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Review Article

Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies

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HIGHLIGHTS

- Review of hydrogen rail activities related to storage and refueling concepts.
- 35 MPa technology dominates, other technologies are currently being investigated.
- Data from manufacturers of hydrogen storage systems were analyzed and compared.

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ABSTRACT

This paper investigates hydrogen storage and refueling technologies that were used in rail vehicles over the past 20 years as well as planned activities as part of demonstration projects or feasibility studies. Presented are details of the currently available technology and its vehicle integration, market availability as well as standardization and research and development activities. A total of 80 international studies, corporate announcements as well as vehicle and refueling demonstration projects were evaluated with regard to storage and refueling technology, pressure level, hydrogen amount and installation concepts inside rolling stock. Furthermore, current hydrogen storage systems of worldwide manufacturers were analyzed in terms of technical data.

We found that large fleets of hydrogen-fueled passenger railcars are currently being commissioned or are about to enter service along with many more vehicles on order worldwide. 35 MPa compressed gaseous storage system technology currently dominates in implementation projects. In terms of hydrogen storage requirements for railcars, sufficient energy content and range are not a major barrier at present (assuming enough installation space is available). For this reason, also hydrogen refueling stations required for 35 MPa vehicle operation are currently being set up worldwide.

A wide variety of hydrogen demonstration and retrofit projects are currently underway for freight locomotive applications around the world, in addition to completed and ongoing feasibility studies. Up to now, no prevailing hydrogen storage technology emerged, especially because line-haul locomotives are required to carry significantly more energy than

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passenger trains. The 35 MPa compressed storage systems commonly used in passenger trains offer too little energy density for mainline locomotive operation - alternative storage technologies are not yet established. Energy tender solutions could be an option to increase hydrogen storage capacity here.

Contents

Nomenclature

Abbreviations

ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
CcH_2	Cryo-Compressed Hydrogen
CGH_2	Compressed Hydrogen
DOE	Department of Energy (U.S.)
FC	Fuel Cell
FCHJU	European Fuel Cell and Hydrogen Joint Undertaking
FCEMU	Fuel-Cell Electric Multiple Units
FCH2RAIL	Fuel Cell Hybrid Power Pack for Rail Applications
H_2	Hydrogen
HRS	Hydrogen Refueling Station
HSS	Hydrogen Storage System
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
LH_2	Liquid hydrogen
LOHC	Liquid Organic Hydrogen Carriers
sLH_2	Subcooled liquid hydrogen
SoC	State-of-charge
TRL	Technology Readiness Level

Introduction

Today, diesel vehicles are primarily used to provide rail services where transport performance does not justify full line electrification for economic reasons. Due to the high share of non-electrified lines worldwide, diesel propulsion plays an important role in global rail passenger and freight transport [1]. One option to reduce tailpipe emissions is a partial electrification of tracks using battery trains that draw electricity from the overhead wire if available and otherwise run in battery mode on short non-electrified sections. Another reason to circumvent full electrification is to avoid visual impairment. Especially for long non-electrified tracks, or routes that are difficult to electrify due to topographic demanding routes or due to long overhead wire approval processes, the use of hydrogen fuel cell or hydrogen powered internal combustion engines can be a suitable option for decarbonization. There are two main options to use hydrogen in rail vehicles. The first option is the fuel cell hybrid powertrain. Hydrogen and oxygen react with one another and produce water in a fuel cell causing an electrical current flow. Fuel cells (FC) are usually not operated in a transient mode, therefore batteries serve as booster and for taking up braking energy. Second, hydrogen can be used in a hydrogen internal combustion engine (ICE). An additional battery for hybridization is possible to reuse braking energy but not mandatory as the ICE can be operated in a transient mode. Further, Bi-Mode configurations, which combine an overhead wire powertrain with a FC or ICE are possible.

Rail is often characterized by long-term transport contracts and high and constant energy demands in closed rail networks. Therefore, hydrogen can be produced at high quantities over many years and hydrogen refueling stations (HRS) can be tailored to the specific hydrogen demands all resulting in competitive hydrogen costs. In times of steady expansion of renewable energy production, fluctuating energy generation can additionally advance sector coupling in this context. Therefore, hydrogen (H_2) production costs could be lowered through high and constant demand from industrial consumers or other means of (public) transport modes consuming hydrogen [2].

Railroad undertakings and operators demand operational flexibility of hydrogen FC and ICE rail vehicles similar to diesel trains, which requires, in particular, comparable vehicle ranges and refueling times similar to diesel vehicles. Therefore, the H_2 storage quantity and the on-board storage technology as well as the underlying hydrogen delivery and refueling concept is key.

The use of vehicle hydrogen storage technologies was investigated in the scientific community in numerous scientific papers for road vehicles. For example, Hassan et al. [3] stated that there is no ideal hydrogen storage technology that fits all applications, while Rivard et al. [4] presented an overview of hydrogen storage systems (HSS) relevant to mobility applications. Further works on hydrogen storage and delivery carried out by Moradi and Groth [5].

To date there are a large number of research projects and vehicle developments for railways in various vehicle classes all over the world. For railways, Hoffrichter concludes that there have been several successful proof-of-concept trials of hydrogen trains since 2002. Hydrogen is deemed suitable for many railway applications, but more demonstrator trains as well as governmental funding are needed [6]. Sun et al. give an overview of hydrogen technologies and engineering solutions for railway vehicle design and operations. They describe that past research and development projects had primarily focused on light rail and regional trains, and hydrogen-powered freight and heavy haul trains come increasingly into focus. Several rail vehicles powered by hydrogen are currently being operated as part of experimental programs, while the fuel cell technology is relatively well developed and hydrogen combustion is not [7].

There are isolated publications on HSS for rail, such as Kang et al. who reviewed LH_2 tanks for locomotive application [8], but in general the scientific literature is scarce. Currently, there is no comprehensive analysis available for H_2-on-board storage and refueling options in the rail sector, because the technology has evolved only recently and many projects are still in the development phase. Normally, rolling stock manufacturers do not disclose the technical specifications they provide to their selected suppliers. There are also not yet directly applicable standards or regulations for hydrogen on-board storage and refueling particularly for rail applications, which is why hydrogen and fuel cell standardization and harmonization across the rail sector is still in its infancy.

This paper aims at analyzing the current stage of hydrogen storage for railways in terms of storage technology, pressure level, hydrogen amount and installation concepts inside rolling stock. Furthermore, refueling concepts for demonstration and vehicle fleets are compared. Also, available hydrogen storage systems of worldwide manufacturers were analyzed in terms of technical data.

Methodology and data

Data collection and processing was carried out within the framework of the project Fuel Cell Hybrid Power Pack for Rail Applications (FCH2RAIL) [9]. The data set of worldwide hydrogen rail activities was created for past, current and future railroad projects, using data of project reports, publications in scientific journals and conferences and railway magazines of the last 20 years. These data were complemented by vehicle and hydrogen storage manufacturer presentations and press releases from railway undertakings, in particular for the announced and contracted railroad projects. We largely used the primary source, which the articles refer to. In addition, we consulted sources from (rail) energy companies, railroad associations and other industries such as the gas industry and infrastructure companies.

We differentiated between 1) projects, in which vehicles are built or converted, 2) studies, which include academic and feasibility studies and 3) intended objective (demonstrator, prototype and vehicle operation). In addition, we differentiated between vehicle categories: trams, railcars and locomotives.

