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Analysis of existing non-gaseous on-board storage and refuelling

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R E P O R T

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CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

AEM	Alkaline Exchange Membrane
CcH2	Cryo-compressed Hydrogen
DBT	Dibenzyl Toluene
DME	Dimethyl ether
DMFC	Direct Methanol Fuel Cells
EIHP	European Integrated Hydrogen Project
FC	Fuel Cell
(C)GH2	Compressed Gaseous Hydrogen
GTRs	Global Technical Regulations
H2	Hydrogen
HDV	Heavy-duty Vehicles
LDV	Light-duty Vehicles
LH2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
MCH	Methylcyclohexane
PEM FC	Proton Exchange Membrane Fuel Cell
sLH2	subcooled LH2
TRL	Technical Readiness Level

1 INTRODUCTION

Hydrogen for transport is currently undergoing an accelerated market expansion from primary use in light-duty vehicles (LDV) to also include use in heavy-duty vehicles (HDV) and other on-, off- or non-road applications. This imposes two overall challenges regarding technical capability of fuelling equipment and the commercial fossil parity targets to be reached.

This document aims to compare different existing approaches of non-gaseous storage onboard of applications, such as liquid (cryogenic) hydrogen (LH2), liquefied natural gas (LNG), cryo-compressed hydrogen storage (CcH2), ammonia, liquid organic hydrogen carriers (LOHC), hydrides and chemical storage. The target is to benchmark them by listing their advantages and disadvantages and current technology readiness level (TRL). New forms of storage will need to exceed compressed gas hydrogen storage (CGH2) metrics including, volume for packaging, technical operating parameters, and customer requirements for cost, efficiency, and refuelling time. Analysis of existing non-gaseous refuelling protocols or applications is given.

2 NON-GASEOUS HYDROGEN REFUELLING

2.1 Liquid hydrogen (LH2)

2.1.1 Background on onboard liquid hydrogen storage

Using LH2 onboard vehicles for increased energy density is not new. LH2 has been a key contributor to the success of space exploration over the last 60 years, starting with Saturn V (Apollo program), the six generations of the European space program Ariane, and more recently Jeff Bezos' Blue Origin. Closer to the application of transportation, storing LH2 onboard terrestrial vehicles has been studied since 1966 with GM's Electrovan (credited with actually being the first EVER fuel cell vehicle!) that contained a liquid hydrogen tank and a liquid oxygen tank. Interestingly, the Electrovan never really worked with LH2 as it was retrofitted with more conveniently accessible gaseous H2 storage to feed the fuel cell. GM was quickly followed by entities like Los Alamos National Laboratory, the German Aerospace Center DLR, BMW AG and the Musashi Institute of Technology (Japan).

Between 1989 and 2000, the European-Quebec Hydro Hydrogen Pilot Project was a 100 MW pilot project to study the shipping of Canadian hydropower converted via electrolysis into hydrogen and the shipping of liquid hydrogen to Hamburg, Germany. A PEMFC bus pilot, carrying 600 l of LH2, was demonstrated.

BMW and Opel/GM had extensive programs between 1980-2010 and both had passenger cars driving on public roads and fuelling at public stations built by Linde. Walther Präzision provided the LH2 fuelling nozzle. The Opel/GM vehicle from 2007 carried 4.6 kg of LH2 at a fuel system weight of 90 kg and a cryogenic tank volume of 68 l. The range of the vehicle was 400 km. BMW performed significant testing on their gasoline/LH2 hybrid vehicle, including crash, bonfire, and drop testing.

In 1999, Mercedes-Benz presented a fuel cell electric version of the A-class that was equipped with an LH2 tank in the trunk, allowing for a driving range of 450 km.[1] The LH2 projects were stopped for several reasons, including challenges in public usability of cryogenic equipment.

In the late 1990s-early 2000s, the European Integrated Hydrogen Project (EIHP), in which Air Liquide was an active partner among others, took upon the task of comparing various hydrogen technologies among different classes of vehicles (light-duty passenger, vans, city buses) and their regulations. EIHP resulted in LH2 storage systems for vehicles such as the BMW 7 and the Renault FEVER. StorHy, another European project that ran from 2004 to 2008, was looking at identifying the most promising hydrogen storage systems for automotive application, with innovative solutions for high pressure, liquid and solid hydrogen storage systems.

EIHP also looked into LH2 station design and demonstration. Most notably, BMW installed a few LH2 dispensing stations in Germany, and one demonstrator in Oxnard, California, at the end of the 1990s. As a matter of fact, LH2 coupling technologies were demonstrated more than 15 years ago for medium- and light-duty applications.

1 For more information, see https://web.archive.org/web/20150306113924/http://www.hycar.de/cars/necar4.htm

GM/Opel developed 2 generations of hydrogen vehicles prototypes storing LH2 between 2000 and 2006, based on the Opel Zafira compact MPV. The last and most successful demonstration of LH2 vehicles was undoubtedly led by BMW, that released a mini-production series of 100 BMW 7 passenger vehicles with dual powered gasoline/LH2 ICEs, in the 2005-2007 timeframe. Air Liquide, through its Advanced Technologies department (=ALAT), was one of the lead manufacturing partners for most of those European projects, building more than 50 on-board LH2 tank units.

All those above-mentioned demonstration/pilot projects were to some extent successful in showing that using LH2 onboard a vehicle was certainly a doable solution. None of them, however, resulted in the massive deployment of LH2 based vehicles. This can be attributed to a few reasons. First, LH2 was never seen a viable distribution pathway until very recently, well proven by the success of FC forklifts supplied by trucked LH2, in the US. The argument was that LH2 was way too expensive to produce regarding capital cost and additional energy consumption, and that it would thus never be available at any refuelling stations, even less onboard a vehicle. Even if LH2 is certainly more expensive to condition than compressed H2, its ease of distribution and dispensing has been proven to outweigh this drawback. Second, it is likely that light-duty passenger vehicles, the main focus of past developments, is not the best market for onboard LH2 storage. Indeed, light-duty passenger vehicles can only store "small" amounts of hydrogen (~5 kg) due to their limited size and range needs, with size factors (shape and absolute volume) that are not very compatible with efficient insulation to limit boil-off losses. Additionally, those vehicles experience a lot of parking, hence the need to store LH2 over long periods (days to weeks), here again unfavourable conditions for cryogenic fluids. Due to the larger tank volumes and the high commercial utilization, the medium- and heavy-duty vehicles market is much more favourable to onboard LH2 storage.

