs are used to determine the correct average pressure ramp rate (APRR) and target pressure. When the APRR is set, the refuelling process begins. For refuelling without communication, the process ends when the target pressure is reached, and for refuelling with communication, the process ends when the SOC is in the range of 95%–100% [10].

4.2.1.2 MC formula-based protocol

The MC formula-based refuelling protocol is an adaptive protocol that dynamically adjusts the rate of change of fuel dispenser pressure and the target end pressure for refuelling based on inputs. This protocol is described in SAE J2601.

The parameters required in this protocol are the same as in the table-based protocol: pressure class, fuel delivery temperature, CHSS capacity, the absence or presence of a communication signal from the vehicle, the ambient temperature and the initial CHSS pressure. Based on these parameters, the protocol calculates the appropriate pressure ramp rate (PRR) and target end pressure. However, unlike the table-based protocol that utilises these parameters throughout the refuelling process, the MC formula-based protocol only uses these fixed parameters for the first 30 seconds of refuelling, after which they are calculated and updated once per second for the remainder of the refuelling process. The MC formula protocol use feed-forward control to dynamically adapt to the actual refuelling conditions [10].

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The structure of the MC formula-based protocol is divided into two parts: PRR control and final pressure control. The PRR control specifies the instantaneous PRR and is based on a regression equation. The equation defines the time required to refuel from minimum pressure to final pressure without exceeding the gas temperature limit of 85 °C. The final pressure specifies the station pressure at which the refuelling should end. There are two options for controlling the final pressure: the MC method or final pressure tables [10].

According to SAE J2601: "The first option is based on a methodology called the MC method which calculates the refuelling gas temperature at the end of the CHSS based on the initial CHSS pressure and CHSS gas temperature combined with the measured enthalpy of the fuel dispenser and elapsed refuelling time". "…The end of fill gas temperature is then used to calculate a pressure target which ensures the fill stops at the appropriate density. The MC Method is a lumped heat capacity model where MC represents the combined heat mass of the control volume and is denoted in units of kJ/K. The M and the C in the name are derived from the concept of mass times specific heat capacity".

"…The second option for ending pressure control is a set of look-up tables providing non-communication fuelling pressure targets, and communication fuelling pressure limits. These look-up tables work in the same way than those utilized in the table-based protocol. However, the determination of which ending pressure table to be used is based on the mass average of the fuel delivery temperature, which is updated continuously throughout the fill".

"…The dispenser manufacturer should choose one or the other of these two ending pressure control options" [10] (page 149).

4.2.2 SAE J2601-2 – H_2 refuelling protocols for heavy duty vehicles

SAE J2601-2 is a standard that establishes the boundary conditions for safe heavy-duty hydrogen surface vehicle fuelling (Figure 11). It is focussed on the refuelling of 35 MPa HDVs, but other pressures are optional, and it is suitable for vehicle CHSS capacities larger than 10 kg and/or mass flow rates of up to 7.2 kg/min.

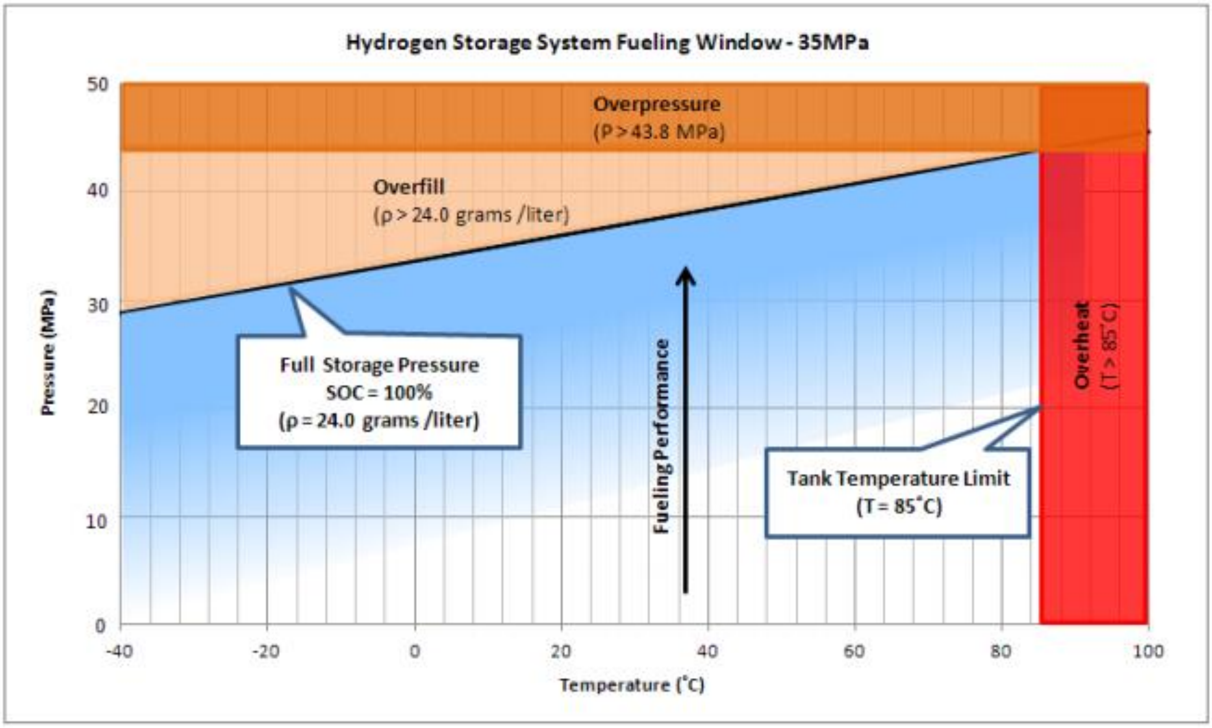

Figure 11: Operation range for a 35 MP NWP vehicle [11]

The refuelling protocol standard for HDVs only provides very little guidance on how to actually carry out the filling process and focusses on the boundary condition limits. SAE J2601-2 is very restrictive in terms of requirements. The dispenser creates a pressure expansion that can increase the temperature. In relation to this standard, the system cannot reach more than 85 °C.

The scope and general requirements of SAE J2601-2 are summarised in the following table:

SCOPE		
Fuelling 35 MPa HDV- Other pressures are optional		
HDV with CHSS >10 kg		
GENERAL REQUIREMENTS		
Boundary parameters for a H35 CHSS	**Temperature**	-40 °C < T < 85 °C
	Pressure	0.5 MPa < P < 43.8 MPa
Hydrogen storage system	**Approvals**	CSA HGV-2
		SAE J2579
		Global Technical Regulation 13
		Any other applicable local or national requirements
Fuelling process limits	**Ambient temperature**	-40 °C ≤ T ≤ 50 °C
	Pressure at the dispenser sensor	P ≤ 125% NWP of the vehicle fuel system
	Pressure within the vehicle fuel system	P ≤ 125% NWP of the vehicle fuel system
	Temperature within the vehicle fuel system	T ≤ 85 °C
	State of charge	SOC ≤ 100%
	Fuel temperature at the dispenser	T ≥ -40 °C

Table 1: General requirements for refuelling protocol [11]

With reference to section 5.3.7 of SAE J2601-2, HRS must restrict the flow to one of the following three options:

Category	Category description	Fuelling rate
Fast refuelling Option A	This option is for the fast refuelling of heavy-duty buses or vehicles. Refuelling covered by this option is typically at variable speed and uses a ‘high flow’ heavy duty hydrogen surface vehicle (HDHSV) connection as defined in ISO 17268:2012.	≤ 7.2 kg/min
Normal refuelling Option B	This option is for normal refuelling of heavy-duty buses or vehicles. Refuelling covered by this option is typically at variable speed and uses a connection as defined in SAE J2600 or ISO 17268:2012.	≤ 3.6 kg/min
Slow refuelling Option C	This option is for slow refuelling of heavy-duty buses or vehicles, also known as ‘time fill’. Refuelling covered by this option is typically at variable speed.	≤ 1.8 kg/min

Table 2: Refuelling options for heavy duty vehicle [11]

4.2.3 Ongoing advances in protocols for heavy duty applications

As the planned capacity for railway applications is higher than the capacity covered by current protocols, several projects are being developed in order to fulfil these requirements.

For example, although not specific to railway applications, the PRHYDE project [12] carried out several preliminary simulations with use cases between 33.6 to 56.3 kg of hydrogen. Even if these capacities are still far from what was expected for railway applications, some interesting conclusions are included regarding the final temperature in tanks, the SOC or the refuelling times, which could be taken as a result for heavier applications.

ISO 19885-3 is also developing a so-called high-flow hydrogen refuelling protocol for heavy duty road vehicles, which could be a valid option for trains. This standard is being developed under the supervision of the ISO/TC 197 and is at a preparatory stage.

5. Specification and analysis of the interfaces between HRS and train

This section develops an analysis of the interface between the refuelling station and the main on-board storage tanks for hydrogen vehicles. The HRS train interface should be identified against a specific standard for rail vehicles. ISO 19880-1 (Gaseous hydrogen - Fuelling stations - Part 1: General requirements) and EN 17127 (focussed only on the refuelling point) have been used in this deliverable, which define the minimum design, installation, commissioning, operation, inspection and maintenance requirements for the safety, and, where appropriate, for the performance of public and non-public fuelling station that dispense gaseous hydrogen to light duty road vehicles. Although ISO 19880-1 is specific to light duty vehicles, the requirements and guidance for refuelling heavy duty road vehicles are also covered, and the general interface scheme between vehicle and refuelling station shown in Figure 12 is also applicable to them.

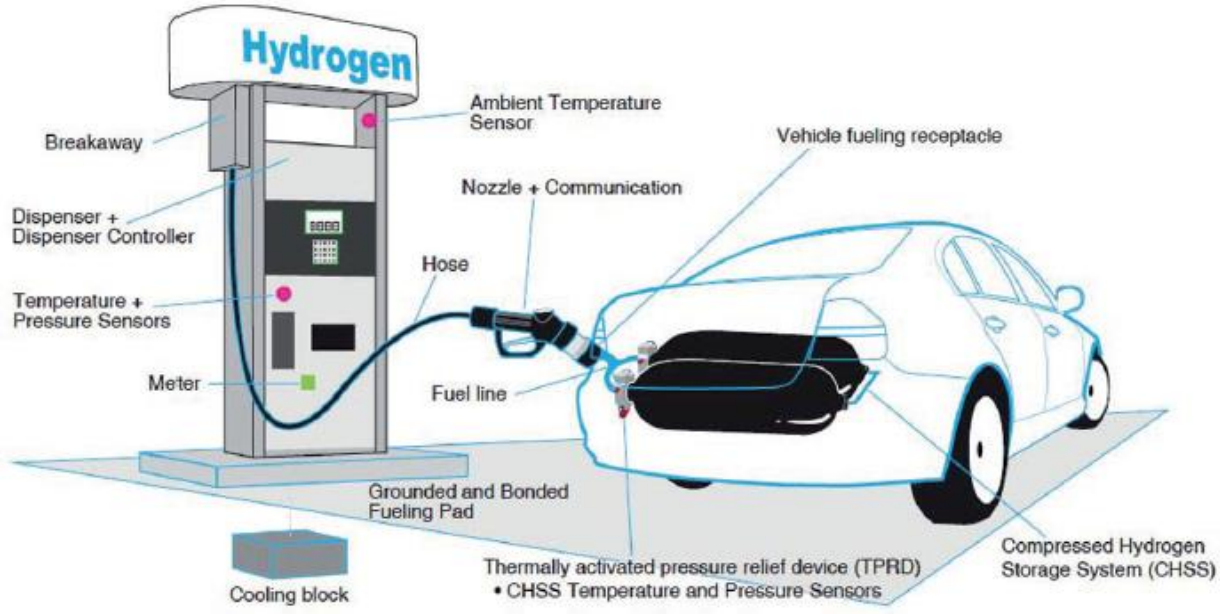

Figure 12: Key components of the fuelling station dispenser including the vehicle CHSS [13]

5.1 Nozzles and receptacles

This section discusses the types of nozzles and receptacles for railway applications depending on the state of the hydrogen: compressed gaseous, liquid and cryo-compressed hydrogen.

A nozzle is a device for connecting the fuel dispensing system. The current state of art in the railway sector shows that there are several hydrogen trains using nozzles and receptacles for CGH_2 [14] [15]. CGH_2 storage is the most mature technology, but it is also possible to refuel with LH_2. In fact, the Korean Railroad Research Institute (KRRI) is working on a research project that will end in December 2024 [16] to develop the world's first LH_2 fuel cell traction to be tested in a light rail vehicle (LRV).

5.1.1 Compressed gaseous hydrogen

Nozzles and receptacles are the connection devices between the refuelling station and the vehicle. The FCH JU Project PRHYDE (Deliverable 2.4 [17]) has collected the standards that regulate the requirements for nozzles and receptacles for CGH_2. These standards are ISO 17268 and SAE J2600, both of which specify compatibility between nozzles and receptacles taking into account the nominal operating pressure and also, in the 35 MPa vehicle case, the mass flow rate.

At the moment, no specific nozzles and receptacles have been developed for the refuelling of rail vehicles. The following table, provided by WEH [18] (manufacturer of refuelling components), summarises the compatibility between nozzles and receptacles for road vehicles.

	Nozzle – pressure range/coding

		25 MPa	35 MPa	35 MPa HF	70 MPa
Receptacle – pressure range/coding	25 MPa	✓			
	35 MPa	✓	✓		
	35 MPa HF	✓	✓	✓	
	70 MPa	✓	✓		✓

Table 3: Compatibility table of nozzle to receptacle [18]

As this sector is moving forward very fast nowadays, new nozzles are being developed to cover more refuelling solutions.