Our specific evaluation focused on a) hydrogen on-board storage, in particular with regard to technology, b) pressure level, c) hydrogen amount, d) installation concepts of storage systems inside rolling stock and e) hydrogen refueling concepts and corresponding facilities. Related literature findings for the latter were based on project reports, tendering and approval process documents, presentations, press releases and websites.

In addition, data on HSS with focus on 35–70 MPa CGH_2 were compiled, since this technology is market available and already established in other transport modes. These data were based on data sheets from the respective hydrogen storages manufacturer's websites. If the data were not available on company websites, hydrogen storage manufacturers were contacted directly. The evaluation focused on gravimetric (stored hydrogen weight in relation to tank systems weight) and volumetric density of H_2 storage systems, to make the technologies comparable.

Based on the previous elaborations, fundamental findings are summarized, barriers and potentials for HSS and refueling technologies for rail are derived and research needs are investigated.

Results

Hydrogen on-board storage fundamentals and current activities for road transport

For hydrogen on-board storage, the secondary energy carrier hydrogen needs to be compressed, liquefied or materially bound in order to achieve higher energy densities, due to the low energy density of about 3 kWh/m^3 under ambient

Table 1 – Density and energy content of hydrogen at different pressure levels [10].

H_2	Pressure	Temperature	Density	Energy content	
	[MPa]	[°C]	[kg/m^3]	[MJ]	[kWh]
1 Nm^3 gas	0.1	25	0.09[a]	10.7	3.0
1 m^3 gas	35	25	23.3	2630	731
1 m^3 gas	70	25	39.3	4276	1188
1 kg liquid	0.1	−253	70.8	120	33.3
1 L diesel	0.1	25	875	35.3	9.8

[a] 0.0899 kg/Nm^3; 1 kg H_2 = 33.3 kWh = 11.1235 Nm^3 H_2.

conditions (Table 1). Compared to conventional diesel fuel, hydrogen shows a significantly lower volumetric and gravimetric energy density at energy storage system level, which in some cases significantly limits vehicle autonomy. This circumstance affects not only the vehicle's energy storage system, but also the refueling process as such and the corresponding distribution concepts (cf. section 3.2.3).

Basically, a differentiation can be made between physical and material-based hydrogen storage technologies (Fig. 1). The former includes *Compressed Gaseous Hydrogen (CGH_2)*, *Cryo-compressed Hydrogen (CcH_2)* and *Liquid Hydrogen (LH_2)* - each at different pressure levels. Higher pressure and lower temperature levels result in higher energy densities at substance level. For example, the energy density can be doubled from about 40 g/L at 70 MPa CGH_2 and 288 K to 80 g/L at 30 MPa CcH_2 and 38 K [11] The demands on the storage systems increase with increasing pressure and decreasing temperature, which is why the systems and current developments are briefly presented in the next sections. Higher energy densities can be achieved with material-based storage systems. Examples here are metal hydrides, sorbents and Liquid Organic Hydrogen Carriers (LOHC), which can be used to store hydrogen through exothermal reactions, in combination with catalysts under pressure. The disadvantage here is the higher weight of these systems as well as the higher demands on components in terms of hydrogen storage, refueling and hydrogen release on the vehicle side. Metal hydride storage systems are used in specific applications, e.g., in submarines, but could not succeed in land vehicles for the above-mentioned reasons. Also, the use cases for the LOHC technology tend to be large-scale and stationary rather than transport applications [12]. For these reasons, the focus here is on physical storage systems.

CGH_2 is typically stored at 35–70 MPa in high-pressure storage cylinders. State-of-the-art in fuel cell buses is a storage pressure of 35 MPa. 70 MPa is used in cars and at present also discussed for use in lorries. CGH_2 vehicle storage cylinders consist of different types and materials. While Type I or II cylinders (full metal vessel or metallic liner with additional carbon fiber reinforcement) are mainly used in stationary applications due to their high weight, Type III or IV (aluminum or polyethylene liner full wrapped with carbon fiber) are used in vehicle applications. Type V tanks are made up of composites without a liner, which results in 20% less weight than type IV tanks. These tanks are currently being used with low-pressure ranges. Many companies successfully developed and attained the commercialization of type IV hydrogen storage tanks [13]. In relation to the other physical forms of storage the technology is simple, requiring no additional components. The cylinders are certified for road and transport applications and designed for 5000 refueling cycles (e.g., EC79, HVG2, EN12245 – PED 2014/68/EU TPED 2010/35/EU for gas transport).

CcH_2 is stored at high pressure (up to 35–50 MPa) in vacuum isolated high-pressure tanks at low temperatures in a range of −240 °C (33 K) to −73 °C (200 K). The wide operating temperature ranges affect a long-term effect on fatigue life and material aging [14]. CcH_2-systems are technologically more complex than the previously mentioned CGH_2-cylinders. CcH_2 vehicle storage systems consist of an inner tank (composite overwrapped pressure vessel) where the cold gas is stored, surrounded by a multilayer insulation and vacuum-insulated outer tank. Also due to the large temperature difference to the environment, heat is introduced into the system after a certain time, causing a temperature and pressure increase. This higher pressure must be relieved, resulting in so-called blow-off losses.

From 2009 to 2015 BMW developed and tested prototypes with CcH_2-storage systems (BMW 5er GT) which provide a maximum useable H_2 capacity of 8 kg (145 kg system weight incl. H_2, 235 L system volume) and 7.1 kg (160 kg system weight incl. H_2) [15,16]. The vehicles have not entered series production though.

Cryomotive GmbH currently develops a CcH_2 storage system for heavy-duty trucks. The dimensions of the CcH_2 storage system are specified between 600 and 700 mm in diameter and 2350–2650 mm in length. With regard to the configuration and vehicle integration, the gravimetric storage density is between 8 and 10%. The volumetric storage density is given between 1.2 and 1.5 kWh/l, while larger tanks have a higher storage density. A holding time before venting of 1–2 days at

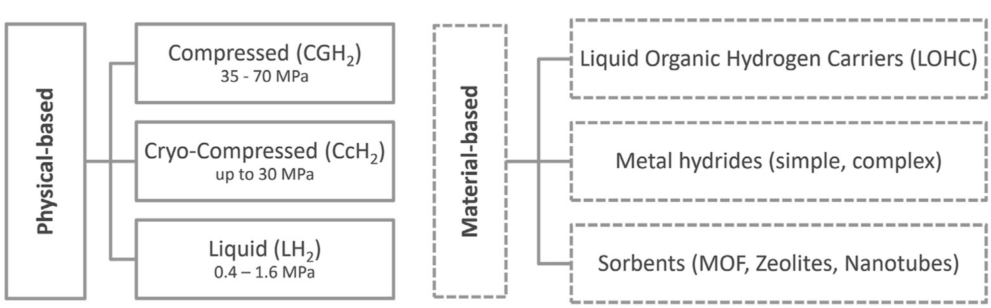

Fig. 1 – Physical-and material-based hydrogen storage technologies.

100% tank capacity and 10–30 days at 50% tank capacity was specified. 2000 refueling cycles could be possible at flow rates up to 800 kg/h (~13 kg/min). The expected energy requirement for CcH_2 compression is estimated to be 0.5 kWh/kg H_2 [17]. Starting in January 2022 the CryoTRUCK project consortium, consisting of Cryomotive, MAN Truck & Bus and others, aims at the development of an 80 kg CcH_2 storage and fast refueling system for long-haul hydrogen fuel cell trucks until 2024/25 [18].