At the moment, onboard LH2 storage for heavy-duty trucks is evaluated as one of the options to store hydrogen on board and considered by few truck manufacturers. The common drawbacks raised against the technology includes the economic penalties of boil-off, the challenges associated with down-scaling a LH2 tank (from trailer size, 3000+ kg capacity, to fuel tank size, 40+ kg capacity) in terms of insulation and mechanical structure, the availability of LH2 and the risk associated with manipulating LH2.

An European project called OBLHyT (=On-Board Liquid Hydrogen for Trucks) was submitted to FCH 2 JU in April 2020, assembling a team of 10+ major European stakeholders (truck manufacturers, academics, station supplier, molecule provider, fuel cell manufacturer, station operators,...); aiming at analysing the value proposition of on-board LH2 for heavy-duty vehicles by demonstrating that (1) it makes sense economically, when compared to 35 or 70 MPa gaseous storage and (2) a full scale LH2 tank can effectively be integrated into the application and meet basic performance targets. Unfortunately, this project was not awarded.

As for heavy-duty vehicles, until recently, there have only been a few LH2 buses for demonstration or research purposes. Recently, as interest in hydrogen use for heavy-duty vehicles has increased, LH2 is being considered because of its high density.

In September 2020, Daimler Trucks presented the Concept GenH2 Truck, a tractor-trailer for long-haul application and a driving range of up to 1000 km. Customer testing is planned for 2023 and start of series production has been announced for the second part of the decade. A concept using subcooled LH2 (sLH2) was proposed by Daimler and Linde, no details have been published at the time of writing.

Advantages of the LH2 storage is the high storage density resulting in high driving range and a payload of 25 tons, comparable to current trucks with conventional drivetrain. The tanks located on the outside of the vehicle frame will have a capacity of 80 kg hydrogen.[2]

2.1.2 RCS situation around LH2

There is limited RCS surrounding LH2 for use as a vehicle fuel:

- For stations using LH2 as the supply for gaseous hydrogen refuelling operations, ISO 19880-1 includes content for LH2 delivery, storage, cryogenic pumps and vaporizers, piping, venting, etc., plus the other general requirements for an HRS. It does however not cover the requirements for dispensing of liquid hydrogen.
- The requirements for LH2 connectors are covered in ISO 13984:1999 Liquid hydrogen — Land vehicle fuelling system interface[3], however it remains to be seen if this document covers the current needs. (A systematic review took place within ISO TC 197 in 2020, and the result was that the document will be revised or withdrawn).
- The requirements for LH2 quality are covered in ISO 14687, but there is no EN document covering this currently as an equivalent to EN 17124

It is worth noting that, recently, the absence of LH2 refuelling related standards was recognized by the European Commission (along with specific standards for the refuelling of gaseous hydrogen heavy-duty vehicles, for road and other applications) with a recent draft Standardization Request relating to standards supporting the Alternative Fuels Infrastructure Directive (AFID). Table 2 of the draft Standardization Request (requesting European standards for the refuelling of road vehicles with liquified hydrogen) and Table 4 (requesting European standards for the refuelling of maritime vessels with liquified hydrogen, also methanol and ammonia) are copied below in Table 1 and Table 2:

2 Daimler, press release: „The most innovative trucks for the electric future: Mercedes-Benz eActros and Mercedes-Benz GenH2 Truck win 2021 Truck Innovation Award" ,November 30th, 2020. Available at https://media.daimler.com/marsMediaSite/ko/en/48289226 (accessed on 10.03.2020)

3 ISO 13984:1999 Liquid hydrogen — Land vehicle fuelling system interface. Available at: https://www.iso.org/standard/23570.html?browse=tc

Table 1: List of new European standards supporting an interoperable infrastructure for hydrogen supply for road transport

Reference information		Deadline for the adoption by the ESOs*
1	European standard containing technical specifications with a single solution for hydrogen refuelling points dispensing compressed (gaseous) hydrogen for heavy-duty vehicles	31.12.2023
2	European standard containing technical specifications with a single solution for hydrogen refuelling points dispensing liquefied hydrogen for heavy-duty vehicles	31.12.2023

Table 2: List of new European standards supporting an interoperable infrastructure for vessels for hydrogen, methanol and ammonia bunkering

Reference information		Deadline for the adoption by the ESOs *
1	European standard containing technical specifications with a single solution for gaseous compressed hydrogen refuelling points and bunkering for maritime and inland waterways hydrogen-fuelled vessels	31.12.2024
2	European standard containing technical specifications with a single solution for liquefied hydrogen refuelling points and bunkering for maritime and inland waterways hydrogen-fuelled vessels	31.12.2024
3	European standard containing technical specifications with a single solution for methanol refuelling points and bunkering for maritime and inland waterways methanol-fuelled vessels	31.12.2024
4	European standard containing technical specifications with a single solution for ammonia refuelling points and bunkering for maritime and inland ammonia-fuelled vessels	31.12.2025

* Proposed for discussion of the Standardisation Request, October 2020. Whilst not mentioned in the draft Standardisation Request, the use of hydrogen as a fuel for rail applications is also to be discussed, for which liquid hydrogen could also be expected to be a solution for the future.

Whilst the solution for this gap is still to be determined, in addition to the Hydrogen Technologies standards of ISO TC 197, there is increased interest in preparing standards for LH2 applications from other technical committees such as ISO TC 252, CEN TC 326, and CEN TC 282, where there is expertise in preparing standards for cryogenic fluids (LNG).

When it comes to using LH2 on board vehicles:

- The regulations EC79/2009 and 406/2010/EU include requirements for LH2 vehicles, however, these are due to be withdrawn in the near future.
- The GTR#13 includes requirements for LH2 vehicles, however at this time these elements have not yet been incorporated into the EU legislation based on the GTR, the UNECE R134.
- Until UNECE R134 will be updated to include LH2 vehicle tank systems, the European Union plans to allow homologation of such vehicles according to a commission regulation. The current draft specifies that "Vehicles with liquefied hydrogen systems shall be approved in accordance with Article 39 of Regulation (EU) 2018/858 concerning exemptions for new technologies or new concepts, based on UN Global technical regulation No 13, on hydrogen and fuel cell vehicles, part II, section 7."
- The only other document in addition to the connector document, ISO 13984, that covers LH2 in a "transport fuel" context is another ISO TC 197 document, ISO 13985:2006 Liquid hydrogen — Land vehicle fuel tanks.[4] As with ISO 13984, this document also underwent systematic review within ISO TC 197 in 2020, and the result was that the document will be revised or withdrawn.