The receptacle can interact with all nozzles that have the same or lower pressure than the receptacle, except for the HF nozzle that is only accepted by HF receptacles. Directive 2014/94/EU requires HRS to be interoperable throughout Europe. This directive was supplemented and amended on 13 August 2019 by the commission delegated regulation (EU) 2019/1745, with one of the changes related to hydrogen being that connectors for motor vehicles for refuelling with gaseous hydrogen must comply with the EN ISO 17268 standard. This regulation is to apply from 12 November 2021.

A WEH nozzle classification for light duty and heavy-duty road vehicles is shown in the following table:

Nozzle type	Light duty vehicle	Heavy duty vehicle
TK17 H2 70 MPa	✓	
TK17 H2 35 MPa	✓	
TK16 H2	✓	
TK16 H2 with data interface	✓	
TK16 H2 HF		✓
TK16 H2 HF with data interface		✓
TK25 H2		✓

Table 4: Nozzle type for light duty and heavy duty road vehicles [18]

There are three types of WEH nozzle for heavy duty road vehicles: TK16 HF with and without data interface communication and TK25. The nozzle should be compatible with the receptacle and to ensure this, the catalogue of WEH includes a compatibility table. Table 5 shows the nozzle and receptacle compatibility for heavy duty applications.

OVERVIEW	Receptacle	TN1 H2 HF TN1 H2 HF for IR	TN1 H2 TN1 H2 for IR	TN5 H2	TN5 H2
Fuelling nozzle	**Pressure**	35 MPa	70 MPa	25 MPa	35 MPa
TK16 H2 HF **TK16 HF with IR**	35 MPa	✓	✓		
TK25 H2	25 MPa			✓	✓
TK25 H2	35 MPa				✓

Table 5: Nozzle-receptacle compatibility for heavy duty application [18]

Accordingly, the possible WEH nozzle-receptacle compatibility for HDVs (Figure 13) are:

- High flow nozzle TK16 H2 (available with and without communications) and the corresponding receptacle TN1 H2 (complies with ISO 17268)
- Fast-filling nozzle TK25 H2 (available without communication) and the corresponding receptacle TN5 H2

Nozzle TK16 H2

Nozzle TK25 H2

Receptacle TN1 H2

Receptacle TN5 H2

Figure 13: WEH nozzle-receptacle for heavy duty applications [18]

In general, 35 MPa is the typical pressure for HDVs such as buses and lorries and is also the usual pressure chosen in current hydrogen train projects [19], [20].

The following table summarises the characteristics and technical data that can be helpful in selecting the receptacle and nozzle. Both receptacles are recommended for railway vehicle refuelling and the main difference between them is the data interface, TN1-H35HF enables working with communication and TN5-H35 does not .

	TN1-H35HF	TN5-H35
Material	Corrosion resistant	Corrosion resistant
Check valve	Yes	Yes
Sealing material	Hydrogen resistant	Hydrogen resistant
Mass flow rate (kg/min)	6-7.2	-
Particle Filter (µ)	40	50
Max. Nominal bore (mm)	8	12
Temperature range (°C)	[-40 … 85]	[-40 … 85]
Approvals	SAE J2600:2002	-
Coding for pressure range	Yes	Yes
Coding for gas type	Yes	Yes
Models prepared for data interface	Yes	No
Kv/Cv *	0.370/0.429	1.002/1.162 (lower pressure drop)
Compatible nozzle	TK16-H35HF	TK25
Nozzle weight (kg)	~ 1.8 ~ 2.4 (with data interface)	~ 4.6

** Kv or Cv is a flow coefficient. This design factor is the ratio between the pressure drop across the receptacle and the flow rate.*

Table 6: Receptacles for heavy duty applications [18]

5.1.2 Liquid hydrogen

The first generation of nozzles for LH_2 was developed by Linde AG in 1994, followed by the second generation of LH_2 nozzles developed in 1999 (Figure 14). This has been used at a number of LH_2 refuelling stations around the world, including Munich Airport, where an automatic LH_2 refuelling system (refuelling robot) has been installed and operated (Figure 15) [21].

Figure 14: LH_2 fuelling nozzles of the first generation in 1994 (left) and second generation in 1999 (right) [21]

The cryogenic refuelling nozzle is super insulated, which makes the system heavier than CGH_2 refuelling nozzles (Figure 16). Refuelling tests from 2003 have shown that return gas-free, and thus loss-free, refuelling requires that the refuelling system as a whole is already in a pre-cooled state of < 50 K [21] . In addition, the supply line for refuelling at the vehicle should have low mass and be as short as possible in order to minimise the evaporation losses of LH_2 [21].

Figure 15: Automatic LH_2 refuelling system at Munich Airport [22]

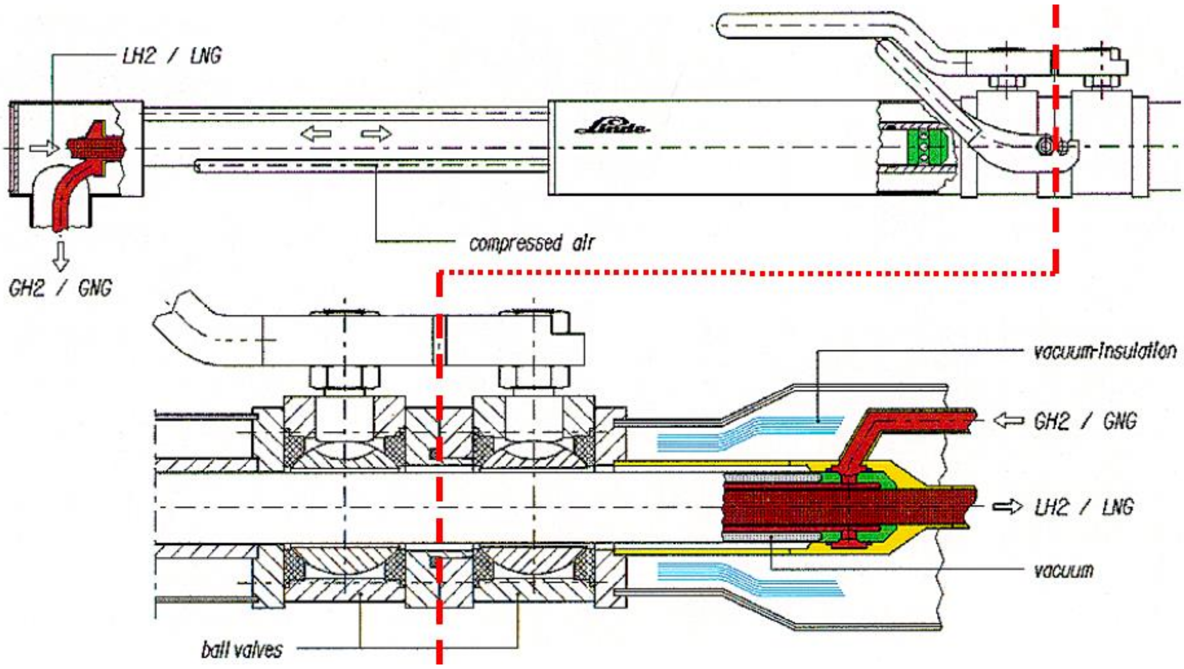

Figure 16: Operating principle of the LH_2 refuelling nozzle [21]

In the following years, the LH_2 refuelling nozzle was adapted and further developed with a quick-connect mechanism (Figure 17, Figure 18). This nozzle also works with double flow (return gas to the station) [23].

Figure 17: The LH_2 quick-connect refuelling nozzle *[24]*

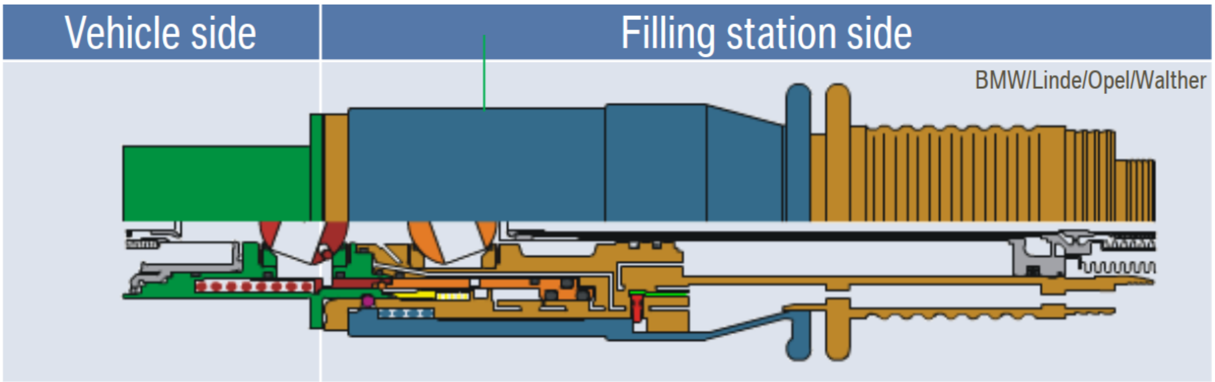

Figure 18: Cross-section of an LH2 refuelling nozzle with quick connector [23]

So far, LH_2 nozzles have only been used for road vehicles, but KRRI is currently developing a project that will end in 2024 in which the LH_2 nozzle will be used to refuel an LRV [16].

According to the Daimler Truck AG and Linde AG consortium, refuelling with subcooled liquid hydrogen (sLH_2) is a further development of the known technology of LH_2 refuelling (at pressures of up to 0.6 MPa), where the pressure corridor of sLH_2 refuelling increases up to 1.6 MPa. No data transmission will be necessary and refuelling stops at a target pressure of 1.6 MPa. The consortium also promotes single flow refuelling without return gas [25]. From the authors' point of view, loss-free refuelling is only possible if the sLH_2 storage system is already pre-cooled and the supply line to the refuelling point on the vehicle is as short as possible.

Cryotherm GmbH & Co. KG is planning sLH_2 refuelling receptacles on both sides for heavy-duty vehicles. However, the filling of 2 tanks can be carried out via a single interface. The refuelling piping system is vacuum insulated. Cryotherm's refuelling system provides a cold gas return for cooling the tank or for pressure relief (Figure 19) [26].

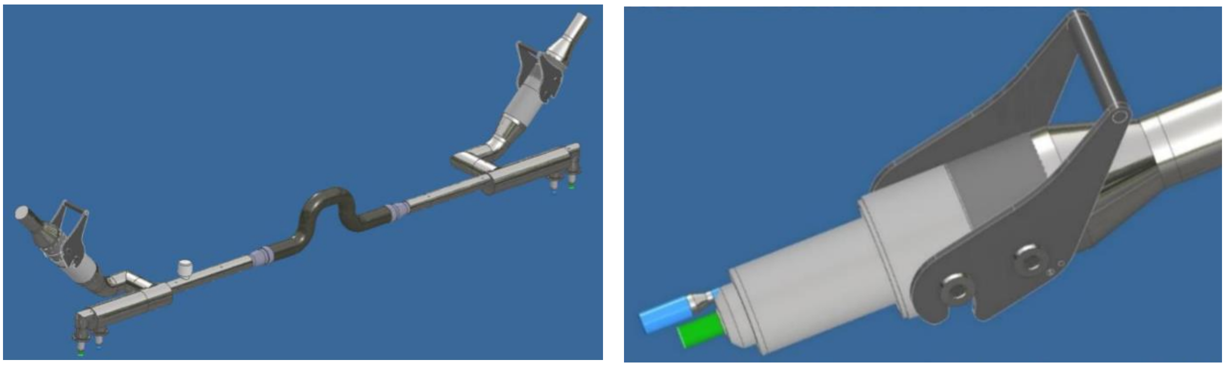

Figure 19: sLH_2 refuelling piping system (left) LH_2 fuel coupling (right) [26]

5.1.3 Cryo-compressed hydrogen

Initial work on CcH_2 refuelling technology was carried out by Linde AG from 2011 as part of the German NIP-funded project "Prototype development of a cryogenic pressure filling system" [27]. In the project, together with BMW, Linde developed and tested a direct single-flow refuelling concept up to 30 MPa via a cryo-pump with a continuous fill rate of 1.7–2 kg/min and quick-connect nozzle concept, without communication between the vehicle and the fuel dispenser (Figure 20, Figure 21) [28] [23].