LH_2 is stored at very low temperatures of −252.85 °C (20.3 K) at 0.4 MPa in cryogenic storage systems. As CcH_2 systems, also LH_2 vehicle storage systems are technologically more complex than the high-pressure storage cylinders. LH_2 tanks consist of an inner tank in which H_2 is stored in liquid state, surrounded by a multilayer insulation and vacuum-insulated outer tank. Due to the large temperature difference to the environment, heat is introduced into the system after a certain time, causing the hydrogen to evaporate, which results in a temperature and pressure increase in the inner tank. This higher pressure must be relieved, which is the so-called boil-off losses. For the intended release of hydrogen, on the other hand, heat is specifically introduced into the system via an electric heater.

Although prototypes and small series had been tested over the past 50 years, the use of LH_2 in the transport sector is not yet commercially available, in contrast to CGH_2. Test vehicles with LH_2-storage systems had been tested in North America, Japan and Germany from 1971 to 1978. In 1995 MAN demonstrated an experimental city bus (MAN SL) and in 2000 Opel produced an experimental car (Opel HydroGen 1), both equipped with LH_2-storage systems. 15 BMW hydrogen 7 cars were demonstrated in 2000 with H_2-combustion engines and LH_2-tanks from MAGNA STEYR [10,19,20].

The LH_2 storage system and corresponding refueling technology is currently being advanced for heavy-duty trucks by Daimler Truck AG and Linde AG by increasing the maximum working pressure from 0.4 to 2.0 MPa which is called subcooled liquid hydrogen (sLH_2). Daimler's approach is designed to enable higher storage density without requiring complex data communication between the service station and the vehicle during the refueling process. The first refueling of a prototype vehicle at a pilot station in Germany is planned for 2023 [21]. The dimensions of this system are specified as 2500 x 710 mm. A reachable gravimetric energy density of 10% was mentioned, which corresponds to a total weight of ~500 kg of one vehicle tank including a useable H_2 amount up to 44 kg. A hold time of 10 h at 100% and 130 h at 80% tank filling level was specified. A flow rate of 400–500 kg/h for refueling per sLH_2 pump (~6.6–8.3 kg/min) could be possible, with an electric energy demand of 0.05 kWh/kg H_2 [22].

Cryotherm GmbH & Co. KG currently also develops a sLH_2-storage system with a total volume of 743 L, 2500 mm length and 710 mm diameter at a maximum operating pressure of 1.9 MPa (single-tank). The 1486 L sLH_2-twin-tank system can store 97.6 kg of H_2 at 1.6 MPa and 26 K and a useable H_2 quantity of 89.3 kg when empty at 0.7 MPa and 36 K. Assuming a gravimetric energy storage system density of 10% this results in a total weight of ~500 kg for a vehicle tank with a useable H_2 quantity of 44.65 kg [23].

Worldwide hydrogen rail activities

Overall 47 past, current and future demonstrator and prototype projects regarding hydrogen on rail could be identified. Additionally, 23 conceptual designs, feasibility and case studies and 13 implemented and planned hydrogen refueling concepts were reviewed. The following sections provide an analysis on the used on-board storage technologies (3.2.1), the installation site and system capacities (3.2.2) and refueling concepts for rail (3.2.3). The most important data and sources on vehicles and the corresponding storage technology and main project findings with focus on hydrogen storage technologies are summarized in Appendix A.

Today, various manufacturers are developing trains with H2-FC propulsion that are already in service or will be in service in the future. Past, current and future hydrogen projects and studies related to rail focused in the USA, Canada, China, Japan, South Korea and Europe (Germany, UK, Austria and Spain) are shown in Fig. 2.

Alstom Transport completed the first two prototypes of the regional passenger train iLINT in 2018 and has tested them in passenger service in Lower Saxony, Germany since then. At the end of the year 2022, the first fleet of 14 iLINT will enter regular operational service there. Since the last years, the number of prototypes and planned demonstration projects with regard to regional passenger trains was increased worldwide. By 2026, the number of vehicle fleets in service running on hydrogen will increase to 13 (Fig. 3).

A total of 70 hydrogen railcars for seven rail networks are currently planned to enter commercial operation until 2025. Alstom Transport was the first railway manufacturer, followed by Stadler Rail and Siemens Mobility who are currently developing Fuel-Cell Electric Multiple Units (FCEMU). The first projects with focus on operation objective starting at the end of 2022 e.g., 14 Alstom iLINT for Weser-Elbe-Netz (evb) in Lower Saxony and 27 Alstom iLINT for Taunusnetz (rmv), 6 S Mireo Plus H for Heidekrautbahn (NEB) (2024) and one Stadler Flirt H2 for San Bernardino County Transportation Authority (2024) (Table 2).

Vehicle maintenance is often contracted to the train manufacturers over the whole train lifetime. H_2 supply is usually subcontracted to gas suppliers, which is described in more detail in section 3.2.3.

Currently, there is also an upcoming number of manufacturers and consortia of companies converting conventional locomotives into hydrogen demonstrators or developing hydrogen prototypes – including trams and railcars – summarized in Appendix A.

Hydrogen on-board storage technologies for rail

A variety of 35 MPa CGH_2 type III and IV hydrogen storage cylinders for hydrogen powered trains are offered by hydrogen storage manufacturers today. Alstom's Coradia iLINT prototype, a fuel cell hybrid electric multiple unit regional train, was equipped with Xperion's Type IV cylinders in 2016 [28], while current iLINT series trains reach mileages of up to 1000 km with 32 roof-mounted 35 MPa Type IV cylinders from NPROXX [2]. The currently planned multiple units Talgo's Vittal-One and Stadler's Flirt H2 will be equipped with