Where:

I. Regulation No 134 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV) [2019/795]

   https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.129.01.0043.01.ENG

   This is the European transposition of the UN GTR No. 13 - Global Technical Regulation concerning the hydrogen and fuel cell vehicles

   https://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29glob_registry.html

II. REGULATION (EC) No 79/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC

[4] ISO 13985:2006 Liquid hydrogen — Land vehicle fuel tanks. Available at: https://www.iso.org/standard/39892.html?browse=tc .

https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:035:0032:0046:en:PDF

The detail supporting this Regulation is provided by COMMISSION REGULATION (EU) No 406/2010 of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles

https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:0001:0107:EN:PDF

2.1.3 Vehicle systems

LH2 vehicles have vacuum insulated tanks which store the hydrogen at cryogenic temperatures at less than 10 bar. Typically, a vehicle will pass the LH2 through a heat exchanger to transform it into usable gaseous hydrogen. However, if the vehicle is not driven for a period of time, the LH2 will evaporate, or "boil-off" and may need to be vented which may be an issue if the vehicle is stored indoors. For example, a study in 2004 showed that after three days of dormancy, a Magna Steyr tank had a boil-off loss of 1-3% per day.[5] In addition, the vacuum seal on the storage tanks is a known potential weakness in a vehicular application which can see significant vibrations. If the vacuum seal is compromised, the evaporation rate of the LH2 will increase.

ZAL (Zentrum für Angewandte Luftfahrtforschung) presented to the PRHYDE consortium in the December 2020 PRHYDE online workshop[6] that there is work ongoing in the aerospace industry to look into refuelling aircraft with LH2 for use in APUs and main propulsion engines. There are no further reaching specifications known at the point of writing.

2.1.4 Fueling Stations

LH2 fuelling stations consist of a LH2 storage vessel, typically a double-walled low-pressure vessel (typical operating pressures are below 5 bar(g)) with vacuum insulation and radiant heat shields in between the two walls.

Liquid hydrogen is typically gravity fed to the suction of a cryopump that ensures the flow and pressure requirements for the refuelling process. The lines between storage vessel, pump and dispenser need to be very well insulated, typically vacuum insulation is used. Due to the very low temperature of LH2, great care needs to be taken to avoid condensating or freezing air, with the possibility of enriched oxygen gathering in unwanted places. Generally, the base of an LH2 station needs to be made of non-combustible material, such as concrete, for this reason. Dispenser, breakaway, hose and nozzle need to withstand very low temperatures without

[5] G. Krainz, G. Bartlok, P. Bodner, P. Casapicola, Ch. Doeller, F. Hofmeister, E. Neubacher, and A. Zieger (MAGNA STEYR Fahrzeugtechnik AG & Co KG): Development of Automotive Liquid Hydrogen Storage Systems, AIP Conference Proceedings (2014) 710:1, 35-40. https://aip.scitation.org/doi/abs/10.1063/1.1774664

[6] For information see https://prhyde.eu/events/

accumulating excessive icing and not posing an injury risk to touch (frost bite). Also, the correct functioning needs to be ensured under these low temperatures. Additional challenges are around making sure there is no air in the hose and nozzle, as air can condense and also partially solidify at these low temperatures.

2.1.5 LH2 refuelling

The filling process is complicated considering the need to precool and air-free the filling hose. A warm hose will cause boiling and pressure differential can cause cavitation resulting in gaseous hydrogen bubbles in the liquid hydrogen which may block initial liquid hydrogen flow through the filling hose. This warm hydrogen gas then requires a second tank outlet with subsequent capture or venting at the station as liquid hydrogen is added to the tank. In general, the filling nozzle and hose geometries require larger and heavier equipment considering the need for insulation or interface heating to ensure the nozzle does not freeze or stick to the fill port. Concepts using sLH2 fuelling that would not necessitate a gas phase return have been suggested by Daimler and Linde, where a top spray arrangement in the vehicle tank would condense the gas phase in the H2 tank. It is unknown whether this concept has been demonstrated in practice on vehicle scale. Pressurized cryogenic filling may mitigate some of the above - mentioned issues, especially when the barrier to supercritical fluid is crossed.

When a vehicle refuels its LH2 system, the tank and fuel lines will be warmer than a full tank of LH2. Therefore, there will be evaporation at the start of the fuelling, in the phase until the transfer lines are cooled down. This gas needs to be captured or vented by the nozzle and stations, or the pressure increase be handled in the fuelling process. Additional energy may be needed to re-convert the boil-off to LH2. Current activities are aiming for a LH2 fuelling with no transfer losses and increased storage density compared to the technology used in the past passenger cars.

Much of the componentry for LH2 stations, such as storage tanks, cryo-pumps, and nozzles already exist and are in use, but there are few suppliers, especially for the latter two. Work has to be done concerning the standardization of the fuelling receptacle and refuelling process of LH2 vehicle tanks.

Analogy: LNG refuelling process

First a connection is made between the station and the vehicle tank by hose, then, in cases where the tank pressure is too high for fuelling, pressure in the LNG tank is released back to the station storage tank, thereby dropping both the pressure and temperature in the on-board tank. Customers reported that this is required in a significant number of the cases. Once the pressure is sufficiently low, LNG is introduced into the tank from the station, causing the gas phase in the on-board tank to condensate and the pressure to drop further. This process continues, until the tank is full of LNG, when a pressure spike can be registered by the station, as no more LNG can enter the on-board tank in liquid form. The station then shuts off the LNG supply and isolates the tank from the nozzle. At some filling stations, the user then has to wait for the LNG in the hose and nozzle to warm up and vaporize, thereby pushing remaining LNG back into the storage tank, before decoupling. This process takes a couple of minutes.

Comparison between LH2 and LNG

In case of LH2 the hose and the fittings including the nozzle / receptacle combination need to be specifically isolated, e.g. by vacuum isolation, in order to avoid air being in contact with cold surfaces. This is due to the lower temperature of LH2 compared to LNG, that is below the boiling temperature of nitrogen and oxygen and air liquefaction may occur at improperly isolated surfaces. Also, the inside of the transfer hose will need to be freed of oxygen by a nitrogen purge and a following helium or GH2 purge to prevent condensation or even solidification of air gases, as the temperatures in play are much lower than in case of LNG.

2.2 Cryo-compressed hydrogen (CcH2)

2.2.1 Background

Cryo-compressed hydrogen storage, or CcH2, is a more recent technology than LH2. It was first investigated in the late 1990's by Dr. Salvador Aceves at Lawrence Livermore National Laboratory, California. The goal was to address the main limitations of LH2 storage for passenger cars: boil-off losses. Indeed, storing liquid hydrogen in insulated pressure vessels overcomes many of the shortcomings of compressed gas or liquid hydrogen tanks and may even open new possibilities. Compared to cryogenic H2 tanks, the dormancy is greatly extended as the allowable pressure inside the vessel increases. The vessel has higher heat receptivity since H2 contained in the vessel is vented at a higher temperature and this further augments dormancy. A vehicle equipped with an insulated pressure vessel cannot be stranded due to evaporative losses because venting stops when the tank reaches ambient temperature at allowable pressure (350 to 700 bar).