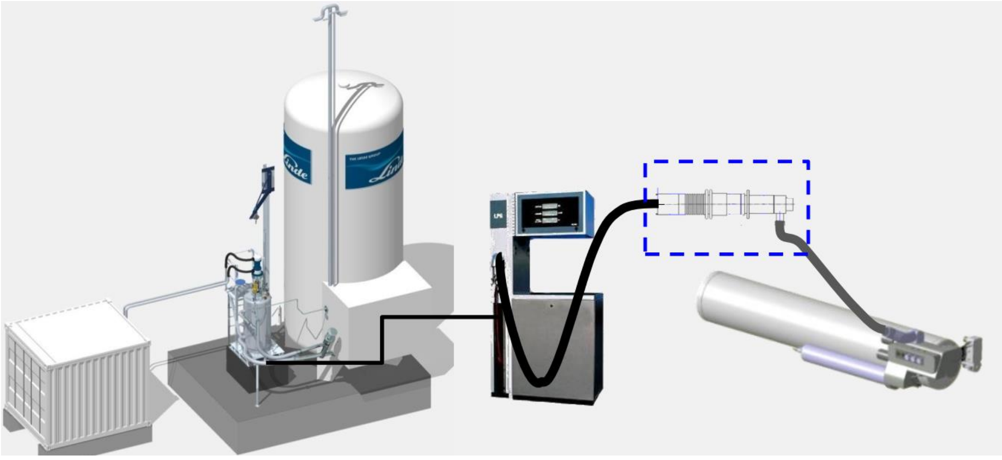

Figure 20: Single-flow refuelling infrastructure with cryo-compression from LH_2 and CcH_2 nozzle (source BMW) [28]

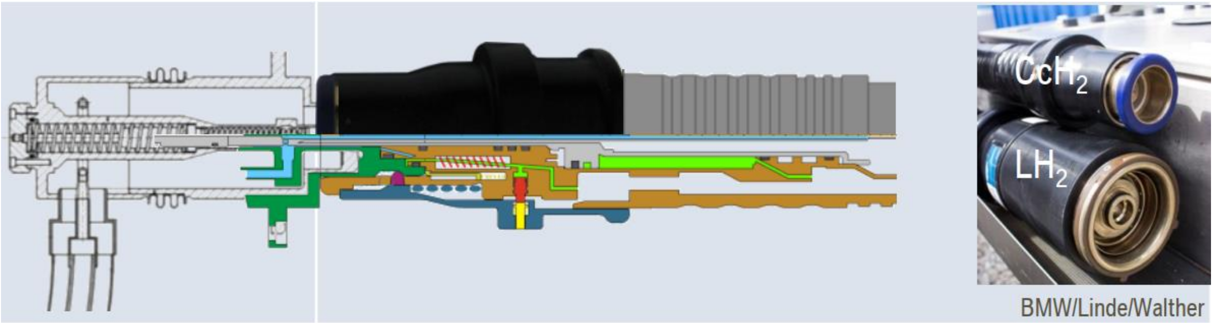

Figure 21: Cross-section of a CcH$_2$ refuelling nozzle with quick connector [23]

Cryomotive plans to develop and validate a high-flow nozzle (12–15 kg/min) and two CcH$_2$ prototype stations for heavy-duty lorry refuelling by 2023. They will also start standardising the CcH$_2$ refuelling interface. The standardisation of the CcH$_2$ refuelling interface should be completed by 2024 to 2025 [29].

Currently, CcH$_2$ storage technology and corresponding CcH$_2$ nozzles are not used in rail vehicles.

5.2 Hose

ISO 19880-1 recommends general safety and performance requirements for public and non-public refuelling stations that dispense gaseous hydrogen to light duty land vehicles, but can also be used as a guide for refuelling HDVs.

The table below shows the main characteristics of the refuelling hoses described in ISO 19880-1.

Design	Depending on the hydrogen supply and the ambient conditions at the place of use
Location	Arranged in such a way to avoid contact with the ground
Permeability	Leakage should not exceed 10 cm^3/h per metre of hose at 20 °C
Material	Non-corrosive metal mesh reinforcement
Strength	It should withstand tensile and torsional loads
Length	The hose should be long enough to fill vehicles but no longer than necessary

Table 7: Hose assembly design [13]

5.3 Breakaway

Breakaway is a safety device in the hose assembly that minimises damage to the dispenser if a vehicle drives off while the dispenser nozzle is connected.

The breakaway device disconnects when subjected to a maximum force of 1000 N, regardless of the operating pressure within the device and incorporating double shut-off valves to isolate both connection sides when disconnected.

There are two types of breakaway devices: single-use and multi-use devices. Multi-use devices require a method of reconnecting and must be pressurised and leak-tested under operating conditions before starting operation again.

Function	Disconnect when force > 1000 N
Design	Double shut-off valves
Durability	100,000 cycles of hydrogen gas pressure pulses
Types	Single-use
	Multi-use

Table 8: Hose breakaway device [13]

5.4 Communication

The dispenser can conduct the filling process either with or without communication with the vehicle.

In the case of communication between the HRS and vehicle, all variables involved in the process are known whereas this is not possible in the case of no communication. In the case of refuelling with communication, the process stops when the target pressure is reached or when the value of SOC is in the range of 95%-100%; in the case of refuelling with no communication, the process stops when the pressure in the station reaches the target pressure. Furthermore, the final SOC target value of 100% may never be reached in a process without communication because the target pressure limits the final CHSS pressure, typically resulting in SOC values below 90% [10].

The advantage of refuelling with communication over refuelling without communication is a higher SOC at the end of refuelling, but not a faster refuelling process. In fact, refuelling with communication can take longer than refuelling without communication because the refuelling ends later and at a higher target pressure [10].

Communication between the vehicle and refuelling station can be carried out with different goals, as mentioned in deliverable D2.3 of the PRHYDE project [17]. The information obtained can be useful to use:

- an internal data register of the fuel dispenser so the values are easily recorded. The recorded data can be analysed for improvement or maintenance purposes.
- a data transfer to manage the refuelling process, e.g. establishing a state of refuelling target as already mentioned above. The SAE J2601 standard defines limits for the refuelling protocol. According to this standard, the maximum pressure in the vehicle's fuel system is less than or equal to 125% normal working pressure (NWP) and the hydrogen temperature in the vehicle's fuel tanks is less than or equal to 85 °C. At 70 MPa, it is more likely to infringe these limits than at 35 MPa, so the dispenser system at 35 MPa does not necessarily integrate this type of communication.

The communication can be wireless or wired (see Figure 22).

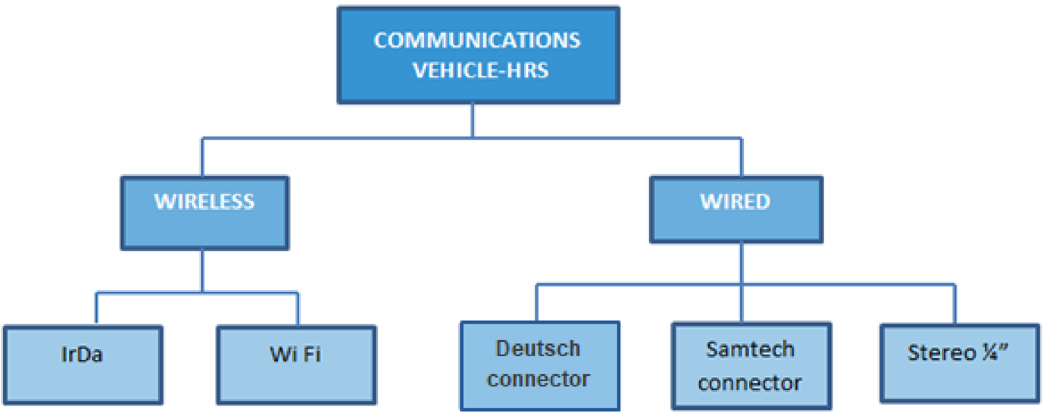

Figure 22: Refuelling station for vehicles with communication. Source: CNH2

The most typical hardware is infrared data association (IrDa) communication and is often used with the protocol defined in SAE J2799.

WiFi is another possible way of wireless communication between the nozzle and receptacle, but this method is not included in any standard.

With regard to HDVs, the following devices have been tested for wired connection [30]:

- Deutsch connector: device with many pins standardised at California Fuel Cell Partnership (CaFCP)
- Samtech connector: device with small pins
- Stereo ¼" cable

5.4.1 Infrared communication (SAE J2799)

The interface between the nozzle and receptacle is shown in the following figure taken from SAE J2799 [31].

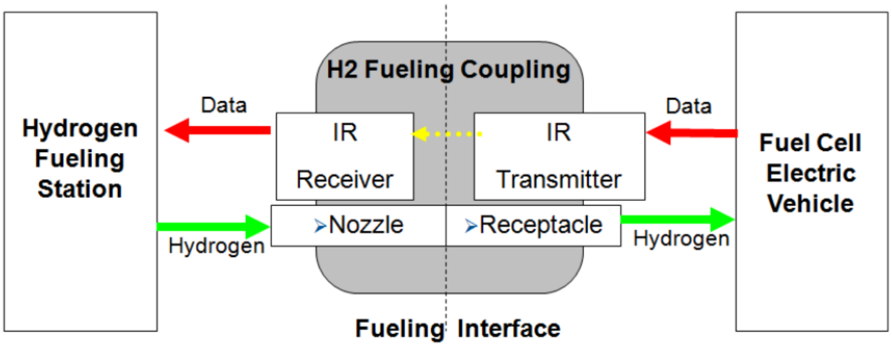

Figure 23: Nozzle-receptacle interface [31]

The communication between vehicle and refuelling station proposed by this SAE standard consists of an infrared transmitter mounted near the receptacle and an infrared receiver mounted inside the nozzle.

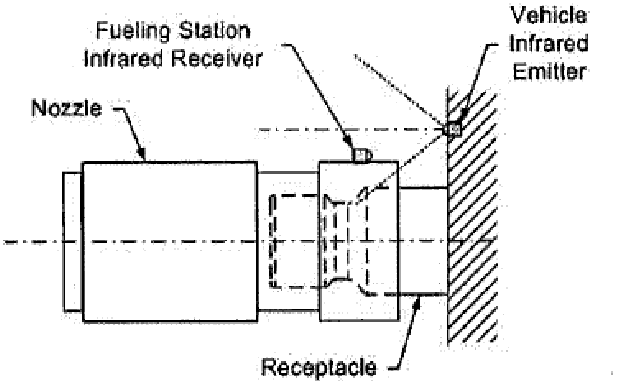

Figure 24: Emitter and receiver placement in infrared communication [31]

The information transferred from the emitter to the receiver includes:

- Protocol identifier
- Vehicle number
- Tank volume (litre)
- Receptacle type
- Fuelling command
- Measured pressure (MPa)
- Measured temperature (Kelvin)

5.5 Dispenser sensors

According to ISO 19880-1: " The ambient temperature of the fuelling station and the temperature, pressure and mass flow rate of the hydrogen refuelling should be monitored. The control unit of the fuelling station uses this data for the control system to control the refuelling process"

- " … The ambient temperature sensor should be placed in a location where it gives an accurate reading and should not be located in direct sunlight"
- " …The hydrogen temperature and pressure sensors that measure the fuel station delivery conditions at the dispenser should be located upstream of and as close as possible to the dispenser breakaway hose. SAE J2601 states that length of pipe between the sensors and hose breakaway should be no greater than 1 m" [13](page 40).

5.6 Refuelling times and energy demand comparison

The high volume and mass flows used in diesel train refuelling are not achievable for all H_2 refuelling technologies, in part because the currently achievable H_2 refuelling times are essentially based on existing technologies for buses and cars. The associated refuelling concepts are, therefore, designed for small quantities of H_2 per vehicle. Currently, there is no hydrogen refuelling technology that comes close to the refuelling times of diesel trains (Table 9).

	Max. volume and mass flow [kg H_2 / min]	[kWh/min]	Min. refuelling time for 2 vehicle tanks (2 nozzles) for 160 kg H_2 [min] a)
Diesel 1)	150 L/min	1.470	2.3 *)
CGH_2 35 MPa 2)	7.2	240	11.1
CGH_2 70 MPa 3)	3.6	120	22.2
CcH_2 35 MPa 4)	2.0	67	40.0
CcH_2 35 MPa 5)	Up to 13 **)	433	6.2
LH_2 6)	2.0	67	40.0
LH_2 7)	6.7 **)	223	11.9
LH_2 trailer filling 8)	8 - 12	400	-

a) theoretical values, heating of tanks not taken into account for CGH_2; *) ≙ 700 L diesel - compared to diesel: η-diesel/FCEMU (0.35/0.45); **) not yet realised for vehicle tank refuelling; 1) state of the art, source DB;
2) max. mass flow without precooling, bus sector: high-pressure storage, overflow, 35 MPa dispenser, SAE J2601-HD;
3) automotive sector: high pressure storage, precooling, 70 MPa dispenser, SAE J2601; 4) automotive sector: 1.7–2 kg/min with cryogenic high-pressure pump, without high pressure storage, without precooling; 5) 3.3–13.3 kg/min @ 30 MPa (cryopump), 35–50 K [29]; 6) automotive sector; 7) sLH2 for heavy-duty vehicles 6.7–8.3 kg H_2/h [32];
8) filling of LH_2 trailers (> 3000 kg): 4–6 h → ~8–12 kg H_2/min, unloading: 1–2 h;

Table 9: Comparison of H_2 refuelling times for different H_2 storage technologies and diesel. Source: DLR

A comparison of the energy demand is also carried out. Table 10 shows the comparison of the energy demand for hydrogen distribution and conditioning before hydrogen refuelling. Due to low plant utilisation, these reference values for the real energy demand in kWh/kg H_2 could be higher. For compression from 35 to 70 MPa, an additional ~ 1 kWh/kg H_2 is required. In general, the required energy demand for the compression of LH_2 at filling stations is lower but, for H_2 liquefaction, it is significantly higher (~30% of the H_2 energy content). The energy demand for conditioning can be reduced by advanced technologies, larger-scale applications and high utilisation.