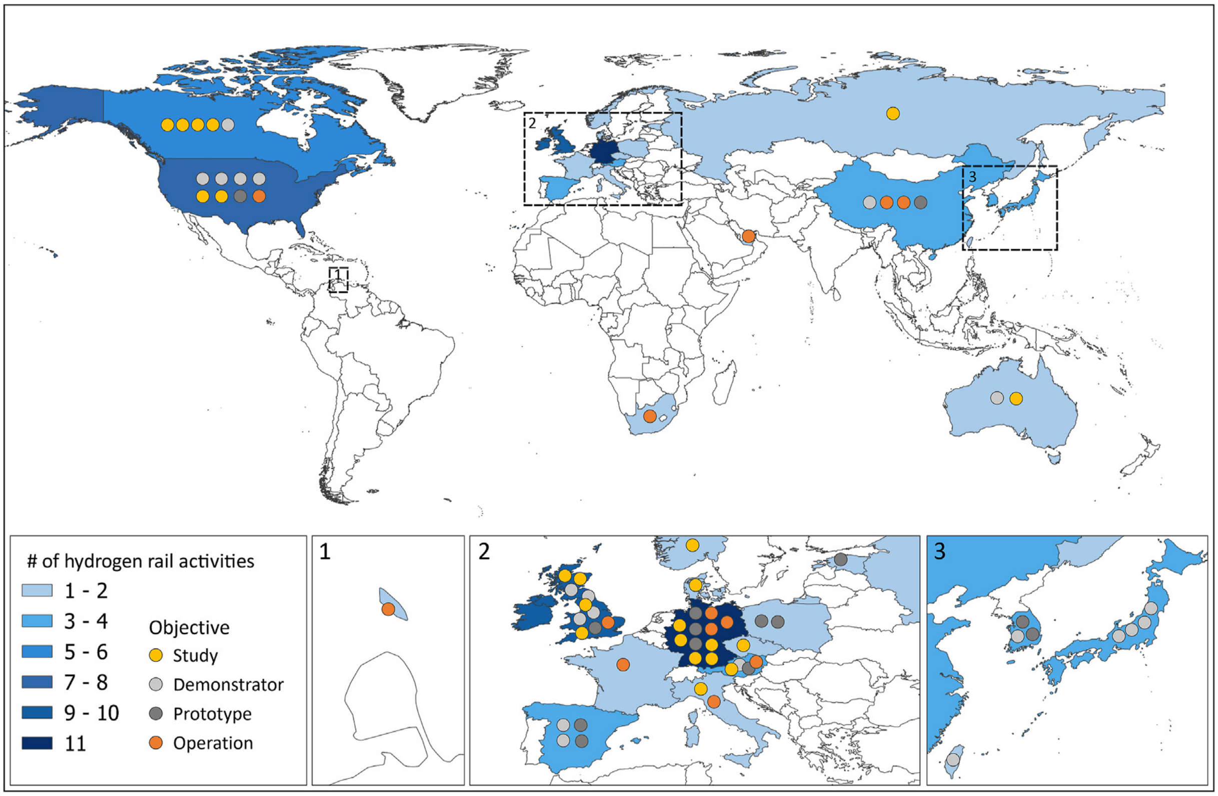

Fig. 2 – Overview of the investigated worldwide hydrogen rail activities and objectives.

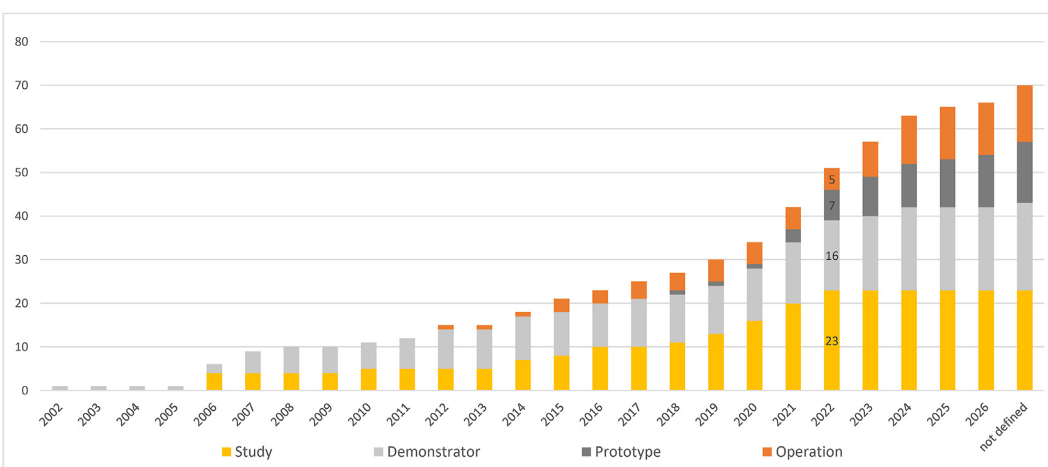

Fig. 3 – Development of worldwide hydrogen rail projects since 2002, cumulative view, Appendix A.

35 MPa Type IV cylinders from Hexagon Purus [29,30]. The cylinders are certified according to rail regulation codes and standards [31]. Other hydrogen railcars were equipped with Luxfer's G-Stor H2 Type III cylinders, such as the future FCH2RAIL demonstrator of CAF. Luxfer announced that every rail project is specifically approved case by case by the railway authority in charge as there is no standard regulation available [32,33]. The Korea Railroad Research Institute will install in its regional train prototype 70 MPa CGH_2 cylinders [34] and in its locomotive a LH_2 storage system [35]. JR East, Hitachi and Toyota announced to use 70 MPa storage cylinders for the hybrid fuel cell test vehicles, model FV-E991 series, in the Japanese HYBARI Project [36]. Most of the investigated projects use 35 MPa CGH_2 pressure storage systems (Fig. 4). The reasons for using a particular H_2 storage technology are diverse. 35 MPa CGH_2 storage cylinder are available on the market and also used in other transport applications. Some of them where adapted from automotive or commonly used in buses or in heavy-duty and also from other railway applications. 35 MPa CGH_2 systems are less expensive than LH_2 or 70 MPa [24]. Metal hydride storage systems are used for safety reasons. With LH_2, the driving range should be increased while reducing refueling time [35]. In studies, also ammonia and LOHC had been investigated (Appendix A).

Table 2 – Future hydrogen railcar operation by train manufacturer and operational area.

Manufacturer	Project details	Source
Alstom	14 x Coradia iLINT from 2022/23 for Weser-Elbe-Netz (evb) in Lower Saxony, Germany + 30 years maintenance and hydrogen supply	[24]
Alstom	27 x Coradia iLINT from 2022/23 for Taunusnetz (rmv) in Germany + 29 years maintenance and hydrogen supply	[24]
Alstom	6 x Coradia Stream from 2024 for Ferrovie Nord Milano, region of Lombardy in Italy	[24]
Alstom	12 x Coradia Polyvalent FCEMU, Bi-mode train (Hydrogen + Pantograph) for France, train validation 2023, start of operation 2025	[24]
Siemens	6 x Mireo Plus H from 2024 for Heidekrautbahn (NEB) in Brandenburg, Germany + 10 years maintenance support and supply of service parts	[25]
Stadler	5 x four car railcars for 760 mm track gauge with 500 kW FC from 2022/2023 for Zillertalbahn (Zillertaler Verkehrsbetriebe) in Austria	[26]
Stadler	1 x Flirt H2 from 2024 for San Bernardino County Transportation Authority (SBCTA) in California, USA	[27]

Installation position and system capacity of hydrogen storage systems

Most of the storage systems in the demonstrator, prototype and ordered railway vehicles are mounted on the roof or inside the machine house. In general, railway vehicles offer much more space for hydrogen storage than for example trucks, but in practice, installation space is limited due to clearance gauge. If there is available space on the roof, it is usually argued that the hydrogen can easily dissipate upwards in the event of failure when it is stored under pressure. In some vehicles, the storage systems are installed in the passenger compartment or underfloor. Two of the investigated projects use a dedicated power car for the integration of the HSS (Fig. 5). The ratio is similar for the studies, although performance indicators are also used in some cases.

Typically, cylindrical pressure cylinders are installed which reduces storage capacity but additional installation space must be accounted for piping, housing and on the like (packaging factor). Vehicles such as the Siemens Mireo Plus H use different cylinder diameters to make better use of the installation space on the roof. Another future possibility could be the adjustment of the tank geometry. In this field, BMW, Bosch, Hexagon Purus and Testnet Engineering are currently working in the project “FlatHyStor” on a flat H_2 tank for cars [37].

The amount of H_2 installed in demonstrators and prototypes was relatively low. Currently, higher H_2 storage capacities are achieved for regional trains than for locomotives (Fig. 6). In general, the available installation space in the vehicle plays a significant role here. For the iLINT series train, it was highlighted that the increased storage capacity was sufficient, while the train reaches mileages of up to 1000 km with 260 kg H_2 stored in 32 roof-mounted 35 MPa cylinders. Therefore, this storage technology is the best option for all types of regional trains [24].