BMW demonstrated a CcH2 vehicle in the 2000's and 2010's and some CcH2 buses have been built for demonstration/research purposes.[7] The BMW 5 GT CcH2 stored 7.1 kg of hydrogen at 350 bar. The vehicle had a fuel system weight of 153 kg in a 120 l tank with a range of up to 700 mi. They performed multiple crash, cycling, burst, and bonfire tests with no relevant damage.

Linde built a few CcH2 stations to support the BMW vehicles. Between 2010 to 2012 one station in Germany performed over 7000 fuellings. Walther Präzision provided the fuelling nozzle.

2.2.2 Vehicle systems

A CcH2 fuel system is similar to a LH2 system except that it is designed for higher gas pressures. Past testing and use have shown that the vacuum seal is a reliability issue, as it is for LH2 tanks.

[7] R.K. Ahluwalia, T. Q. Hua, J. K. Peng, D. Papadias, and R. Kumar (Argonne National Laboratory): „System Level Analysis of Hydrogen Storage Options". Presentation at 2011 DOE Hydorgen Program Review, Washington DC, May 2011. Available at: https://www.hydrogen.energy.gov/pdfs/review11/st001_ahluwalia_2011_o.pdf

CcH2 offers several benefits and challenges compared to LH2. In ideal conditions, the density of the hydrogen in the tank is much higher than GH2 and LH2, thereby giving very good energy density and range for a limited build volume. The technology is under development to determine an appropriate pressure operating range from 100 bar to 700 bar and associated pressure stroke used to determine time to first venting. On road test vehicles have been used at 300 bar fill pressure with venting at 350 bar. In 2016 several attempts were made to develop a thin lined stainless steel CFRP (carbon fibre reinforced polymer) tank for use at higher pressures. However, these either leaked or burst after only few hundred hydraulic cycles, rather than the projected 1500 cycle target.[8]

Also, boil-off problems are eased with the introduction of a CCH2 storage system, as the supercritical state of the hydrogen and the pressure vessel allows for storage of the gas at higher pressures. However, the dormancy time before releasing the gas varies significantly on the amount of CcH2 in the tank relative to the tank volume. If the CcH2 tank is near full, the dormancy is similar to an equivalent LH2 tank (approximately 3 days), but can almost triple for a CcH2 tank which is 65% full. With respect to dormancy time, CcH2 offers more benefits to heavy-duty vehicles, because as the tank volume increases, the dormancy time also increases. There is some indication dormancy or time to first venting may be markedly extended through energy consumed by the conversion of parahydrogen to a room temperature ratio of 3 orthohydrogen to 1 parahydrogen or normal hydrogen and increase fill density by up to 5%[9] or up to 384.1 kJ/kg at 90 K.[10]

One major challenge is the range of the CcH2 vehicle is highly dependent on the usage because infrequent driving increases the amount of heat in the tank system. This heat causes the amount of gaseous hydrogen to increase which, in turn, decreases the density of the system. The heat can only be removed with successive fuelings. For example, BMW showed that it takes 4-5 fuellings to achieve maximum density from a room temperature tank.[11]

Another advantage of CcH2 is that CGH2 can be used in the vehicle tank, with the only issue being range and the reduction of range over the next few fill cycles.

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[8] S. Aceves, et al. (Lawrence Livermore National Laboratory. US Department of Energy): “Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High Pressure Liquid Hydrogen Pump”, 2018. P.4. Available at https://www.hydrogen.energy.gov/pdfs/progress16/vii_c_4_aceves_2016.pdf

[9] S. Aceves, et al. (Lawrence Livermore National Laboratory. US Department of Energy: “Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump”, 2018. P.3. Available at https://www.hydrogen.energy.gov/pdfs/progress18/tahi_aceves_2018.pdf

[10] R. M. Bliesner: “Parahydrogen-Orthohydrogen Conversion For Boil-Off Reduction From Space Stage Fuel Systems” ,Masters Thesis, Washington State University School of Mechanical and Materials Engineering 2013. P.13. Available at https://s3.wp.wsu.edu/uploads/sites/44/2014/08/Bliesner-Masters-Thesis-Final-P-O-heat-shielding.pdf

[11] T. Brunner (BMW Group): “Cryo-compressed Hydrogen Storage”. Presentation at US DOE COMPRESSED & CRYO-COMPRESSED HYDROGEN STORAGE WORKSHOP, Washington DC. February 15th, 2011. Available at https://www.energy.gov/sites/prod/files/2014/03/f12/compressed_hydrogen2011_7_brunner.pdf

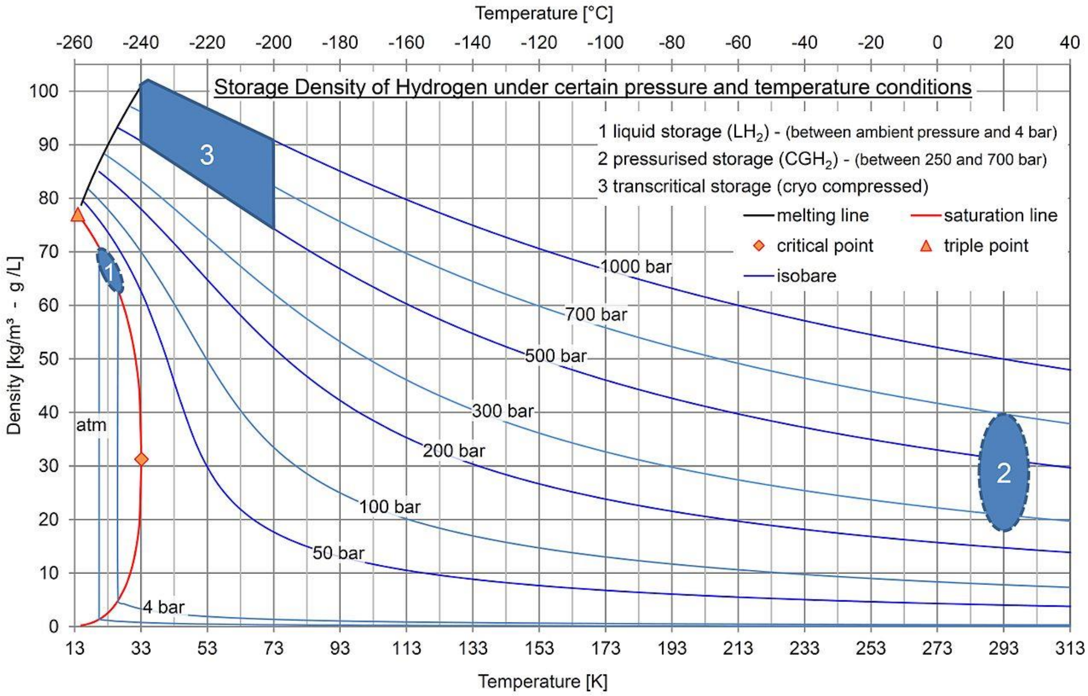

Figure 1: Density of CcH2 (field 3) Source: Moritz Kuhn (ILK Dresden)[12]