Refuelling technology	Transport a)	Compression b)	Liquefaction c)	Pre-cooling b), d)
CGH_2 35 MPa	3.43	2–2.2 1)	-	
CGH_2 70 MPa	1.03	2.67–3.0 1)	-	0.1 (0.45) 1)
CcH_2 35 MPa	*)	1.3–1.5 2)	*)	-
LH_2	0.34	0.05 3)	10–13 1)	-

a) 300 km road transport, trailer fuel consumption 35 l diesel/100 km, 3000 kg LH_2, 30000 l LOHC, 1000 kg CGH_2 (50 MPa), 300 kg CGH_2 (20 MPa); **b)** CGH_2: Origin GH_2 – 1 MPa to 44 MPa (35 MPa), 1 MPa to 70 MPa; if compressed from LH_2: less energy required for compression; no precooling but subsequent heating required; **c)** after H_2 generation, LH_2 transfer only pumping, no compression; **d)** 15 °C to -20 °C (ΔT = 35 K), (30 °C to -40 °C (ΔT = 70 °K)); *) see LH_2 if cryo-compressed from LH_2; **1)** Based on DOE Hydrogen and Fuel Cells Program Record #9013: [33]; **2)** Based on LLNL FY 2013 Annual Progress Report: Rapid High-Pressure Liquid Hydrogen Refuelling for Maximum Range and Dormancy [34]; Based on Linde and Daimler [32]

Table 10: Energy demand for hydrogen distribution and conditioning [kWh/kg H_2]. Source: DLR

6. Evaluation of different hydrogen on-board storage options

To provide the necessary information for evaluating the most suitable option for each use case, the following sub-sections describe the options for on-board storage and their main types of integration solutions.

6.1 On-board H_2 storage system

Hydrogen has a low density (0.0899 kg/m^3) under ambient conditions, so this value must be increased to enable the use of hydrogen in the transport sector. Increasing the pressure and decreasing the temperature are two ways of raising its density value per volume.

Different physical-based storage methods are then shown:

- Compressed gaseous hydrogen (CGH_2)
- Liquid hydrogen (LH_2)
- Cryo-compressed hydrogen (CcH_2)
- Material-based hydrogen storage methods, such as hydrogen stored in chemical or physical compounds in or on solids or liquids, are still in the laboratory stage and are omitted from our analysis

Figure 25 provides an overview of the hydrogen density at substance level for various temperatures and pressures. There are three zones, one for each type of storage: CGH_2 zone (yellow) – ambient temperature with high pressure, LH_2 zone (blue) – cryogenic temperature under pressures up to 0.4 MPa and CcH_2 zone (green) – with a wide temperature and pressure range. In this last zone, the hydrogen reaches its higher densities.

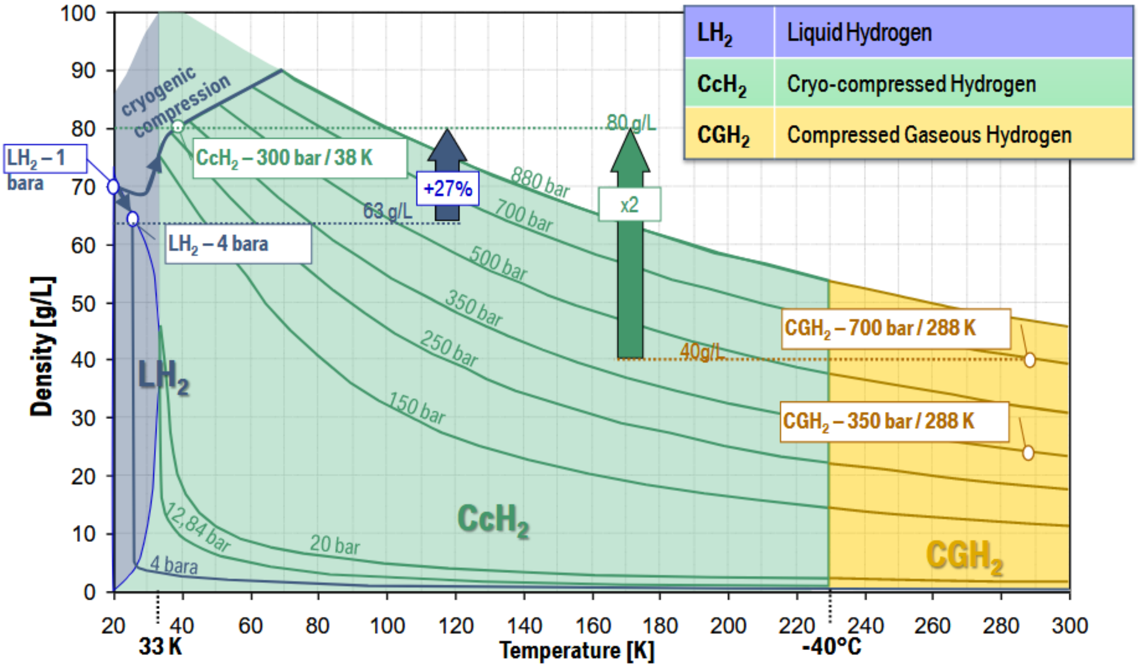

Figure 25: H_2 density at substance level for different temperatures and pressures [35]

Table 11 shows the density and energy content of hydrogen at different pressures:

H_2	Pressure	Temperature	Density	Energy content	
	[MPa]	[°C]	[kg/m^3]	[MJ]	[kWh]
1 kg	0.1	25	0.08	120	33.3
1 Nm³				10.7	3
1 m³ gas	35		23.3	2630	731
1 m³ gas	75		39.3	4276	1188
1 kg liquid	0.1	-253	70.8	120	33.3
1 m³ liquid	0.1			8495	2360

Table 11: Density and energy content of hydrogen at different pressures [36]

6.1.1 Compressed gaseous hydrogen

Gaseous hydrogen storage is the most advanced technology. CGH$_2$ is stored at different NWPs (35 MPa, 50 MPa, 70 MPa) in high-pressure storage cylinders. Up to 7% of the energy content can be lost during compression.

35 MPa is the storage pressure level predominantly used in buses and trains today, 50 MPa storage cylinders are typically used for the transport of H_2 gas on vehicle trailers and 70 MPa is used for cars and is currently being discussed for use in lorries.

Pressure vessels are classified according to the manufacturing materials and the maximum working pressure (Types I, II, III and IV) (Table 12). There are four types of vessel, but when the condition of on-board storage is added, only vessel Type III and Type IV are recommended due to their weight. Type III and Type IV are lighter than Type I and Type II due to the materials used in their manufacture.

Tank type	Material	Pressure (MPa)	Characteristics
I	Pressure vessel made entirely of metal (steel or aluminium)	15–30	Very heavy with thick wall. Stationary applications
II	Pressure vessel made of a metallic liner hoop wrapped with a fibre-resin continuous filament	45–80	Very heavy. Usually used as a buffer or intermediate tank in stationary applications
III	Pressure vessel made of metallic liner fully wrapped with a fibre-resin composite	35–70	Mainly used in mobility and transport applications
IV	Pressure vessel made of a polymeric liner fully wrapped with a fibre-resin composite	35–70	Mainly used in mobility and transport applications

Table 12: Type of vessels

The evolution of vessels has led to a new type of vessel, a fully-composite vessel without liner. The Type V vessel is a fully-wrapped composite cylinder without liner. Currently, there are very few Type V pressure vessels due to their high cost.

More information about vessel types III and IV is given in ANNEX B.

6.1.2 Liquid hydrogen

LH_2 is stored in cryogenic storage systems at low temperatures of -252.85 °C (20.3 K) at 0.4 MPa. These systems are technologically more complex than the previously mentioned high-pressure storage cylinders and consist of an inner tank in which LH_2 is stored, surrounded by multilayer insulation and vacuum-insulated outer tank.

The LH_2 tanks are not designed to withstand internal pressure but to store a cryogenic liquid. For this reason, vacuum insulated tanks should be used. Due to the large temperature difference to the environment, heat is introduced into the system after a certain time, causing the hydrogen to evaporate resulting in an increase in temperature and pressure in the inner tank. This higher pressure must be relieved – this is referred to as boil-off losses. For the intended release of H_2, on the other hand, heat is specifically introduced into the system via an electric heater (Figure 26).

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

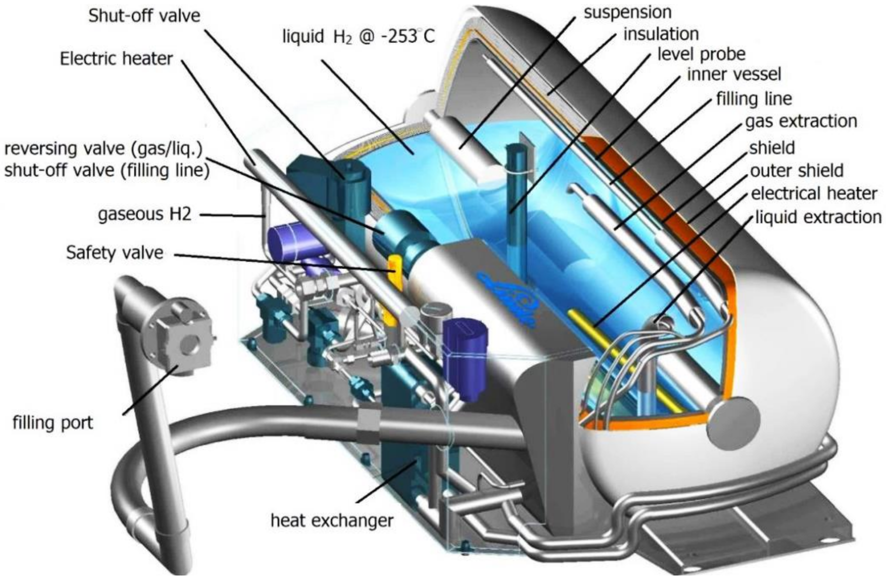

Figure 26: LH_2 hydrogen storage system [37]

The liquefaction process requires compressors, heat exchangers and expansion valves. This process requires considerable energy – between 30%–40% of the energy content of liquefied hydrogen – but, in contrast, the density of LH_2 at atmospheric pressure is higher than the density of compressed gas, also at 100 MPa.

Cryogenic liquid hydrogen tanks are spherical and cylindrical to maximise internal volume over heat exchange area.

Although prototypes and small series LH_2 tanks have been in use for 50 years, the use of LH_2 in the transport sector has not become established. LH_2 storage systems were tested in demonstration vehicles in America, Japan and Germany from 1971–1978. In 1995, MAN demonstrated an experimental city bus (MAN SL) and, in 2000, Opel demonstrated an experimental car (Opel HydroGen 1), both equipped with LH_2 storage systems. In 2000, BMW demonstrated 15 hydrogen 7 series cars with H_2 combustion engines and LH_2 tanks from MAGNA STEYR [36], [38], [39].

It can be concluded from this, that there are no series vehicle storage tank systems for LH_2 available on the market today. For heavy-duty lorries, there are currently efforts to increase the system pressure of LH_2 storage tanks, described as sLH_2.

6.1.2.1 Subcooled liquid hydrogen

sLH_2 is a further development of the 0.4 MPa LH_2 tank systems already described, where the storage pressure is increased to 1.6 MPa (maximum working pressure up to 2 MPa). This system and the associated refuelling technology are currently being developed for heavy-duty lorries by Daimler Truck AG, Linde AG and Cryotherm GmbH & Co. KG (Table 13). According to the manufacturers, this approach enables a higher storage density, avoids so-called boil-off effects and will not require complex data communication between the filling station and the lorry during refuelling. The first refuelling of a prototype vehicle at a pilot station in Germany is planned by Daimler and Linde for 2023 [40]. The sLH_2 twin-tank system from Cryotherm is shown in Figure 27 [26].

Manufacturer	Usable hydrogen	Length	Diameter	Volume	Weight (incl. H_2)	Grav. capacity
	[kg]	[mm]	[mm]	[L]	[kg]	[%]
Daimler Truck AG and Linde AG	44	2500	710	760	500	~10
Cryotherm GmbH & Co . KG	44.6	2500	710	743	500	~10

Table 13: 1.6 MPa sLH_2 storage systems [40], [26]

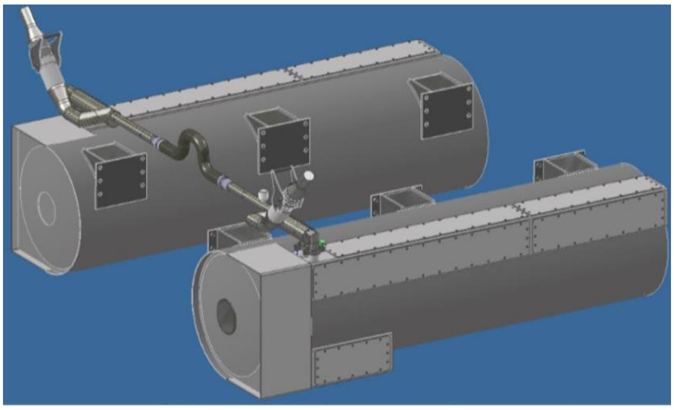

Figure 27: sLH2 twin-tank system, source Cryotherm [26]

6.1.3 Cryo-compressed hydrogen storage

CcH_2 is a combination of low temperature and high pressure that combines the best advantages of the two conventional storage types (CGH_2 and LH_2). CcH_2 storage refers to the storage of hydrogen at cryogenic temperatures in a vessel that can be pressurised (up to 35–50 MPa), as opposed to cryogenic liquid vessels that store LH_2 at near ambient pressures. The pressure applied to the hydrogen allows the cryogenic temperature to rise (in a range of -240 °C to -73 °C), decreasing the cost of liquefaction and providing sufficient thermal resistance to reduce boil-off. The wide operating temperature ranges have a long-term effect on fatigue life and material ageing [41].

The cryo-compression tank is a Type III composite pressure vessel with a metallic liner encapsulated in an insulated secondary jacket (vacuum envelope), whose function is to limit heat transfer between the inner tank and the environment (Figure 28).