When hydrogen is stored inside dedicated machine housings placed on locomotive frames of shunting locomotives, less storage capacity tends to be possible than on the roof of railcars. For example, Pesa's shunting locomotive prototype contains 32 tanks with a storage capacity of 175 kg H_2 at 35 MPa [38,39]. More H_2 storage capacity could be installed in mainline locomotives, because more space is available. However, the power and energy requirements in this segment are significantly higher than in shunting locomotives, which is why other storage technologies are being considered here. A LH_2 locomotive demonstrator of Korea Railroad Research Institute and Hyundai Rotem will be completed in 2024 [35].

Energy tender solutions are also a way to increase hydrogen storage capacity and were proposed in individual studies, but

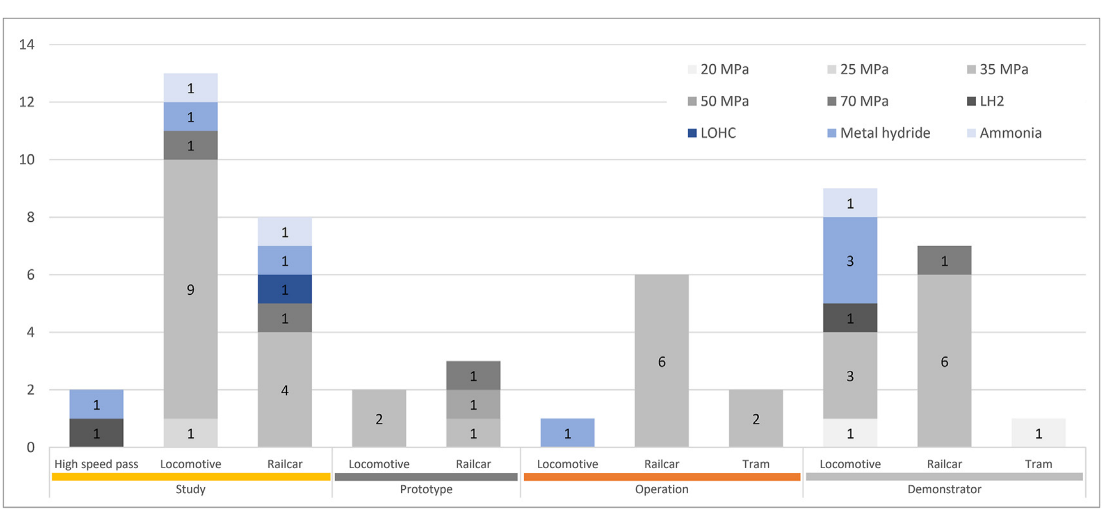

Fig. 4 – Hydrogen storage technologies in the railway vehicles sorted by project objective, Appendix A.

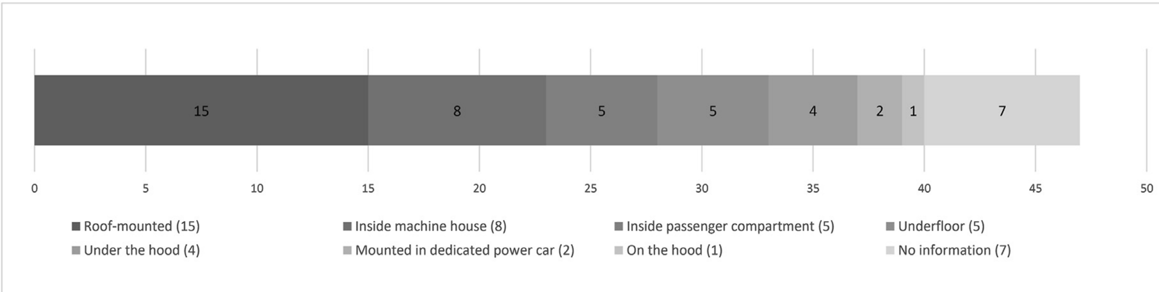

Fig. 5 – Placement of hydrogen storage systems in the investigated demonstrator, prototype and ordered railway vehicles, Appendix A.

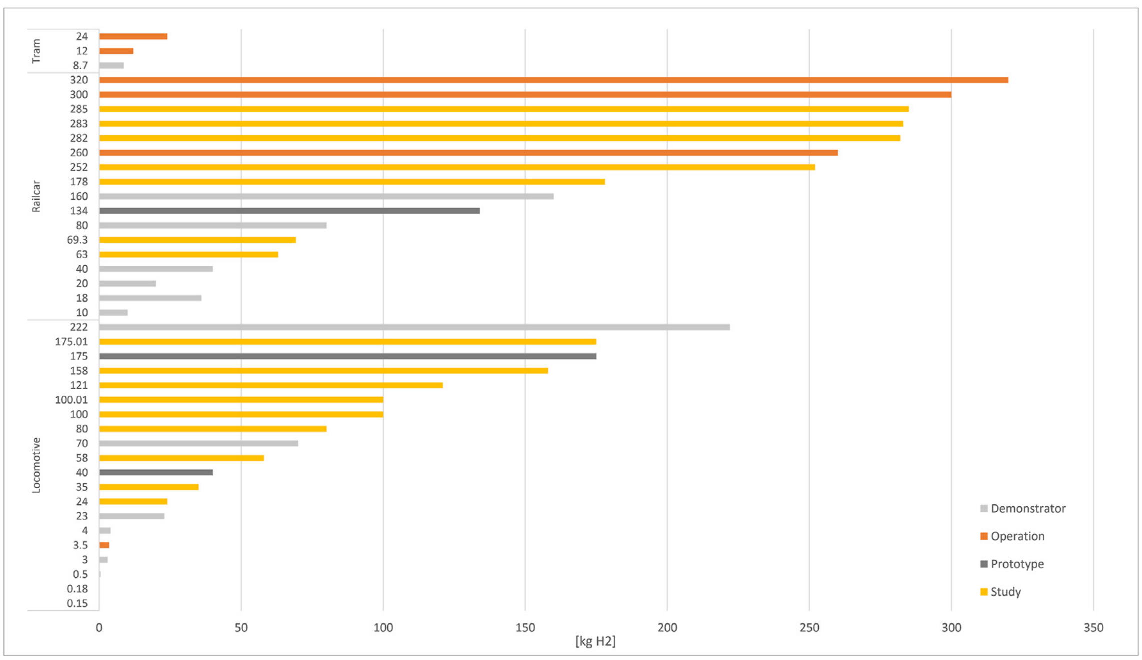

Fig. 6 – Hydrogen storage capacity in the investigated railway vehicles, Appendix A.

not further investigated. Talgo plans to integrate the hydrogen storage inside the passenger compartment in the TPH2 train project (L-9202 Travca locomotive + pendular set). Talgo currently tests its hydrogen components in the TPH2 train project (basis: L-9202 Travca locomotive). Talgo claim that the storage system could be included in the passenger compartment. But since transfer of hydrogen across two carriages is problematic from a safety point of view the storage and fuel cell system were installed in the same car. For enabling the transition of hydrogen across cars, Siemens Mobility applied for a patent (DE102019203105A1) in the year 2020 [40].