2.2.3 Transferring CcH2

Cryo-compressed hydrogen is LH2 that is pressurized by a cryopump into a supercritical state and pumped into a well-insulated pressure vessel on board the vehicle. On one hand it combines the simplicity of switching on a pump at the beginning of the fill and switching it off again at the end, when a certain pressure has been reached; but it also combines the disadvantages, as both cryogenic liquids and high pressures have to be handled at the same time. Also, the range of the vehicle cannot be predicted with great accuracy, as it depends on the amount of heat in the tank system that can only be removed with successive fill cycles. Under ideal conditions, the density of the hydrogen in the tank is much higher than CGH2 and LH2, thereby giving very good energy density and range for a limited build volume.

CcH2 tanks can be refuelled using simply a cryogenic pump with a single flow insulated high-pressure hose, as opposed to dual flow refuelling with LH2.

Linde, in partnership with BMW, has been pioneering CcH2 refuelling, with one mobile refueler (used for field testing of the BMW car) and 2-3 dispensers still functional in Germany.

12 Wikimedia Commons, by Moritz Kuhn (ILK Dresden): https://www.ilkdresden.de/en/service/research-and-development/project/hydrogen-test-area-at-ilk-dresden/ , CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=41458600

2.2.4 Fueling Stations

In contrast to LH2 stations, the boil-off does not need to be vented or captured by the stations. Therefore, the componentry on the station is slightly less complex. However, much of the remaining components are similar to LH2 stations and have the same issue of few suppliers.

2.3 Ammonia

Ammonia has the highest volumetric H_2 density among the different carriers. Ammonia is liquid at moderate cryogenic temperatures of -33°C at ambient pressure or at ambient temperature and ~10 bar. However, ammonia is corrosive, flammable and toxic, already at low concentration. Hence, it is recommended to use ammonia in unmanned spaces equipped by automatic shut-off, detection, and ventilation systems. Alternatively, staff (operators, drivers etc.) needs to have a special safety training and the sites need suitable installations for monitoring and handling leakages and fires. In many countries, a road transportation is restricted, especially in urban areas.

Despite all drawbacks, ammonia has a large potential as energy or H_2 carrier. It can be used to generate H_2 on purpose (using ammonia cracking plants) with a significantly reduced footprint and low costs for the local storage vessels compared to LH2 and GH2. In addition to its usage as feedstock for H_2 production, it can also be used as fuel directly in combustion engines or direct ammonia fuel cells. As maritime fuel, ammonia is currently under demonstration, e.g. by the Norwegian engine manufacturer Wärtsilä [13] and has a large potential for this kind of applications.[14] The use in passenger vehicles is possible [15], but is not mature and many open issues need to be solved: NOx mitigation during combustion, street safety and regulations, as well as performance, costs, and performance of direct ammonia fuel cells. If suitable cell systems based on AEM (alkaline exchange membranes) gain technical maturity for electrolysis applications, direct AEM ammonia fuel cells are a promising option to reach low transport costs, reduced footprint for storage, no direct CO_2 emissions during usage and no need for costly ammonia pre-splitting.

If large scale exports/imports of renewable or low-carbon ammonia for power production develop over time, ammonia might therefore also gain importance as vehicle or maritime fuel.

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[13] Wärtsilä, press release: “World’s first full scale ammonia engine test - an important step towards carbon free shipping“ June 30th, 2020. Available at: https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test---an-important-step-towards-carbon-free-shipping-2737809

[14] Ammonia energy conference by Ammonia Energy Association. August 27-28th, 2020.

[15] See also https://www.nh3fuel.com/index.php/faqs/16-ammonia/36-can-ammonia-be-used-as-motor-fuel

2.4 Liquid organic hydrogen carriers (LOHC)

Liquid organic hydrogen carriers are a way to bind hydrogen in a form that is typically easier to transport, i.e. in a liquid state. LOHCs require a form of treatment at the site of the hydrogen generation, where hydrogen is chemically loaded onto the carrier, and at the location of use, where the hydrogen is again chemically removed from the carrier. In between, LOHCs make it easier to transport hydrogen, as often no special pressure vessels or cooling is required, in some cases the handling of LOHCs is as easy as and very comparable to the handling of diesel fuel. Chemically speaking, the LOHC carrier fluids typically are unsaturated organic compounds, that can be loaded with hydrogen and dehydrogenated at the point of use. There is a variety of potential carrier fluids available. In general, the bonding / release process can be described as followed:

$$\text{LOHC (carrier fluid)} + H_2 \leftrightarrow \text{LOHC (loaded)} + \text{Heat}$$

LOHCs can be grouped in two categories:

- Atmospheric Carbon Return: The LOHC is decomposed and CO_2 is released during operation, while the hydrogen is released,
- Liquid Carbon Return: The LOHC gets unloaded and is still present as a liquid after the hydrogen is extracted.

LOHCs can in principle be used in two ways to get hydrogen to the application:

- Either by recovering the hydrogen at the station and then dispensing gaseous hydrogen or
- by directly loading the LOHC on board of the application.

Since the first path is only a means of supplying hydrogen to the station and the energy transfer to the application remains unaffected (one still has to carry out refuelling using gaseous hydrogen, which is the main topic of this project), only the second path, where the LOHC is directly transferred to the application is regarded further, as is a potential alternative to gaseous fuelling.

Below is a comparison chart and reference for the energy required for various hydrogen carriers compared to gaseous hydrogen.

Endothermic dehydrogenation step including pressure swing adsorption (PSA) at the gate is the largest contributor to the increase in energy consumption of LOHCs compared to gaseous hydrogen:

- Total energy includes fuel plus electrical energy, assuming 33% efficiency in generating electrical power
- Energy consumption (in kWh/kWh-H2): MCH ≅ammonia (2.52) > methanol (2.26) > GH2(1.64)[16]

[16] T. Autrey (Pacific North West National Laboratory), A. Ahluwalia (Argonne National Laboratory. US Department of Energy): “Hydrogen Carriers for Bulk Storage and Transport of Hydrogen”, 2018. P13.