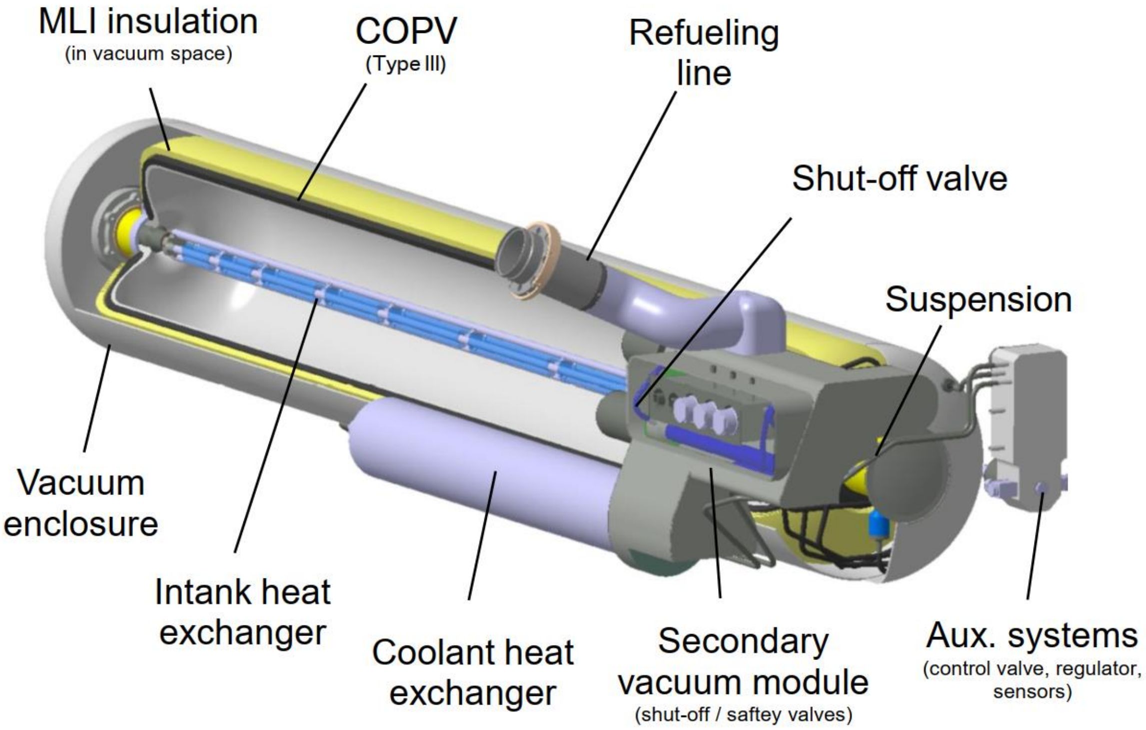

Figure 28: BMW carbon fibre overwrapped pressure vessel for the storage of CcH_2 gas [28]

From 2009 to 2015, BMW developed and tested CcH_2 storage systems in series prototype cars [28], [42]. The CcH_2 vehicles did not go into series production. Cryomotive GmbH (Germany) is currently developing a CcH_2 storage system for heavy-duty lorries (Figure 29). According to the manufacturer, 2000 refuelling cycles could be possible at mass flow rates up to 13 kg/min. The expected energy requirement for CcH_2 compression is estimated to be 0.5 kWh/kg H_2 [29]. Selected characteristics of CcH_2 storage systems are shown in Table 14.

Manufacturer	Usable hydrogen	Length	Diameter	Volume	Weight (incl. H_2)	Grav. capacity
	[kg]	[mm]	[mm]	[L]	[kg]	[%]
BMW	7.1	-	-	-	160	4.6
BMW	7.8	-	-	235	145	5.7
Cryomotive GmbH	25	2350	600	664.4	337.5	~8
Cryomotive GmbH	35	2650	700	1019.8	472.5	~8

Table 14: CcH_2 storage systems. Source: DLR

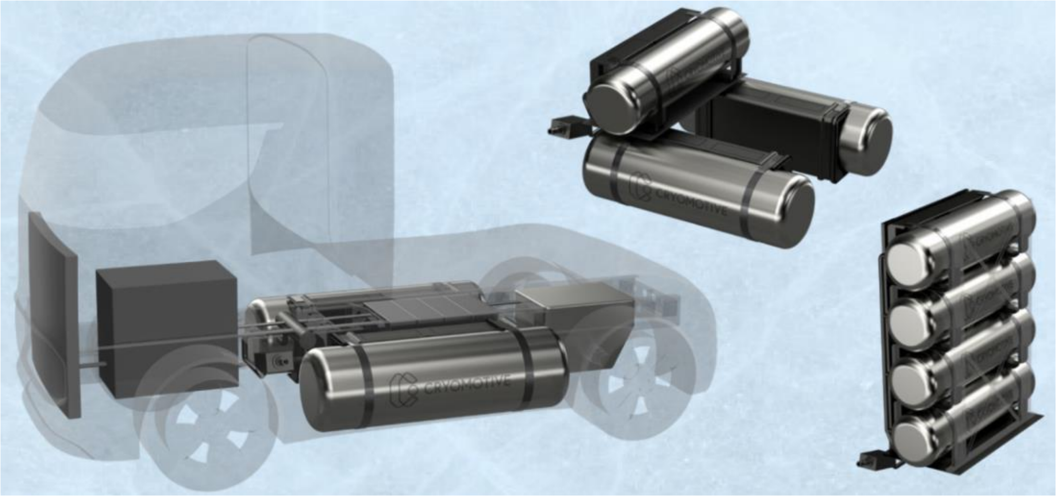

Figure 29: CcH$_2$ storage system vehicle integration example for CcH$_2$ capacities of 78, 105 A and 115 kg [29]

6.1.4 On-board H$_2$ storage systems comparison

As mentioned in the previous sections, there are three main methods for hydrogen on-board storage. Figure 30 and Figure 31 show the system weight, system volume and hydrogen capacity for these methods. The data is based on inquiries and data specifications from the following CGH$_2$ storage manufacturers (shown in ANNEX B: Table 18, Table 19 and Table 20): Hexagon Purus (Norway, US), NPROXX (Netherlands), Quantum (US), Faurecia (France), Luxfer (Germany, UK), Worthington (US), Faber (Italy), Mahytec (France), Steelhead Composites (US), CLD (China) and supplemented by literature references on LH$_2$ and CcH$_2$.

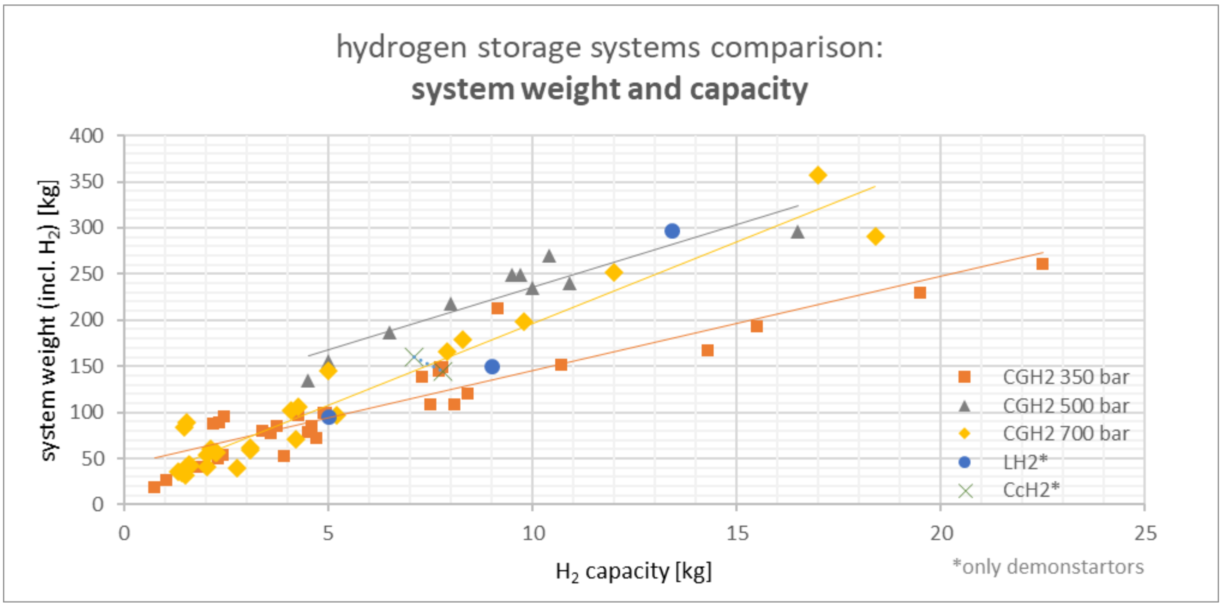

Figure 30: System weight and H$_2$ capacity of H$_2$ storage systems

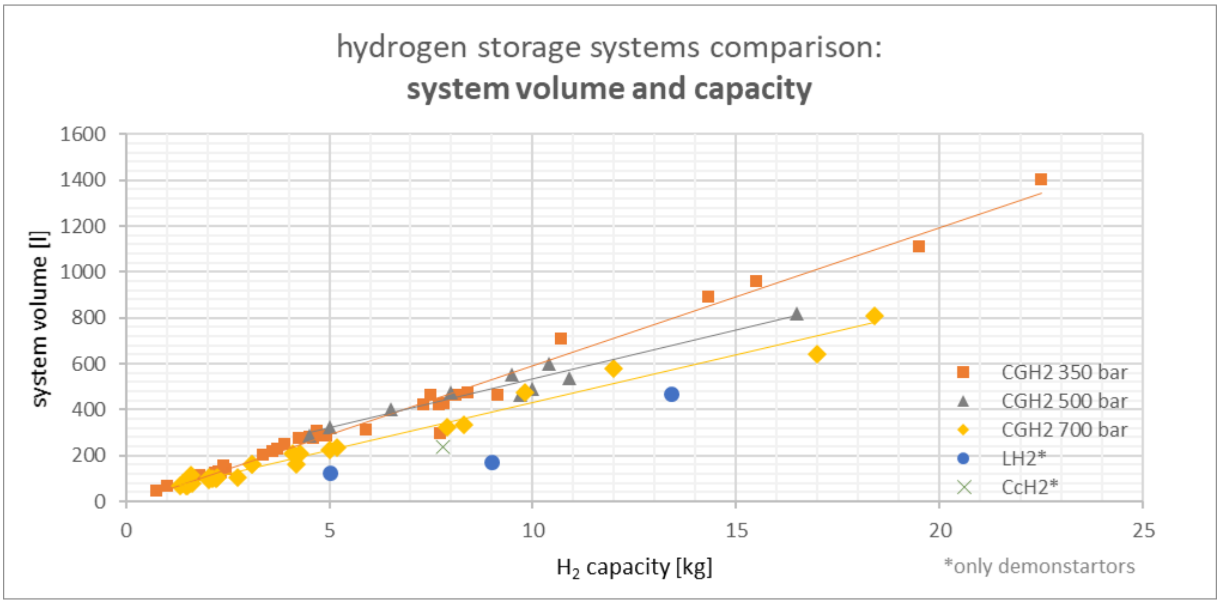

Figure 31: System volume and H2 capacity of H2 storage systems

Table 15 shows the comparison of CGH$_2$, LH$_2$ and CcH$_2$ storage systems regarding pressure, density on the substance level, volumetric and gravimetric capacity and technological readiness level (TRL). Doubling the storage pressure from 35 to 70 MPa only results in an increase of the energy density on the substance level of a factor of 1.68 due to the isothermal properties of hydrogen (70 MPa is 39.2 g/L; at 35 MPa, it is 23.3 g/L [43]). With LH$_2$ and CcH$_2$ storage systems, the volumetric energy storage capacity could be doubled compared to CGH$_2$ systems. Boil-off and blow-off losses may not be relevant for lorries and rail vehicles due to the longer operating time in contrast to passenger cars. Currently, there are no series vehicle storage tank systems available for LH$_2$ and CcH$_2$, but development is being driven by the industry. For heavy-duty lorries in particular, there are currently efforts for LH$_2$ and CcH$_2$ storage systems. The development and validation of the first prototype vehicles is expected to be completed in 2023.

		CGH$_2$	CGH$_2$	CGH$_2$	LH$_2$*	sLH$_2$*	CcH$_2$*
Pressure	[MPa]	35	50	70	0.4	1.6	30
Density (substance)	[g/L]	23.3[1]	30.8[1]	39.2[1]	63[2]	> 63[2]	72[3]
Vol. capacity	[g/L]	16–18	16–20	19–23	28–40	58–60	33–46[3]
Grav. capacity	[%]	4.2–6.9	3.4–4.2	3.8–5.0	4.5–5.3	~10	7.5–10[3]
TRL	–	7–9	7–9	7–9	7	4	7[4]

* *technology is being developed for road transport, no series tank systems are currently available;*
[1] [43] *isothermal data for T = 25 °C for hydrogen at substance level;* [2] *Source BMW presentation 2012* [35];
[3] *Cryomotive presentation 2021,* [41];
[4] *for cars, TRL 7–8 for heavy-duty lorries in 2023-2024;*

Table 15: Comparison of CGH$_2$, LH$_2$ and CcH$_2$ storage systems. Source: DLR

6.1.5 Standardisation for H_2 on-board storage

Currently, there are no directly applicable standards and regulations on the use of hydrogen storage systems in rail vehicles. Most hazards can be controlled by applying existing regulations from other hydrogen usage sectors in combination with existing railway-specific standards. The remaining hazards must be covered by individual actions down to an acceptable remaining risk, whereby the corresponding procedure is not yet uniformly regulated at present [44]. For hydrogen-powered motor vehicles, for example, hydrogen pressure storage systems must have a type approval in accordance with regulation (EC) no. 79/2009 of the European Parliament and the Council of the European Union. There is currently no separate regulation for rail vehicles.