Hydrogen refueling concepts for rail

Possible H_2 supply and refueling concepts for multiple units with a tank pressure level of 35 MPa in the vehicle are shown schematically in Fig. 7. The basic layout of a hydrogen refueling station (HRS) for railways depends on a number of factors, which mainly concern the different H_2 delivery and storage concepts: path a) - d). Path a) and b) show LH_2 and CGH_2 delivery by truck trailer, path c) shows H_2 supply via pipeline from the chemical industry, and path d) shows H_2 generation from on-site electrolysis. General conditions that affect the layout of an HRS include:

- On-board H_2 storage concept and pressure level.
- Required refueling speed and state-of-charge (SoC).
- Number of vehicles to be refueled, required H_2 quantities as well as necessity of parallel refueling.
- Requirement of redundancy solutions (e.g., back-up H_2 supply).
- H_2 supply option (close to hydrogen sources, required hydrogen quality, and preference for H_2 generation from renewable energy plants).
- Available space for the HRS and, if applicable, for the new H_2 production facilities to be constructed.

In the following, implementation examples of HRS are presented. The focus is on concepts for 35 MPa CGH_2 storage system refueling, as most rail vehicles are equipped with these storage systems.

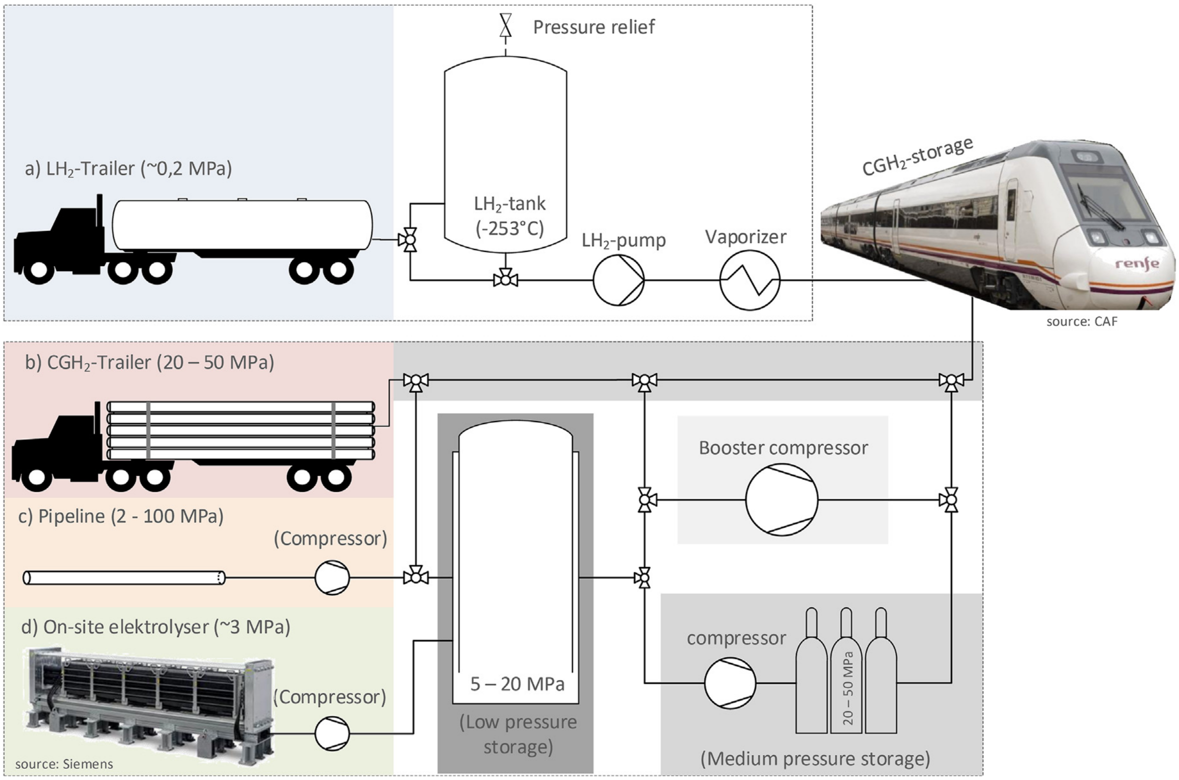

Fig. 7 – Hydrogen refueling concepts for CGH_2 rail vehicle storage: variant a) - d), source own illustration.

Different hydrogen refueling concepts for rail are shown in Table 3, where portable HRS are currently most widely used for hydrogen refueling at different locations for vehicle tests and demonstrations. Here, LH_2 and CGH_2 supply with road trailer are widespread delivery paths. Type I steel cylinders and cylinders bundles were also used for lower hydrogen capacities. For "Mini Locomotives" in demonstration projects the metal hydride systems and the CGH_2 cylinders were exchanged.

Mobile HRS concepts, in particular container and trailer refueling solutions for various modes of transport, exist worldwide and are offered to more and more customers by various manufacturers from the gas industry (e.g., Linde, Air Products, Wystrach, Nanosun, Atawey). Refueling concepts for buses can also be used to a limited scope for test operations of rail vehicles, provided that complete refueling and short refueling times are not required. In general, full refueling (100% SoC) is not required in most cases for test and demonstration purposes. E.g., the iLINT was partially refueled in Groningen, Netherlands in March 2020 up to a storage pressure between 17 and 20 MPa with a filling time between 35 and 72 min, while the two cars were refueled in sequence [41].

In commercial train operation, HRS requirements will likely be higher because the vehicles need to be refueled back to back with a larger hydrogen amount and more quickly. The system specifications of HRS which are currently planned or under construction in Germany are summarized in Table 4. Further HRS-projects are currently planned in Mayrhofen (Austria) [26] and Basdorf (Germany) [42] (Table 5). For H_2 supply and refueling, vehicle manufacturers also work closely together with gas suppliers. Overall, compressed gas storage with a maximum of 50 MPa seems to be becoming established on HRS storage system side. In Tübingen DB, DB Energy and Siemens Mobility will test a H_2 fast refueling system and they will also develop a HRS-train communication standard. The consortium is also investigating pre-cooling for train refueling in the H2goes Rail project. DB Energy also plans to include pre-cooling in Rottenbach. In Bremervörde, no pre-cooling is provided by Linde. Nevertheless, it is planned to achieve a filling time of about 15 min with a comparable vehicle storage capacity for all projects with two dispensers.

Standardization activities of H_2 on-board storage and refueling technologies for rail

At present no rail specific applicable regulations and standards on the use of HSS are available. By applying existing regulations from other areas of hydrogen usage in combination with existing railway-specific standards, most hazards can be managed. Remaining hazards must be addressed by individual actions up to an acceptable level of residual risk, although the corresponding procedure is not yet uniformly regulated at present [65]. For example, hydrogen pressure storage systems for hydrogen-powered motor vehicles require type approval in accordance with regulation (EC) no. 79/2009 of the European Parliament and the Council of the European Union, which is replaced by R134 after July 2022. In 'PNW 9–2697 ED1: Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system', international standardization work is planned to be

Table 3 – Implemented hydrogen refueling concepts for rail, worldwide.

HRS	Project details
iLINT, Europe	Transportable, containerized HRS for Alstom iLINT prototypes, source: LH_2 trailer with > 3t H_2 capacity (Air Products), flexible dispensing unit with two refueling nozzles [43,44], used for different locations for trail operation in Europe: e.g., Wien, AUT [24,45,46]
iLINT, Europe	CGH_2-Trailer as overflow solution for Alstom iLINT refueling in Groningen, Netherlands [24,41,47]
HydroFlex, UK	HyQube hydrogen refueller from Fuel Cell Systems Ltd and external CGH_2 hydrogen storage (steel cylinders) at 26th United Nations Climate Change conference in Glasgow (COP26) [48,49]
HydroFlex, UK	Mobile hydrogen refueling truck from Fuel Cell Systems Ltd with 65 kg H_2 [50,51]
Hydrogen Pioneer, UK	Exchange of metal hydride or 20 MPa storage cylinders [52]
Vehicle projects, USA	20 MPa tube trailer (Air Products) + temporary compressor for demonstration in [52]
Taiwan	Low-pressure metal hydrogen storage canister recharging station [53]

completed in February 2024 by the International Electrotechnical Commission (IEC) [66].