2.4.1 Atmospheric Carbon Return (CO_2 as hydrogen carrier): Example methanol

One of the most common LOHC is methanol. Less common carriers are formic acid or formate salts. In any case, CO_2 serves as H_2 carrier, i.e. various hydrogenation products of CO_2 can be considered, i.e. formic acid, methanol, methyl formate, DME, and methane. However, with increasing degree of hydrogenation, the dehydrogenation gets more and more challenging. The strongest argument against this type of H_2 supply is that the system is still based on CO_2: CO_2 needs to be captured in the beginning (from CO_2 sources like glass, cement or chemical industry, power plants or the air) and CO_2 is still emitted in the end. This makes this solution more complicated in terms of certification and the evaluation of the environmental impact.

On the volume basis, methanol has 40% more H_2 than LH2 at -253°C and 140% more H_2 than compressed hydrogen at 700 bar. Methanol is available worldwide due to globally distributed Methanol production and a worldwide ship-based supply chain with relatively low shipping costs. Methanol is a toxic and flammable liquid with a much wider explosion range than gasoline and diesel (6.7 – 36% vol). Hence, for filing the hose should have manual & automatic valves. The fuelling line should be purged from liquid after refuelling, then it should be inerted and degassed. Nevertheless, methanol has a relatively high vapour pressure and evaporates in the tank leading to the pressure increase. However, evaporation is much slower than boiling, hence the pressure builds up much slower for methanol compared to cryo fuels. ethanol needs to be reformed onboard of the vehicle before it can be used in a PEM fuel cell. This can be done using reformer technology that has been developed and successfully demonstrated over the last two decades (on a prototype level). Still, this technology is challenging since it requires a steam supply, H_2 purification, and a heat integration. All this makes methanol reforming challenging for onboard H_2 supply.

The direct combustion of methanol in a combustion engine is common practice in China (typically M15-M25 blends with 15-25% Methanol in gasoline). In China approximately 7 Mt fuel blends were used in 2018[17]. A combustion of pure Methanol in car engines is also possible, but more modifications and additives are needed. In the maritime sector methanol is also widely discussed as a clean fuel, because it is sulphur-free and its production can be decarbonized. For the use as maritime fuel, methanol is normally combusted directly, without a reforming to hydrogen.

Direct Methanol Fuel Cells (DMFC) can take methanol directly as a fuel and do not need a reformer. Currently, DMFC are available with a maximum capacity of a few kW of power[18]. The main drawbacks and challenges of DMFC are slow kinetics, low

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Available at https://www.energy.gov/eere/fuelcells/downloads/hydrogen-carriers-bulk-storage-and-transport-hydrogen-webinar

17 K. Zhao: „Methanol Fuel Blending in China", Trinidad and Tobago Methanol Fuel Blending Forum, January 24th, 2019, https://www.methanol.org/wp-content/uploads/2019/02/6.-Kai-Zhao-Methanol-Fuel-Blending-in-China.pdf

18 M. Mueller, D. Stolten, "The costs of Direct Methanol Fuel Cells", Forschungszentrum Jülich, 2011.

power density, high material costs (like typical for PEM) and methanol crossover through the membrane, leading to decrease of efficiency.[19.]

In summary, these factors make Methanol suitable as an energy carrier for combustion (turbines, combustion engines) or small-scale fuel cells (power supply of electronic devices etc.). Its potential as fuel for fuel cell electric vehicles (FCEV) is rather limited.

The extraction of H_2 from Formic Acid is easier than from Methanol since it can be achieved at near ambient conditions with suitable catalysts [20]. However, the H_2 content in formic acid and its derivatives is so low that no real benefit for its transport and storage can be achieved.

2.4.2 Liquid Carbon Return (aromatics as hydrogen carrier)

Aromatic components contain of one or more aromatic rings (toluene, dibenzyl toluene) or heteroaromatic rings (carbazoles, indoles etc.). The most promising candidates as hydrogen carrier are those which can easily be hydrogenated and dehydrogenated and have no or limited hazards. Among them toluene and dibenzyl toluene are the most prominent ones, Toluene (promoted by e.g. Chiyoda) because of its low price and good availability and dibenzyl toluene (DBT, promoted by e.g. Hydrogenious) because of its low vapour pressure and safe handling (non - toxic, non - flammable). A side effect of this method of transportation is that the carrier liquid adds a considerable amount of non-working capital to the transportation stream and needs to be maintained in good condition throughout its life, further adding to the costs.

Transferring an LOHC from a tank into a vehicle (car, ship) or another tank is very simple and comparable to the transfer of diesel fuel. Typical hydrogen loadings obtainable today are 6% by mass and about 1 kg/H_2 per 17 l of LOHC, which means that for a 40 t truck with 8 kg/H_2 and 31 l_{diesel} per 100 km driven, the required volume to be transferred roughly quadruples. This is not a limitation today and can be simply accounted for by choosing adequate pump and tank sizes.

Today, such LOHC's are mainly considered as means to transport H_2 from the place of production to the place of usage, i.e. in this case the refuelling station. Its onboard dehydrogenation is in very early stage of development. Therefore, most LOHC-based supply schemes would still require a dehydrogenation unit adjacent to the station and the typical GH2 station and tank infrastructure.

One such approach for onboard dehydrogenation, albeit in its very early stage, is the use of a transfer hydration step, where the hydrogen is temporarily loaded onto an acetone carrier and directly used in a DIPAFC (Direct Isopropanol fuel cell)[21]. This

[19] M.F. Sgroi et al Energies (2016), 8, 1008-1026.

[20] K. Sordakis et al. „Homogeneous Catalysis for Sustainable Hydrogen Storage in Formic Acid and Alcohols", Chem. Rev. 118 (2),372-433, 2018.

[21] G. Sievi, D. Geburtig, T. Skeledzic, A. Bösmann, P. Preuster, O. Brummel, ... & J. Libuda (2019). Towards an efficient liquid organic hydrogen carrier fuel cell concept. In: Energy & Environmental Science, 12(7), 2305-2314.

requires an additional loop and is in very early development stages, but has the advantage that there is no CO2 release nor any molecular hydrogen on board of the application.

