A Classification of Existing and Emerging Hydrogen Storage Technologies

2023 IEEE Belgrade PowerTech, PowerTech 2023

Bosch, Niamh; Bianchi, Alessio Belmondo; Torbaghan, Shahab Shariat

https://doi.org/10.1109/PowerTech55446.2023.10202988

This publication is made publicly available in the institutional repository of Wageningen University and Research, under the terms of article 25fa of the Dutch Copyright Act, also known as the Amendment Taverne.

Article 25fa states that the author of a short scientific work funded either wholly or partially by Dutch public funds is entitled to make that work publicly available for no consideration following a reasonable period of time after the work was first published, provided that clear reference is made to the source of the first publication of the work.

This publication is distributed using the principles as determined in the Association of Universities in the Netherlands (VSNU) 'Article 25fa implementation' project. According to these principles research outputs of researchers employed by Dutch Universities that comply with the legal requirements of Article 25fa of the Dutch Copyright Act are distributed online and free of cost or other barriers in institutional repositories. Research outputs are distributed six months after their first online publication in the original published version and with proper attribution to the source of the original publication.

You are permitted to download and use the publication for personal purposes. All rights remain with the author(s) and / or copyright owner(s) of this work. Any use of the publication or parts of it other than authorised under article 25fa of the Dutch Copyright act is prohibited. Wageningen University & Research and the author(s) of this publication shall not be held responsible or liable for any damages resulting from your (re)use of this publication.

For questions regarding the public availability of this publication please contact
openaccess.library@wur.nl

A Classification of Existing and Emerging Hydrogen Storage Technologies

Niamh Bosch, Alessio Belmondo Bianchi and Shahab Shariat Torbaghan
Environmental Technology, *Wageningen University and Research* Wageningen, the Netherlands
niamh.bosch@wur.nl

2023 IEEE Belgrade PowerTech | 978-1-6654-8778-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/POWERTECH55446.2023.10202988

Abstract—**Hydrogen as an energy carrier is expected to play a significant role in the energy systems of the future. Storing hydrogen at utility scale is a relatively new application for which technologies are yet to mature. This paper provides a review of the existing and emerging hydrogen storage technologies. The technologies are categorized based on the phase of storage - gas, liquid or solid - and the type of bonds - compound or free hydrogen. For each category, the storage technologies are compared based on technological operational parameters, technology efficiency, safety, and economic projections.**

Index Terms—**hydrogen, energy carrier, grid balancing service, hydrogen storage technologies, comparison criteria**

I. INTRODUCTION

The decarbonization of energy systems entails a shift from greenhouse gas emitting fossil-based sources towards environmentally-friendly renewable energy sources (RES) [1] [2]. RES energy production, however, is dependent on primary intermittent energy sources such as wind and solar irradiation. As a result, large scale integration of RES can lead to a higher level of uncertainty in planning and operation of energy systems. One way to handle this problem is to increase flexibility in the system through energy storage systems.

Energy storage technologies are generally capital intensive. They are mostly built from materials that are limited such as lithium, obtained through harmful mining [3]. Therefore, there is a need for alternative energy carriers to support a smoother transition considering various challenges associated with transport, storage and even end-user consumption.

Hydrogen is considered a promising alternative to natural gas that can replace its application while addressing challenges associated with transport and storage at utility scale [4]. Hydrogen's potential has already been examined and investigated in various applications including heavy industries such as refineries, space applications [5] [4], heavy-duty transport [6] and chemical industries [7].

However, there are numerous technical, economic and legal challenges to come over before hydrogen economy becomes operational [8]. Starting with hydrogen production: only 4% of the global hydrogen production today is obtained from non-potable water resources using RES produced electricity - so-called Green Hydrogen [9] [4]. Shifting to 100% Green Hydrogen production requires an unrealistically massive amount of investment in RES which is deemed infeasible at least in the foreseeable future, thus a limiting factor [10]. Despite the availability of RES, the process of large-scale hydrogen production from non-potable water resources can yield a significant amount of concentrate, necessitating appropriate management [11]. In addition, a hydrogen economy would require a new hydrogen infrastructure, but creating this induces costs and possibly other unforeseen consequences [12].

Regardless of the method of production, another major technological challenge is hydrogen storage [13]. That is, an adequate storage technology that can be employed at utility scale is yet to be developed. At the production side, hydrogen storage technologies are needed to store the substantial amount of hydrogen that is expected to be produced in the future. At the distribution level, hydrogen storage technology is mostly expected to provide auxiliary services, especially to the power system. That is, it can be used to provide *grid balancing services* in the short-run [14], and long-term seasonal storage services (i.e., level out the variation in energy consumption and production systems) in the long-run [15].

Most of the hydrogen storage technologies proposed in literature are not yet ready to be deployed in the real-world, for various reasons. This is mainly due to hydrogen's explosive nature [16] and the high investment costs [17].