In the bus and passenger car sector, 35 and 70 MPa *refueling processes* are standardized and are continuously updated. The standardization activities in this field include e.g.,

- SAE J2719: "Hydrogen Fuel Quality for Fuel Cell Vehicles"
- SAE J2799: "Hydrogen Surface Vehicle to Station Communications Hardware and Software"

Table 5 – Planned hydrogen refueling stations for rail (detailed data not available).

HRS	Specification
AUT, Mayrhofen	0.8–1.3 t H_2/d (ø 292 t H_2/a), H_2 Electrolysis (electricity from hydroelectric power plants): 538 Nm^3/h, two-day H_2 backup, redundancy: CGH_2-trailer delivery and refueling (Jenbach, AUT), operation from 2022/2023 [26]
GER, Basdorf	6 trains (Mireo Plus H), On-site electrolysis 100% from renewable sources, operation from 2024 [42]

- SAE J2600: "Compressed Hydrogen Surface Vehicle Fueling Connection Devices"
- SAE J2601: "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles"
- SAE J2601-2: "Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles"

Since there are again no directly applicable standards and regulations for the refueling of FCEMUs, existing regulations from other industries are used in combination with existing rail-specific standards. Current standardization activities for hydrogen refueling of rail vehicles are CEN/TC 256/WG 43 Work programme (WI = 00256,957) Railway applications - Ground based services - Hydrogen refueling equipment. The standard specifies the requirements for the interfaces in the vehicles and at the designated refueling points for hydrogen refueling systems for all rail vehicles with hydrogen propulsion systems. It does not apply to mobile or temporary refueling stations [67].

Table 4 – Planned hydrogen refueling stations for rail, Germany (selection).

HRS	Bremervörde	Höchst	Rottenbach	Tübingen
Involved companies	Alstom, Linde, LNVG, evb	Alstom, RMV, Infraserv Höchst	DB Energy	DB, DB Energy, DB Regio, Siemens Mobility
Supply	2-3 truck trailers/day at 20/30 MPa from DOW Chemicals (Stade)	by-product H_2 from chlor-alkali electro-lysis (pipeline), construction of an additional 5 MW electrolysis	On-site electrolysis, 259H^2 kg/d, back-up supply via truck trailer	H_2 high pressure trailer + mobile refueler, later Electrolysis in Tübingen
Compression	50 MPa	membrane compressors 0.6–55 MPa	min. 9.4 kg/h, container for outdoor installation	30 MPa
Storage	64 constant pressure tubes, 2030 kg H_2, 50 MPa	4 x 40 ft. Container with ADR certification 4400 kg H_2, 50 MPa	cascaded pressure system: 62 kg 4–6 MPa, 600 kg 30 MPa, 720 kg 50 MPa	30 MPa Trailer, up to 900 kg H_2
Refuelings/d	12 x 130 kg	14 (27)	2 x 100 kg	test facility, 180 kg
pressure	35 MPa	35 MPa	35 MPa	35 MPa
Planned refueling time	app. 15 min	app. 15 min	max. 20 min	app. 15 min (wireless communication)
Status	operation from 2022	under construction, operation from 2022	procurement cancelled, new evaluation in progress	Under construction, trial operation from 2024, prior testing from 2022
Dispenser	2, for 2 trains/h	2	2	2
Precooling	no	no information	min. 2x 70 kW	yes
Sources	[54]	[55–58]	[59–61]	[62–64]

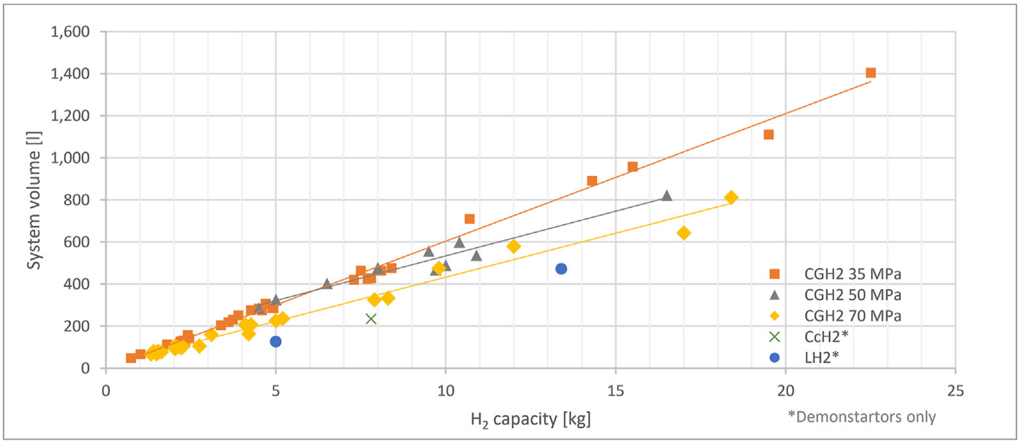

Fig. 8 – System volume and H_2 capacity of H_2 storage vessels based on manufacturer data, Appendix B.

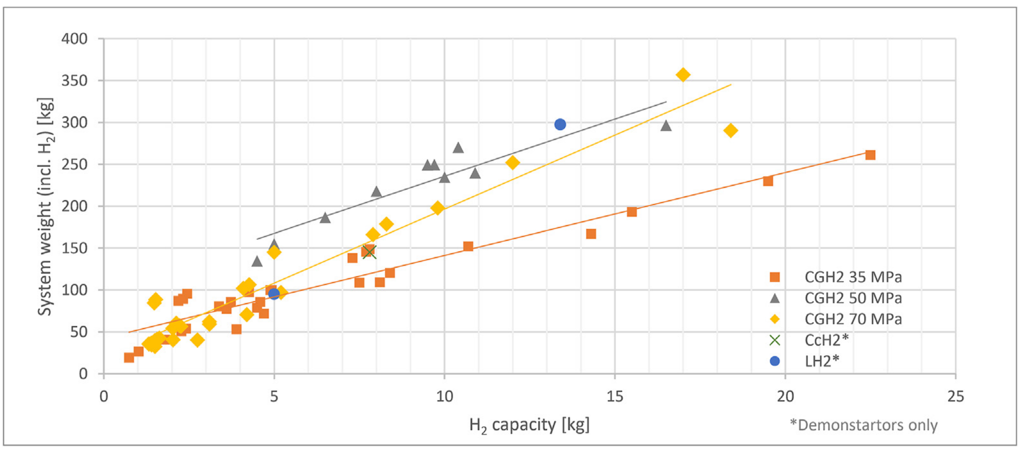

Fig. 9 – System weight and H_2 capacity of H_2 storage vessels based on manufacturer data, Appendix B.

On-board hydrogen storage systems comparison

As 35 MPa CGH_2 storage technology is dominating and available on the market, we primary collect data of this physical-based storage method here. LH_2 and CcH_2 vehicle storage systems, which were already installed in prototypes of road vehicles in the past are added for comparison. However, these technologies are not yet commercially available. Material based hydrogen storage methods, e.g., hydrogen stored in chemical or physical compounds in or on solids or liquids, are still in the laboratory stage and being skipped from our analysis. Fig. 8 and Fig. 9 show the system volume, system weight and hydrogen capacity for different vessels. These data are based on requests and data specifications from worldwide CGH_2 storage manufacturers 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

Table 6 – Comparison of different hydrogen storage vessels, Appendix B.