In the International Electrotechnical Commission (IEC) TC 9, specifically in 'PNW 9-2697 ED1: Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system', international standardisation work is ongoing in the field of hydrogen storage systems for rail. The publication of the results is planned for February 2024 [45].

6.2 H_2 storage systems vehicle integration options

Regardless of the type of train, the design of the H_2 storage system for railway applications can differ significantly depending on the location of the storage cylinders.

According to the space available, there are two options for integrating the storage unit in the vehicle:

- If the limitations of the gauge loading are not restrictive, the hydrogen storage tanks can be installed on the roof of the train.
- If there is no space available on the roof, the hydrogen storage tanks can be installed inside the technical carriage in the train set

Assessing the capacity of on-board hydrogen storage means estimating the volume that can be used for H_2. The key dimensions here are length, width and height.

In the case of roof integration, these key dimensions are determined by the carriage length and gauge restrictions, whereas in the case of integration the storage inside the technical carriage, the length and height are determined by the dimensions of the carriage itself and the width is determined by passage restrictions.

In addition to the previously mentioned dimensions, the following two factors must be taken into account when assessing the capacity of the hydrogen storage tank:

- Volume factor = 0.85
  This factor accounts for the external volume of a cylinder in relation to its internal volume. It is obtained from the cross-section of the cylinder (circular cross-section) assuming a wall thickness of 15 mm.

- Packing factor = 0.6

This factor is used to take into account the free space between the cylinders in the storage system. It is obtained by calculating the ratio between the area of a square with side L and the area of the circular cross-section of a cylinder; (ratio = $\pi/4 = 0.785$). Since the upper part of the cylinder is spherical and not cylindrical and the structure of the rack itself will require space, this ratio is lowered to 0.6 to obtain a more conservative value.

Although more detailed information about the two types of integration and the calculations performed is given in ANNEX C, it is possible to summarise that approximately the same amount of hydrogen can be stored in a multiple train with both integration options.

7. Conclusions

In conclusion, this report examined the different technological options for the hydrogen refuelling system. The advantages and disadvantages and main characteristics were explained for each of them. The reasons for the different on-board energy supply and storage solutions for railway vehicles are summarised below.

Hydrogen is supplied to the train in an HRS according to a refuelling protocol. Currently, there is no standard for hydrogen refuelling protocols for heavy duty vehicles with high flow as only SAE J2601-2 is specific to heavy duty vehicles, but it is a guideline that does not provide the details required for a full standard. Some research and development should, therefore, be speedily carried out in order to provide solutions for trains that require a large amount of hydrogen at each refuelling.

During the refuelling process, communication is useful to control the pressure and temperature values in the CHSS at all times, as both of them are measured directly by integrated sensors in the vehicle's tank whereas, during a refuelling process without communication, these values are measured by the sensors of the fuel dispenser and, therefore, may not correspond exactly to the pressure and temperature in the CHSS. The advantages of data communication protocols are in minimising refuelling time and achieving SOC values of between 95–100%.

The interfaces of HRS fuel cell hydrogen trains should be determined using a specific standard for rail vehicles. Nevertheless, in the absence of such specific standards, ISO 19880-1 has been used in this deliverable. This standard is specific to light duty road vehicles but also serves as a guide for heavy duty road vehicles. The most important interface for the HRS train system is the nozzle/receptacle. No specific nozzles and receptacles have yet been developed for the refuelling of rail vehicles, and the devices available on the market are designed for hydrogen road vehicles. Both devices must be compatible, so the receptacles recommended by manufacturers such as WEH for gaseous compressed hydrogen are the TN1 HF (with or without communication) and TN5, whose compatible nozzles are the TK16 HF (with or without communication) and the TK25 respectively.

The hydrogen is supplied from the refuelling station to the vehicle tank. Currently, there are no standards and regulations directly applicable to the use of hydrogen storage systems in rail vehicles. At the moment, around 10 manufacturers worldwide produce sufficiently sized CGH_2 storage systems at different pressure levels that could potentially be used for rail vehicles. Nevertheless, the conclusion could be drawn that there are no mass-produced vehicle storage tank systems for LH_2 available on the market today. At present, there are efforts to increase the system pressure for heavy-duty lorries. CcH_2 storage technology is also not currently used in rail vehicles, but is under development for lorries.

In general, CGH_2 storage is the most advanced technology (TRL 7-9), but significant efforts are being made to promote the development of LH_2 and CcH_2 storage (TRL 4-7). Hydrogen rail vehicles use CGH_2 on-board storage at the moment, but LH_2 storage is being considered in other research projects aimed at developing the world's first liquefied hydrogen-based traction system. Because 35 MPa is the standard pressure for HRS of heavy-duty vehicles, 35 MPa storage technology is being used for the latest developments in other rail projects. If the storage pressure is increased from 35 to 70 MPa, this results in a factor of just 1.7 of the energy density increase at the substance level and a factor of 1.3 in volumetric density at the storage system level. It was shown that the volumetric energy storage capacity of LH_2 and CcH_2 storage systems could be doubled at storage system level compared with CGH_2 systems.

Finally, as far as the on-board storage is concerned, it can be placed on the roof (i) or integrated in the technical compartment (ii). The amount of hydrogen that can be stored on board in each option depends on the type of train.

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A.1 List of Figures

A.2 List of Tables

ANNEX A

State of the art of diesel refuelling

A.1 Definition of diesel refuelling points

According to the 2021 Network Statement of the Administrator of Railway Infrastructures (ADIF) in Spain, diesel refuelling points are defined as facilities equipped with the appropriate technical means for dispensing traction diesel to railway vehicles with the appropriate safety measures.

Railway undertakings may supply their vehicles with fuel through:

- Mobile supply points
- Network of fixed fuel supply points

The management of diesel refuelling stations in the railway sector depends on the individual country. In the case of Spain, the fixed refuelling points are managed directly by ADIF while the mobile supply points are placed under the authority of the Sub-Director of Fuel Management upon request. In the latter case and only in the case of diesel suppliers other than ADIF (self-supply), railway undertakings must inform the operator of the installation and always comply with the conditions of use of the installation.

A.1.1 Mobile refuelling points for diesel

The supply at the mobile points is carried out by tankers. The procedure is as follows: A request is made and the delivery is planned directly from the lorry to the train for the specific day and time at the authorised point.

Diesel supply facilities vary in their configuration and dimensions depending on their characteristics. The mobile points have road access only for the supply vehicles, rail access and protective elements in some cases. This information is explained in more detail in the following sub-sections.

The use of these points is minor compared to fixed supply points. They usually have high time usage associated with temporary movements but, in many cases, they end up having very few operations per year.

A.1.2 Fixed refuelling points for diesel

Fixed refuelling points offer more complex facilities including storage elements, loading, drive, supply points, fire protection, security installations and/or electricity.

Figure 32 shows a map of the fixed diesel refuelling points managed directly by ADIF. This map is in an annexed document of the 2021 ADIF Network Statement and can be consulted on the ADIF website [46].

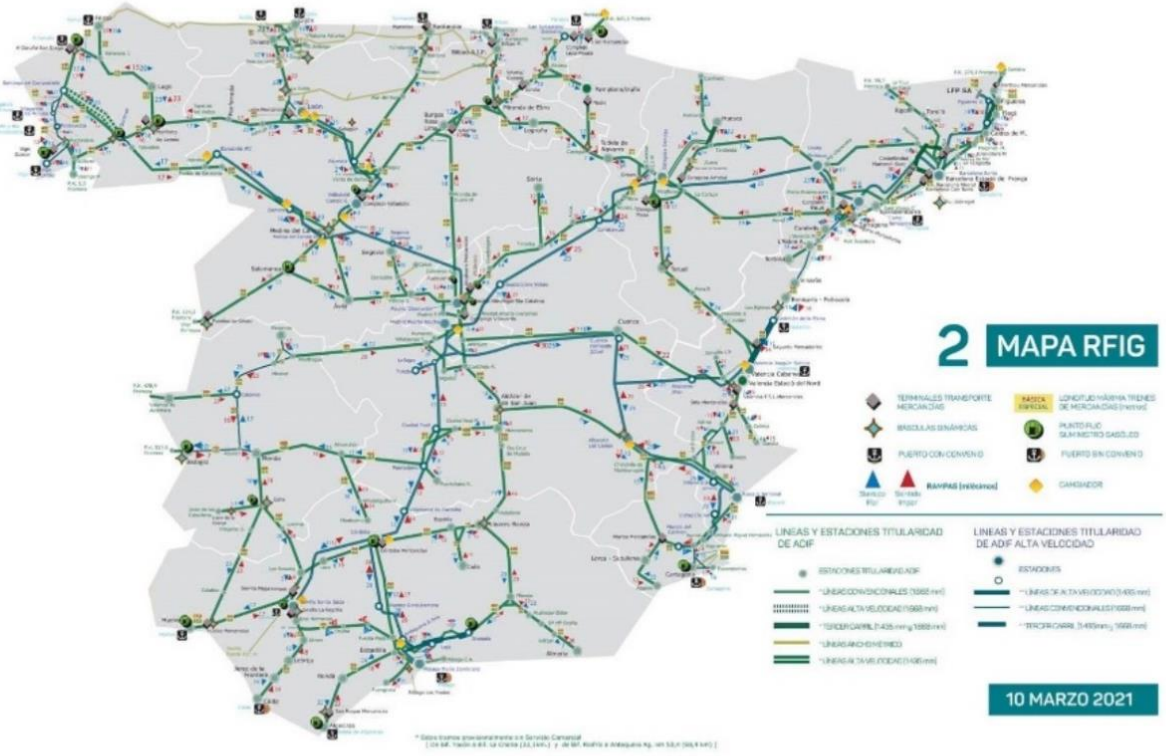

Figure 32: 2021 ADIF Network Statement map *[46]*

The storage capacities of fixed refuelling points vary according to refuelling needs. As an example, Table 16 shows a list, with some technical and dimensional parameters, of the 22 main supply facilities in ADIF linked to the main freight terminals.

The main refuelling point in Spain is located at the Fuencarral Terminal (in Madrid) which is the main supplier in Spain with three supply points, working separately.

Facilities	Storage capacity (L)	Refuelling point	Litres supplied per year	Refuelling number
Fuencarral	3 x 100,000	3	10,920,469	6546
Vicálvaro	80,000	2	4,528,706	1363
Abroñigal	50,000	2	1,925,699	609
Badajoz	75,000	1	1,233,089	1248
Zafra	30,000	1	563,921	391
Algeciras	15,000 + 20,000	2	2,174,212	1376
Almería	50,000	1	0	0
Córdoba	50,000	1	642,233	353
Granada	60,000	1	0	0
Huelva	50,000	1	2,436,093	1248
Sevilla	2 x 80,000	3	2,544,008	2672
Alicante	50,000	1	1,496,039	2272
Cartagena	60,000	1	2,275,541	3907
Zaragoza Plaza	30,000 + 80,000	1	2,795,421	2080
Irún	55,000	1	87,255	131
Coruña	2 x 80,000	2	1,923,462	2339
Monforte	2 x 50,000	2	2,378,843	1076
Orense	50,000	1	1,666,124	1490
Vigo Guixar	58,000	1	1,514,210	1385
Miranda	20,000	1	271,145	105
Salamanca	2 x 60,000	1	3,570,920	2970
Valladolid	75,000	1	59,1475	412

Table 16: List of main fixed diesel supply points. Source: ADIF

Based on the diesel supply requirements shown in Table 16, it is expected that an extensive network of HRS will be developed in the future.

A.2 Main functional area in diesel refuelling points

The main functional areas in refuelling facilities are storage, sanitation, electrical system, fire protection and security. Its principles of operation and the elements of each functional area are described below in detail.

The operating flow of hydrocarbons in a fuel installation can be described according to the following scheme:

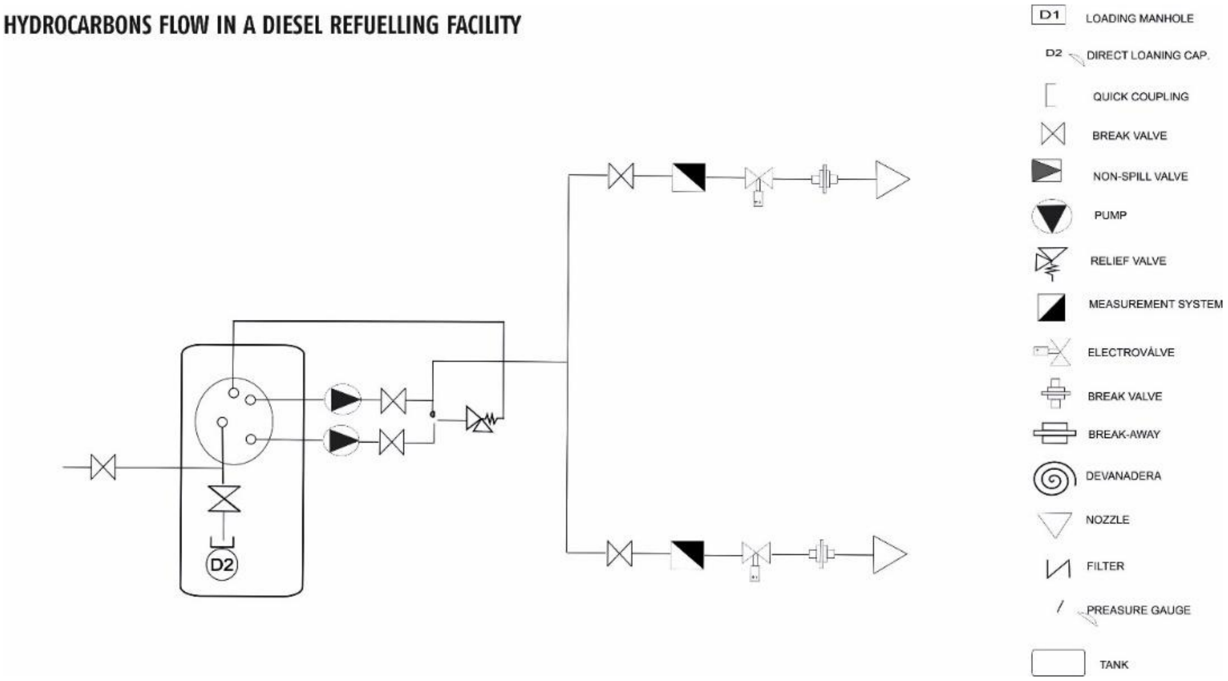

Figure 33: Hydrocarbons in a fuel installation scheme. Source: ADIF

A.2.1 Storage

The storage system consists of tanks, venting, electronic measurement, load and drive.