During operation, the hydrogenated liquid is passed over a catalyst bed and heat is supplied externally to drive the H_2 release. In an endothermic reaction, hydrogen is released from the carrier at ~ 300°C and needs to be separated and cleaned for a use in a H_2 fuel cell. In case of DBT, the H_2 purification is simple [22], in case of toluene as carrier, the volatility of the carrier and its partial decomposition to light components requires a more complex cleaning and in addition leads to increased H_2 and carrier losses.[23]

One major drawback of liquid carbon return LOHCs, both, in terms of supply and onboard usage, is that the dehydrogenated liquid needs to be returned and reprocessed. This raises currently unsolved questions around carrier liquid degradation, tank design, cleanliness, contamination with water, other fluids and particles, mixing with other LOHC liquids and other similar issues.

A second major drawback is the need to maintain temperatures above freezing or even higher temperatures, to maintain required viscosity for sufficient flow rates of some LOHC candidates.

In terms of economics and carbon footprint, the largest challenge is the large amount of heat needed for the dehydrogenation. Around 10 kWh heat per kg of H_2 are required. In case of onboard dehydrogenation of LOHC, a heat integration is not easily possible if low temperature fuel cells (PEM, alkaline) are used. The required options, e.g. use of an additional fuel for heating, partial combustion of H_2 product and upgrading the heat via a heat pump or electric heating are making it challenging to use LOHC for onboard applications. A promising option for onboard applications is the use of direct LOHC fuel cells. The first concepts have been published recently [24,25], but this technology is far from commercialization.

Loading LOHC onto an application (e.g. vehicle) is simple, as it behaves similar to a diesel like oil and can be pumped and stored in similar ways.

One significant difficulty with the loading is that, unlike in conventional diesel refuelling, the spent LOHC carrier liquid needs to be returned to the refuelling stations, making the overall process more difficult. This requires some sort of return line, as well as

[22] A. Seidel, „Refuelling of fuel cell vehicles by hydrogen from the LOHC process", Gas for Energy 01/2019. Available at: https://www.gas-for-energy.com/fileadmin/G4E/pdf_Datein/2019/Fachbericht_Seidel_Hydrogenious/gfe1_19_fb_Seidel_V3.pdf

[23] M. Niermann et al., Energy & Environ. Sci. 2019, 12, 290-307.

[24] G. Sievi et al. EnergyEnviron.Sci. (2019) 12, 2305-2314.

[25] H. Cheng et al. « Energy storage and supply system and direct fuel cell based on organic liquid hydrogen storage materials", US Patent US2014080026 A1

supporting flow system (e.g. gravity or pump-fed) and poses significant challenges on the infrastructure side:

- Contamination of the fluid
- Mixture of different LOHC fluid types
- Moisture
- State of loading of the LOHC
- Return of the LOHC carrier liquid to a H_2 production facility and its required treatment

These challenges mentioned above lack scalable solutions at the time of writing, making a fast and large-scale rollout of LOHC unlikely in the near future.

With LOHC in the open market it can become difficult to precisely indicate the amount of H2 stored in the LOHC, given the above, and may pose a further, legal problem in the weights and measures.

2.5 Other hydrogen storage concepts

Beside the hydrogen storage and refuelling concepts described above, additional approaches are in development, including metal hydrides, bundle swap and local generation of GH2 from an aluminium metal matrix.

Although these concepts have not reached a high technology readiness level yet, a brief introduction is given in the following.

2.5.1 Hydrides

Metal hydrides, or in general solid state hydrogen storage materials, are solids that can chemically bond hydrogen and reversibly release hydrogen again. In general, the bonding / release process can be described as followed:

$$\text{M (Metal)} + H_2 \leftrightarrow MH_x \text{ (Metal Hydride)} + \text{Heat}$$

Research on suitable storage materials is done for several decades, also prototype vehicles (passenger cars) have been developed with such tank systems in the past. However, until now, no such tank system is commercially available.

For a temperature T, hydrogen is absorbed (stored) at a specific pressure p, which shows as the plateau in a graph. The width of this plateau corresponds to the net storage capacity at the temperature T. It can be seen that storage density decreases and storage pressure increases with increasing temperature. Furthermore, the reaction rate is also highly depending on the temperature. The numeric values of the named parameters are specific for each material. Suitable storage materials must combine a high storage density and reaction rate at relatively low temperatures and moderate pressures.

Fueling a metal hydride tank is basically done by applying hydrogen at a sufficiently high pressure, so the hydrogen can bond to the material. According to the reaction formula above, this process releases heat, with results in the increase of the temperature and therefore in the increase of the plateau pressure (and decrease of storage density). Once the temperature reaches the value corresponding to the applied pressure the reaction stops. To allow the reaction to continue the material needs to be cooled continuously during the fuelling process. For fast fuelling processes, the required cooling power can typically be in the range of several 100 kW, which requires complex cooling circuits directly integrated into the storage material to achieve homogeneous temperature level. Charging speeds and storage densities are challenging, and, at the time of writing, much slower than refuelling with GH2. Accordingly, charging times around 30 min are quoted for systems with storage volumes comparable to passenger car applications. Several papers published on the subject seems to suggest that there are paths to improve charging times and ease requirements on temperature levels for discharging, too, which are both key improvement areas to enable use in transport applications. Given the low commercial availability level (there are first of kind products on the market) of hydride storage products, the availability of sources and sinks for heat, the low gravimetric hydrogen content and the lack of widely adopted standardization in the field, in view of the

PRHYDE partners, it is unlikely that this storage method will play a significant role within this decade.

2.5.2 Bundle swap

Bundle swap is strictly speaking not a refuelling process, but more a process of moving already fuelled CHSS onto the application, comparable with the concept of swapping batteries. Hereby, a filled CHSS is lifted into the application and attached, such that the hydrogen can be used on board of the application.

First concepts are shown, mostly in marine context, that apply a swap concept for refuelling. One such example is the concept for passenger ferries in Hamburg, developed by the ferry operator HADAG in cooperation with NaValue GmbH.[26] The 33 m long ferry is to be fitted with a fuel-cell-battery-hybrid powertrain and refuelled via the exchange of palletized hydrogen pressure cylinders, much like a MEGC. Advantages quoted are fast refuelling and short handling times, while the disadvantages are handling of large weights and the transfer of a load from shore to a floating vessel via a roll-on/roll-off process. Additionally, a non-permanent connection is required to be made during bundle swap and maintained under pressure during operation, requiring a good technical solution to prevent potential leaks.

On a larger scale, inland barges have been conceptualized that would be able to be refuelled by lifting a 20 ft container containing hydrogen pressure vessels on board. In principle this concept is compared to other refuelling alternatives in a BMVI study and mentions easy refuelling at loading location and low investment costs as advantages[27]. Indeed, the concept would allow for one set of pressure vessels to play a role as both transport and storage vessel, though a challenge would be to manage the “right time to swap” and unused hydrogen remaining in the swap containers.