		CGH_2	CGH_2	CGH_2	LH_2 [a]	sLH_2 [a]	CcH_2 [a]
Pressure	[MPa]	35	50	70	0.4	1.6	30
Density (substance)	[g/L]	23.3 [b]	30.8 [b]	39.2 [b]	63 [c]	>63 [c]	72 [d]
Vol. Capacity	[g/L]	15–18	15–21	18–26	28–40	58–60	33–46 [d]
Grav. Capacity	[%]	2.5–8.6	3.2–5.6	1.7–6.8	4.5–5.3	~10	7.5–10 [d]
TRL	–	7–9	7–9	7–9	7	4	7 [e)]

[a] no series tank systems available, technology in development for road transport.
[b] Isothermal data for T = 25 °C [68].
[c] BMW presentation 2012.
[d] Cryomotive presentation 2021 [14].
[e] For cars, TRL 7–8 for heavy-duty trucks in 2023/24.

literature findings with regard to LH_2 and CcH_2. Appendix B show the data of the available CGH_2-storage vessels for 35, 50 and 70 MPa in more detail.

Table 6 summarizes the available data on CGH_2, LH_2 and CcH_2 storage vessels are compared regarding pressure, density on substance level, volumetric and gravimetric capacity and TRL. Due to the physical properties of hydrogen, the energy density increases by a factor of 1.68 when the storage pressure is doubled from 35 to 70 MPa. But since more vessel material is required for 70 MPa vehicle storage systems, the energy density increases only by factor 1.25. For all storage system integrations, additional packaging factors need to be considered, which include valves, pipes and mounting depending from the respective diameter and construction space. LH_2 and CcH_2 storage systems could double the volumetric energy storage capacity compared to CGH_2 systems. However, there are no series vehicle storage tank systems available for LH_2 and CcH_2, but there are currently efforts in the heavy-duty truck sector on that matter. Here in particular, boil- and blow-off losses may not be relevant due to the longer operating times compared to passenger cars, where this technology was not further investigated. The first prototype vehicles are expected here in 2023 with higher TRL in the following years.

Discussion and conclusions

A number of manufacturers worldwide produce sufficiently dimensioned CGH_2 storage systems at various pressure levels that are used or could be used for rail vehicles. The main considerations for series vehicles integration go towards 35 MP CGH_2 storage, while this technology offers an acceptable storage capacity at comparable low costs for regional passenger transport. CGH_2 storage is currently the most advanced technology. For freight locomotives, no prevailing hydrogen storage technology is in sight so far. Especially in mainline locomotives storage technologies with higher energy densities are required because of constant high-power demand. Energy tender solutions for CGH_2 or LH_2 might be a solution here. LH_2, rail certified storage tank systems are not yet available but development activities in the field of LH_2-tank systems can be observed for heavy-duty trucks. Here are currently efforts to increase the system pressure of LH_2-storage tanks. For this technology the volumetric energy storage capacity could be more than doubled at storage system level compared with CGH_2 systems.

On-board HSS do not yet reach the technical targets. E.g., for light duty vehicles the U.S. Department of Energy (DOE) targets are 30 g H_2/L in 2020, 40 g H_2/L in 2025 and 50 g H_2/L for the ultimate target in terms of volumetric capacity [69]. Since balance-of-plant components such as pipes and mounting brackets, which are included in the DOE targets, were not considered in the collected CGH_2 storage vessels data (Appendix B), these targets are more distant. For on-board CGH_2 storage tanks the volumetric capacity targets of the European Fuel Cell and Hydrogen Joint Undertaking (FCHJU) are only reached for 70 MPa (23 resp. 26 g H_2/L for the year 2017, cf. section 3.4 Table 6) [70]. The FCHJU targets will also increase to 30 g H_2/L in 2020, 33 g H_2/L in 2024 and 35 g H_2/L in 2030. Because of the physically set density at substance level, it will be very challenging to achieve these values with CGH_2 systems in the next few years. For this reason, there is still a great need for research in this area. Even higher pressures or LH_2 would be an option here. The targets with regard to gravimetric capacity of on-board HSS will increase from 5.0% in 2017 to 6.0% in 2030 [70]. As the collected data on the gravimetric capacity in section 3.4 (Table 6) do not include in-tank valve injector assembly, the FCHJU targets are not comparable.

For CGH_2 refueling, the filling speed is a crucial factor to be comparable with diesel refueling. The hydrogen temperature in the CGH_2-storage system increases during the refueling process due to transferred heat from the refueling station, the thermal masses of the vehicle, the Joule-Thomson heating of hydrogen during throttling through the fuel line orifices and the heat of compression inside the CGH_2-storage system [71]. For example, hydrogen heats up by an average of about 8 K at a throttle when expanded from 35 to 2 MPa due to the negative Joule-Thomson coefficient of hydrogen [72]. The main influence on temperature increase is the heat of compression, which cannot be avoided in the cylinders due to high pressure increase. To prevent the vehicle tanks from overheating, the hydrogen is therefore pre-cooled to as low as −40 °C for fast refueling at high pressures of 70 MPa. The simulation results of the PRHYDE-project [73] show that there is no need for precooling at an ambient temperature of 15 °C to avoid overheating for 35 MPa hydrogen refueling, but 10 min fillings are too short to reach a SoC of 100%. For 15 min fillings and precooling at −20 °C SoC reaches values close to 100%. However, current simulation results for 350 L 35 MPa CHG_2-storage cylinders show overheating at ambient temperatures of 40 °C. On the other hand, 50 L tank configurations achieve approx. 10 °C lower temperatures compared to the configuration with 350 L tanks due to a higher heat exchange external surface area. Furthermore, type III tanks result in a lower final filling temperature compared to type IV tanks, because aluminum provides a higher heat transfer coefficient than polyethylene liners [73].

In summary, there are still some challenges for hydrogen in the rail sector. Apart from 35 MPa in railcars, higher storage densities will be needed in the future, which could be achieved by alternative storage methods in the future, especially for the locomotive segment, for example. If the LH_2 technology succeeds in heavy-duty trucks, there could be many synergies with rail vehicles - in terms of quantities and correspondingly, costs of such systems will drop. However, the storage decision also affects the refueling infrastructure, for which the requirements and framework conditions must be clarified. In this context, the question of the achievable refueling speed with and without precooling still needs to be answered. Last but not least, the sector coupling perspective should be integrated more strongly in future research and development.

Future work related to scientific issues should include a more detailed study and comparison of other storage technologies for rail, such as material-based storage systems. In addition, analysis of typical hydrogen demand in rail operational use cases should be included in upcoming research. Topics could include the correlation of line length with pressure level and type of storage, as well as the relationship between storage capacity and refueling location. Another focus could be the investigation of the competition with battery trains as well as a detailed look at further hydrogen applications, especially for shunting and mainline locomotives.

Contributions

MB conceived and designed this paper based on his contributions in the FCH2Rail deliverable D1.5 [9]. MB also collected, processed and evaluated the additional data. AFDR, JP, MV and BNC conducted a comprehensive paper review and provided valuable comments. SHP supported with the paper's structure and created the world map. All authors read and approved the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.08.279.

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