- The storage system is made up of one or more double-wall steel tanks. Those tanks are usually installed with an overfill valve on the surface and one or two manholes at the top for access to the interior and to accommodate the main elements installed in the tank.
- The venting system is responsible for providing the necessary ventilation for the tank and consists of a steel ventilation pipe and a flame-extinguishing grid.
- The electronic measurement system consists of a magnetic control indicator, a register and control console.
- The loading system mainly comprises a piping system with a no-spill system, valves and hose quick coupling.

- In turn, the drive system is composed of a pipe, submerged pumps, variable frequency drives, mechanical leak detection, valves, relief valves and pressure gauges.

In aerial sections (registrable), the pipes are made of steel and in buried sections the pipes are coated in polyethylene. The supply point has metering equipment with a pulse generator and a volumetric meter, hose, nozzle, winding, pressure gauge, ball valve, electro valve and breakaway valve.

The supply area is protected by steel waste collection containers connected to the hydrocarbon separator, with a tramex platform on top to ensure the safety of the operators of the installation.

A.2.2 Sanitation

The sanitation concept of a diesel refuelling system for hydrocarbon water may look as shown in Figure 34.

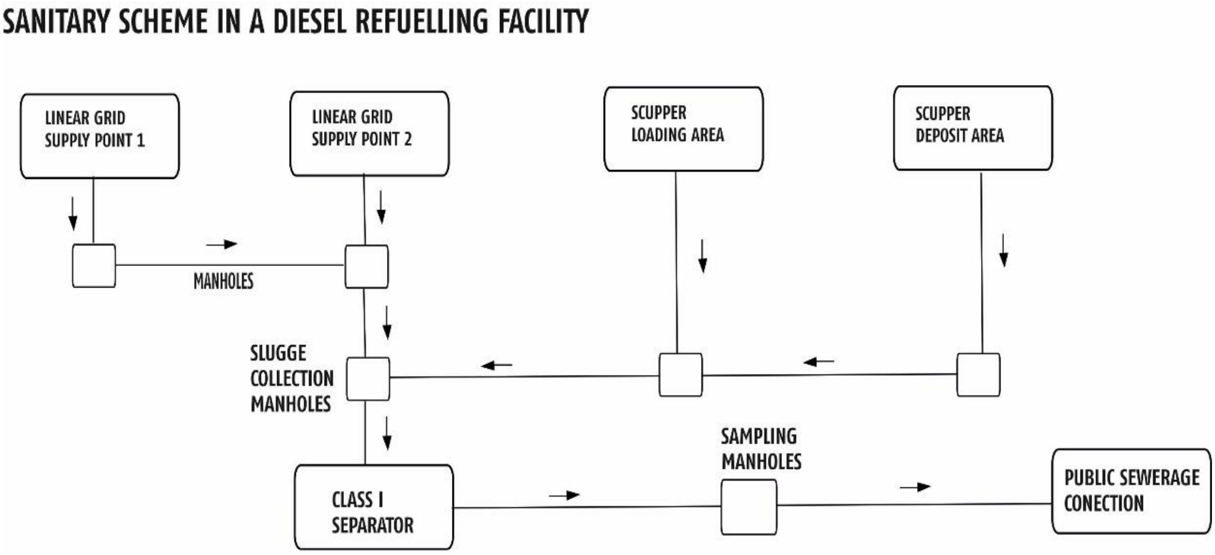

Figure 34: Sanitation scheme of a diesel refuelling facility. Source: ADIF

The main elements of the installation are pipes, a class I separator, scupper and linear grid.

The areas where hydrocarbon water can accumulate are sometimes located in the area of the bucket with a scupper in the back of the tank’s tiling; another scupper is in the sealed area of the loading area and the sealed panels under the tramex grids in each of the supply points.

All hydrocarbon water collected in the various areas of the installation is directed to a class I hydrocarbon separator.

A sludge collection elbow is usually installed upstream of the decanter. Downstream of the decanter, a sampling elbow is installed, and downstream of this, as is the case of wastewater with pollution levels below the specified values (approx. < 5 mg/litre), the wastewater network is connected to the general wastewater network of the railway complex or the public sewage system.

The facility also has a sufficient amount of absorbent material to eliminate small fuel leaks. The absorbent used is stored in an exclusive container that can be removed later by an authorised manager. A hydrant is also included next to the tiling of the tank and a water connection for maintenance work.

The facility also has a clean water meter to measure the amount of water it uses as well as the pipes that flow through the hydrant.

A.2.3 Electrical system

The electrical system essentially consists of an electrical panel, an earthing network, a meter and a lighting network. A typical one-line diagram of a diesel refuelling system is shown in Figure 35.

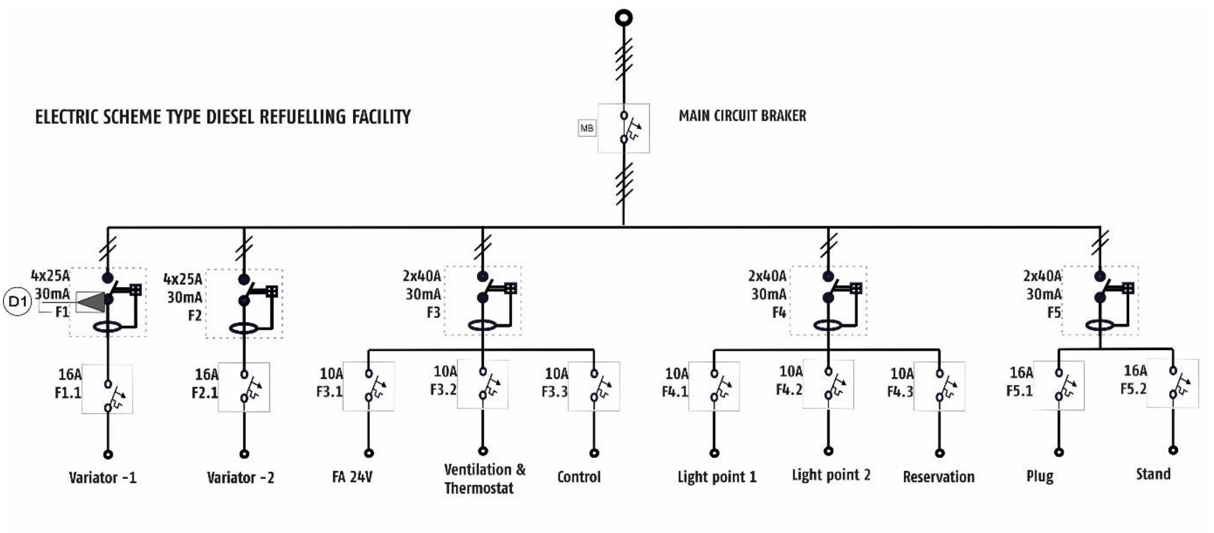

Figure 35: One-line type diagram of a diesel refuelling facility. Source: ADIF

The electrical installation has a general earthing network and should comply with ATEX regulations. In addition, the electrical installation complies with the Low Voltage Directive (2014/35/UE).

A.2.4 Fire protection equipment

The fire protection equipment has at least the following extinguishers:

- CO_2 extinguisher of 2 kg and efficiency 89 B next to the electrical panel
- ABC multi-purpose powder fire extinguishers of 6 kg and efficiency 89 B, next to the tank and supply points
- ABC polyvalent dust cart extinguisher of 25 kg in the lorry's unloading area

A.2.5 Security system

The main elements of the security system are an emergency alarm system with acoustic signal, emergency lighting, signalling systems, security fencing, video surveillance system, mechanised access control door and identification card system at the point of supply.

There is also be an external switch to shut down the electrical panel and an emergency shutdown button with acoustic signal and shutdown of all electrical signals.

Figure 36: Diesel refuelling facility (example). Source: ADIF

A.3 Procedures for diesel refuelling

The infrastructure manager of each country has internal operating procedures related to the delivery of diesel fuel. These procedures define the actions, incidents, rules, schedules, measures or safety protection systems in these facilities.

A company authorised by the infrastructure manager supervises the refuelling process. This process is similar to the refuelling of lorries or trailers. The refuelling times depend on the amount of fuel to be supplied (size of tank and initial level of filling) and on the dispenser (nozzle and working pressure). On average, the refuelling time for trains with a capacity of approximately 3,000 litres is 15 minutes (flow rate ≈ 200 L/min).

As mentioned above, in the case of Spain, ADIF oversees diesel refuelling operations and in order to manage the public use of these diesel refuelling points ADIF has public procedures. The list of the main internal operating procedures of ADIF's freight facilities related to diesel fuelling are:

- PROCEDIMIENTO DEFENSA CONTRA INCENDIOS EN INSTALACIONES GOB (PRN_TOD_001)
- PROCEDIMIENTO GESTIÓN DE LIBROS DE MANTENIMIENTO (PRN_TOD_003)

- PROCEDIMIENTO SUMINISTRO GO B (PRN_TOD_004)
- PROCEDIMIENTO DESCARGA DE GO B (PRN_TOD_005)
- PROCEDIMIENTO MANTENIMIENTO CORRECTIVO (PRN_TOD_006)
- PROCEDIMIENTO CONTROL MEDICIÓN ELECTRÓNICA (PRN_TOD_007)
- PROCEDIMIENTO MANTENIMIENTO PREVENTIVO (PRN_TOD_008)
- NORMAS ESPECÍFICAS DE LA INSTALACIÓN
- HORARIO DE PRESTACIÓN EN LA INSTALACIÓN
- OTRA DOCUMENTACIÓN DE LA INSTALACIÓN
- ACTIVIDADES QUE CONFORMAN LA PRESTACIÓN DE SERVICIOS
- RELACIÓN DE ACTUACIONES BÁSICAS ANTE DETERMINADAS INCIDENCIAS

For these procedures, an operating manual should be drawn up. The main information that the operating manual should contain is the following:

- Description of the functional areas of the facilities
- Graphical schematics
- Inventory of elements
- Signalling and safety elements
- Self-maintenance plan
- List of contact persons
- General and protective information
- Operational procedures

ANNEX B

Types of vessel

B.1 Main characteristics of Type III and IV vessels

Type III is a pressure vessel made of metallic liner fully wrapped with a fibre-resin composite and Type IV is a pressure vessel made of a polymeric liner fully wrapped with a fibre-resin composite. The composite material prevents mechanical stress while the liner prevents hydrogen leakage. A summary of some differences between Type III and Type IV vessels is shown in Table 17.

Characteristics	Comments
Filling efficiency	Type IV is less susceptible to overfilling in cold conditions than Type III
Heat tolerance	The failure of a Type III vessel is inherently safer than a Type IV plastic-lined vessel as the metallic liner will not degrade or melt before the pressure can be safely vented in a controlled manner through the valves. On the other hand, melting of the inner liner can also enhance the safety. If the inner liner melts, hydrogen can be released through the carbon fibres.
Weight	The polymeric liner means Type IV vessels are lighter than Type III vessels

Table 17: Characteristics of Type III and Type IV vessels

Table 18, Table 19 and Table 20 also show CGH_2 storage systems with a capacity > 4 kg H_2 per cylinder for 35, 50 and 70 MPa respectively, that are available on the market, based on supplier inquiries and data provided by hydrogen storage manufacturers.