A similar concept is thought of for aircraft, where so called “capsules” are stored in the aircrafts cargo bay and used to provide hydrogen to a fuel cell that is permanently fixed to the airframe, which in turn produces power to drive the engines. The hydrogen supply chain is built on the basis of intermodal freight, i.e. the capsules are refuelled at a location where hydrogen is available and e.g. cheap, then transported in a container-like fashion and loaded into the aircraft at the airport for “refuelling”.[28]

All these concepts have in common that the actual act of “refuelling” the storage systems that are later lifted into the application is just decoupled from the application. This means the transfer of gaseous (or, in some cases, liquid) hydrogen is still a technical challenge that needs to be mastered, even for those applications. The PRHYDE project is also highly relevant to those systems and concepts, as it is highly advantageous to optimize the fuelling of the swappable containers, too. Most likely, the optimization will not focus on achieving very high speeds, but to reduce cost, e.g.

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[26] HADAG, press release: Ready for hydrogen. December 20th, 2020. Available at http://hadag.de/media/20191220_pi_vorstellung_neubau.pdf

[27] Ludwig-Bölkow-Systemtechnik et al. Strombasierte Kraftstoffe für Brennstoffzellen in der Binnenschifffahrt. Studie im Auftrag des BMVI (NOW), 2019, Available at: https://lbst.de/wp-content/uploads/2021/03/LBST-DNVGL-IfS_2019_ShipFuel_Hintergrundbericht_NOW.pdf

[28] For more, see e.g. Universal Hydrogen: https://www.hydrogen.aero/about

by not utilizing any precooling. Also here, the PRHYDE project could support with providing proven and safe refuelling methods.

2.5.3 Local generation of GH2 from an aluminium metal matrix

A number of scientific research groups have in the past and present studied the possibility to generate hydrogen locally by reacting aluminium with water to aluminium oxide and gaseous hydrogen:

$$2\ Al + 6\ H_2O \leftrightarrow 2\ Al(OH)_3 + 3\ H_2.$$

According to a US-DoE whitepaper[29], the gravimetric hydrogen capacity from this reaction is 3.7 wt.% and the volumetric hydrogen capacity is 46 g_{H2}/L. The main issue seems to be to keep the reaction happening continuously, predictively and under controllable rates and conditions, as the formation of aluminium oxide acts like a passivation reaction. There are research activities to study the use of reaction promoters in the form of metal oxide nanoparticles, claiming significant improvement on the hydrogen generation.[30]

Even given successful development of these issues, the approach is not yet standardized, which means it will require several years to develop an industry consensus before such a solution could be deployed at a wider scale. Both the gravimetric and volumetric energy densities can be surpassed by other H2 storage systems. A key difference in the refuelling process would be to need solid material handling capabilities at a refuelling station, as opposed to gaseous or liquid carriers.

[29] Reaction of Aluminum with Water to Produce Hydrogen, A Study of Issues Related to the Use of Aluminum for On-Board Vehicular Hydrogen Storage, U.S. Department of Energy, 2008 (John Petrovic, George Thomas) Available at: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/aluminium_water_hydrogen.pdf

[30] Generation of hydrogen from aluminum and water – Effect of metal oxide nanocrystals and water quality, Hong-Wen Wanga, Hsing-Wei Chunga, Hsin-Te Tenga, Guozhong Caob, 2011. Available at: https://doi.org/10.1016/j.ijhydene.2011.08.077

3 CONCLUSION AND SUMMARY

It appears that the refuelling of hydrogen applications with gaseous hydrogen is the most relevant and most mature of the refuelling methods (see Table 3). Some applications may be explored with alternative storage and refuelling methods, such as LH2 or CcH2 storage, though both will need significant work to reach higher TRLs and be adopted by the market. Other alternative technologies, such as LOHCs, hydrides, Ammonia and local generation from aluminium still have severe technical challenges to overcome, such that a widespread application in nearby future is very unlikely. Bundle swap only moves the point at which the hydrogen is transferred into its primary containment, therefore it is closely related to refuelling with CGH2.

Table 3: Summary of different H2 storage and refuelling options

Technology	Advantage	Disadvantage	TLR
CGH2	Mature, well understood, commercially deployed, suitable for decentralized use and application. refuelling rates higher than J2601 developed in this project	Requires a good understanding of the involved thermodynamics,	8-9
LH2	High storage densities. refuelling rates equal or higher than J2601 possible	Requires centralized liquefaction, lack of standardization	7-8
CcH2	Very high storage densities, refuelling rates equal or higher than J2601 possible	Requires centralized liquefaction, lack of standardization	7
Ammonia	High storage densities. refuelling rates equal or higher than J2601 possible, but additional severe safety precautions needed.	Poisonous, lack of standardization	5-6
Hydride storage	Relatively low pressures involved.	Relatively low storage densities, complex heat management, long loading times, currently not competitive with SAE J2601	5-6
LOHC	Moderate storage density, easy to handle most LOHCs. High transfer rates	Unsolved dehydrogenation issues, unattractive energy balance due to high amount of energy for	4-5

Technology	Advantage	Disadvantage	TLR
	possible, equal or higher than J2601 possible	dehydrogenation. Lack of standardization, unsolved issues on LOHC quality control and ageing throughout the lifetime, unsolved issues around determining the degree of hydrogenation, different and incompatible LOHCs on the market	
Bundle Swap	Fast transfer of large amount of hydrogen to the application, potentially use of intermodal transport for supply chain	Lack of standardization, does not immediately resolve the issue of filling vessels	6-7
Local generation from Al	Hydrogen generation on demand	Reaction kinetics not well enough understood, Al2O3 as waste (not harmful, but unsolved concept of what to do with it),	3-4

What is PRHYDE?

With funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), the PRHYDE project is aiming to develop recommendations for a non-proprietary heavy duty refuelling protocol used for future standardization activities for trucks and other heavy duty transport systems applying hydrogen technologies.

Based on existing fuelling protocols and current state of the art for compressed (gaseous) hydrogen fuelling, different hydrogen fuelling protocols are to be developed for large tank systems with 35, 50, and 70 MPa nominal working pressures using simulations as well as experimental verification. A broad industry perspective is captured via an intense stakeholder participation process throughout the project.

The work will enable the widespread deployment of hydrogen for heavy duty applications in road, train, and maritime transport. The results will be a valuable guidance for station design but also the prerequisite for the deployment of a standardized, cost-effective hydrogen infrastructure.

Further information can be found under https://www.prhyde.eu. For feedback on the PRHYDE project or the published deliverables, please contact info@prhyde.eu.

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