Type	Approval	Capacity	Length	Diameter	Volume	Weight (incl. H_2)	Grav. capacity	Vol. capacity
		[kg]	[mm]	[mm]	[L]	[kg]	[%]	[g/L]
3		4.3	972	602	277	97	4.4	15.4
4	EC79	4.5	2,096	415	284	79	5.7	15.9
4	EC79	4.6	2,100	408	275	86	5.4	16.7
4	EC79/HVG2	4.7	2,110	430	306	72	6.6	15.3
3		4.9	2,110	415	285	100	4.9	17.2
3		7.3	3,048	419	420	138	5.3	17.4
4	EC79/HVG2	7.5	3,190	430	463	109	6.9	16.2
3		7.7	3,128	415	423	146	5.3	18.2
3		7.8	3,165	415	428	149	5.2	18.2
4	EC79	8.1	2,360	500	463	109	7.4	17.5
4	EC79	8.4	2,342	509	477	120	7.0	17.6
3		9.1	3,128	435	465	213	7.0	19.7
4		10.7	1,899	690	710	152	8.6	15.1
4		14.3	2,042	745	890	167	8.0	16.1
4		15.5	2,561	690	958	193	8.5	16.2
4		19.5	2,306	783	1,110	230	8.6	17.6
4		22.5	2,607	828	1,404	261	4.4	16.0

Table 18: 35 MPa CGH_2 storage systems with capacity > 4 kg H_2 per cylinder available on the market. Source: DLR

Type	Approval	Capacity	Length	Diameter	Volume	Weight (incl. H_2)	Grav. capacity	Vol. capacity
		[kg]	[mm]	[mm]	[L]	[kg]	[%]	[g/L]
4	PED/TPED	4.5	1,580	480	286	135	3.3	15.7
4	PED/TPED	5.0	1,800	480	326	155	3.2	15.4
4	PED/TPED	6.5	2,220	480	402	187	3.5	16.2
4	PED/TPED	8.0	2,630	480	476	218	3.7	16.8
4	PED/TPED	9.5	3,070	480	556	250	3.8	17.1
4		9.7	3,070	440	467	250	3.9	20.8
3		10.0	3,048	452	489	235	4.3	20.4
4	PED/TPED	10.4	3,310	480	599	270	3.8	17.4
4	TPED	10.9	2,424	531	537	240	4.5	20.3
4	PED	16.5	3,277	565	822	297	5.6	20.1

Table 19: 50 MPa CGH_2 storage systems with capacity > 4 kg H_2 per cylinder available on the market. Source: DLR

Type	Approval	Capacity [kg]	Length [mm]	Diameter [mm]	Volume [L]	Weight (incl. H_2) [kg]	Grav. capacity [%]	Vol. capacity [g/L]
3		4.1	900	541	207	102	4.0	19.8
4	R134	4.2	1,670	352	163	71	5.9	25.8
3		4.3	900	541	207	106	4.0	20.6
3	R134	5.0	1,360	460	226	145	3.4	22.1
4		5.2	1,651	427	236	97	5.4	22.0
4		7.9	2,156	438	325	166	4.8	24.3
3	TPED	8.3	2,048	455	333	179	4.6	24.9
4	EC79/HGV2	9.8	2,154	530	475	198	5.0	20.6
4	*	12.0	3,070	490	579	252	4.8	20.7
4	*	17.0	2,200	610	643	357	4.8	26.4

** in process until 12/2021*

Table 20: 70 MPa CGH_2 storage systems capacity > 4 kg H_2 per cylinder available on the market. Source: DLR

The storage solutions offered by manufacturers for projects where a hydrogen train is being developed are summarised below:

- Hexagon Purus will deliver a high-pressure cylinder for a hydrogen prototype train in the second half of 2021 [47]. This is a Type IV cylinder and has a NWP of 35 MPa. Hexagon Purus has announced on its website that its cylinders are approved according to rail regulation codes and standards. Furthermore, these vessels are equipped with pressure regulation to achieve constant output pressure as well as a thermal and pressure relief divide (TRPD) [48].
- XPERION ENERGY & ENVIRONMENT manufactured the X-STORE high-pressure hydrogen vessel of Type IV that was used for railway applications in 2016. Its NWP is 50 MPa [49].
- Luxfer's G-Stor H2 cylinders have been used for railway applications. These vessels are Type III and are also available with high-pressure hydrogen electronic solenoid valve. Luxfer indicates that every rail project approval is specifically approved case by case by the local railway authority because there is no standard available [50] [51].
- NPROXX announces a vessel focussed on railway applications. This Type IV vessel is certified to PED, based on EC79 requirements, its NWP is 35 MPa and its piping and instrumentation diagram (P&ID) includes a tank valve (OTV) composed of a manual valve and additional solenoid valve in the charge/discharge panel. However, these characteristics are also common for vessels designed for heavy-duty lorries. The difference of this vessel with respect to the others that NPROXX highlights are the tests. The tests passed are more restrictive, with 20,000 instead of 5,000 cycles [52].

ANNEX C

Detailed options for the integration of H_2 storage systems in vehicles

C.1 Integration on roof

If the limitations of the gauge are not restrictive, hydrogen storage cylinders can be installed on the roof of the train. In fact, this type of integration has already been used in some railway projects [14], [53].

For multiple units, there are different carriage lengths depending on the country, the specific gauge and any weight restrictions. Here, we assume an average carriage length of 20 m.

In a hydrogen train, the main components that can be installed on the roof are the HVAC system, the fuel cell system, its cooling system and the hydrogen cylinders. Taking into account the usual dimensions for these components in railway applications, it is estimated that a maximum of approximately 40% of the roof length is available for the installation of the H_2 storage system.

Figure 37 shows an example of a DMU train.

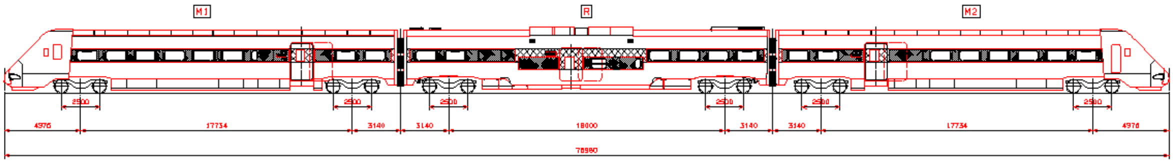

Figure 37: Example of an S-599 DMU train manufactured by CAF

Due to gauge restrictions, a maximum width of 2 m and a 0.55 m high section on the roof can be considered as the space available for installation of the H_2 storage system (Figure 38).

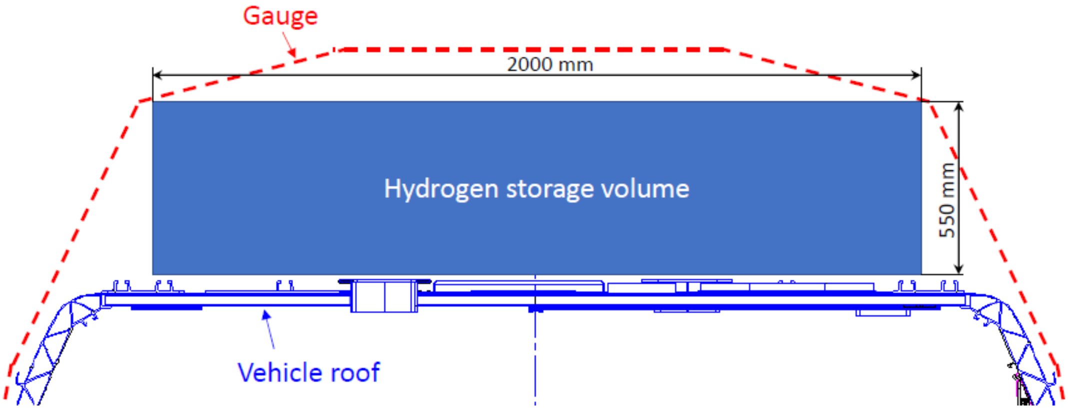

Figure 38: Space available for installation of H_2 storage system on the roof. Source: CAF

Figure 39 shows a representative H_2 storage system for rooftop installation in this respect. The storage system consists of several cylinders in a frame.

Figure 39: Representative integration of H_2 storage systems on roof [54]

The assessment of on-board H_2 storage can be carried out taking into account the estimated space available for integration of the hydrogen storage on the roof. Below are the steps required to estimate the amount of H_2 that could be stored if integrated on the roof:

1) The available volume per carriage with the H_2 storage system integrated on the roof is:

   $\text{Volume}_{\text{available}}$ = percentage available for tanks on roof x $\text{length}_{\text{roof}}$ x $\text{width}_{\text{roof}}$ x $\text{height}_{\text{roof}}$ = 40% x (20 m x 2 m x 0.55 m) = 8.8 m^3

2) Applying the packing factor, the cylinder will occupy the following volume:

   $\text{Volume}_{\text{cylinders}}$ = packing factor x $\text{volume}_{\text{available}}$ = 0.6 x 8.8 m^3 = 5.28 m^3

3) Applying the volume factor, the volume of H_2 stored in the cylinders will be:

   Volume_{H2} = volume factor x $\text{volume}_{\text{cylinders}}$ = 0.85 x 5.28 m^3 = 4.488 m^3

4) Considering the density of hydrogen of 35 MPa shown in Table 11, the kilogrammes of hydrogen that can be installed on-board each carriage will be:

   kg_{H2} = volume_{H2} x $\text{density}_{35\text{ MPa}}$ = 4.488 m^3 x 23.3 kg/m^3 = 104.6 kg of hydrogen/carriage

It should be noted that this is an estimated figure for the hydrogen capacity on the roof and may vary slightly depending on the vehicle-specific dimensions, the H_2 cylinders selected and other factors. It can, however, be used as a reference of the capacity of H_2 that can be stored on board.

C.2 Integration in the technical compartment

If there is no space available on the roof, the hydrogen storage cylinders can be installed inside the technical carriage in the train composition (Figure 40). The hydrogen storage system must be installed in an enclosed space (space not normally occupied by personnel).

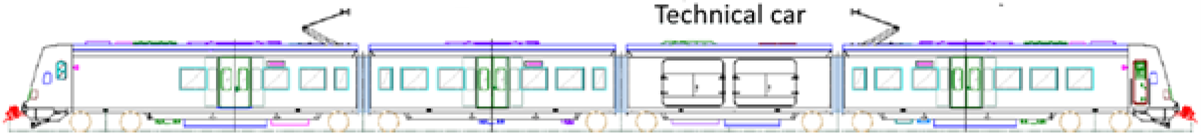

Figure 40: Example of a multiple unit with a technical carriage. Source: CAF

The standard length of this type of technical carriages is between 7–9 meters.

For hydrogen multiple units or bi-mode hydrogen unit applications, fuel cells and their cooling system, the battery system and the H_2 storage system are installed inside the technical carriage. It can be assumed that a maximum of 30% of the space available in this technical carriage will be used for H_2 storage. Thus, assuming an average length of 8 metres for a technical carriage, the maximum length for the H_2 storage is estimated to be 2.4 m.

To allow passage, the maximum width is limited to 0.9 m and the maximum height to 2 m. Figure 41 and Figure 42 show a possible distribution of two hydrogen storage systems installed in a technical carriage.

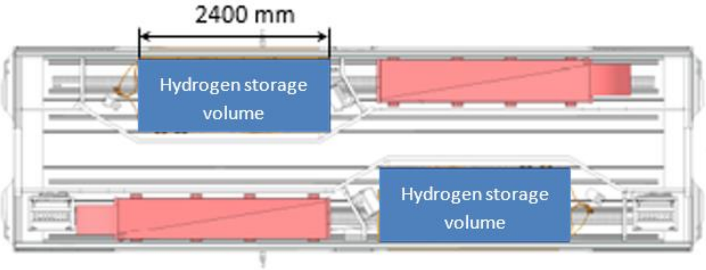

Figure 41: Layout of a possible distribution of the H2 storage system. Source: CAF

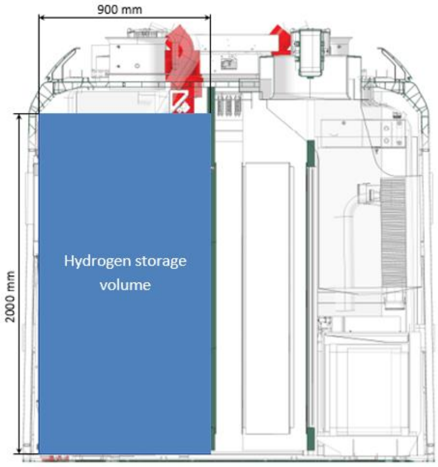

Figure 42: Vehicle cross-section showing the space for the storage system. Source: CAF

A representative H_2 storage system for inside installation is shown in Figure 43 below. The storage system consists of several cylinders mounted in a metal frame.

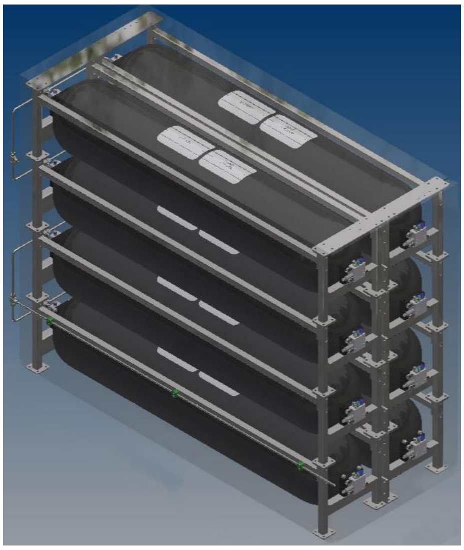

Figure 43: Representative integration of H_2 storage system in the technical carriage. Source: CAF

On-board H_2 storage in a technical carriage is similar to on-board H_2 storage integrated on the roof, so the steps required to estimate the amount of H_2 are the same:

1) Available volume in the technical carriage of the train:

   $\text{Volume}_{\text{available}}$ = 2 modules x (length x width x height) = 2 x (2.4 m x 0.9 m x 2 m) = 8.64 m^3

2) Applying the packing factor, the volume of the cylinders is as follows:

   $\text{Volume}_{\text{cylinders}}$ = packing factor x $\text{volume}_{\text{available}}$ = 0.6 x 8.64 m^3 = 5.18 m^3

3) Applying the volume factor, the volume of H_2 stored in the cylinders is:

   Volume_{H2} = volume factor x $\text{volume}_{\text{cylinders}}$ = 0.85 x 5.18 m^3 = 4.41 m^3

4) Taking into account the density of hydrogen at 35 MPa shown in Table 11, the kilogrammes of hydrogen that can be installed on board each carriage is:

   kg_{H2} = volume_{H2} x $\text{density}_{35\ \text{MPa}}$ = 4.41 m^3 x 23.3 kg/m^3 = 102.67 kg of hydrogen