Hydrogen storage technologies have been widely investigated in literature from purely technological and economic prospective. However, several other aspects related to storage, efficiency and safety have not been in the focus of existing literature. This paper aims to take upon those aspects. Section II provides an overview of available hydrogen storage technologies, categorized by form and subsequently phase of storage. The technologies are then analyzed in Section III, based on four criteria: operational conditions, storage efficiency, safety and economic projections. Section IV concludes the paper.

II. OVERVIEW OF TECHNOLOGIES

Hydrogen can be stored in 3 different phases: gas, liquid or solid. It can be stored either as free state hydrogen or as a compound containing hydrogen molecules. In light of this description, six categories of hydrogen storage technologies are defined: Free Hydrogen Gas (FHG), Free Hydrogen Liquid (FHL), Free Hydrogen Solid (FHS), Compound Hydrogen Gas (CHG), Compound Hydrogen Liquid (CHL), and Compound Hydrogen Solid (CHS). The hydrogen storage technologies are classified accordingly and discussed in the following.

A. Free State Hydrogen Storage

Hydrogen is in its free state when hydrogen atoms are stored without modifying the chemical structure, thus remaining H2.

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

1) Gas Phase: Hydrogen is a gas at room temperature. Hydrogen storage in its gaseous state requires compression due to its extremely low density (0.089 kg/m3) under normal conditions [18] [19]. The storage pressure is restricted by the safety regulation and other operational considerations [20].

The utility scale storage systems that are available today do not exceed 100-200 bar of pressure. Higher pressure increases the hydrogen density inside the tank to 7,8 kg/m3, and induces high energy requirements and operation costs. Compressed hydrogen gas storage can be divided into 2 categories:

- above-ground storage technologies that make use of metallic vessels [20] or small-scale glass structures. The latter has been introduced recently and enables storage at very high pressures up to 1000 bar [21] [22] [23],
- below-ground storage technologies that make use of existing geological features such as existing salt cavities, retired oil/gas reservoirs, aquifers, or pipelines [20].

2) Liquid Phase: Liquid hydrogen (or cryogenic hydrogen) storage is attracting more attention due to the high hydrogen content, and relatively low risks - corresponding to the low storage temperature and pressure [24]. The main disadvantage of cryogenic hydrogen is the high investment and operational costs - corresponding to the higher energy requirement [19].

The energy requirement for operating liquid storage is more than 50% higher than of high-pressure gas storage technologies [19]. This links to the liquefaction of hydrogen, for which the gas needs to be cooled to approximately 20°K at normal pressures (1 bar) or higher [25]. The liquefaction process increases the density of hydrogen to approximately 70 kg/m3 (at 1 bar) [20]. Besides the relatively high energy requirement, liquefaction entails substantial installation costs due to the unsuitability of existing infrastructure and availability issues [26]. Even more importantly, part of the hydrogen is lost to the environment as boil-off, raising safety issues [22].

Liquid hydrogen can be stored in specially designed cryogenic storage vessels, both for terrestrial and marine applications [22] [26]. These should be suitable for operation at extremely low temperatures and be able to maintain the pressure at which the gas is liquefied [27].

3) Solid Phase: Solid state storage of hydrogen occurs through physisorption. In this case, hydrogen itself is not in solid form but rather the adsorbent. Hydrogen molecules stick to the surface of the solid adsorbent. This type of hydrogen storage is extensively investigated due to its promising properties such as fast kinetics, good reversibility and high storage capacity [18]. The main disadvantage of solid state storage lies in complex operation, and space. Several exogenous factors such as temperature and pressure should be adjusted optimally to achieve the desired hydrogen density (i.e., energy density) in solid-state storage [20].That is, the exothermic reaction needs appropriate heat management to reach higher adsorption rates, and additives to make the process more effective. In addition, even though hydrogen can be stored using adsorbents, the adsorbents themselves also need to be stored. For example in a so-called Adsorptive Hydrogen Storage Tank [28]. The extra space makes it difficult to apply and adjust pressure [29].

Suitable adsorbents are Metal Organic Frameworks (MOFs), Carbon structures (e.g. Activated Carbon (AC), Graphite (G) and Carbon Nanofibres (CN)), and Zeolites [30].

B. Compound Hydrogen Storage

Hydrogen can also be stored as a compound, bonding it to another chemical. It can form gas, liquid or solid compounds.

1) Gas Phase: The most well-known gaseous compounds in which hydrogen can be stored are ammonia (NH3) and methane (CH4). Ammonia (NH3) is a specially interesting alternative due to its relatively high hydrogen storage density and the broad range of applications [31]. Ammonia can be used directly [18], in a fuel cell or combustion engine, or indirectly, by converting it to hydrogen, requiring extra purification steps [22]. Ammonia advantageously makes CO2-free energy but can release other GHGs during combustion [32]. Liquefying ammonia leads to higher volumetric energy densities, beneficial for transportation and storage purposes [33]. Storage can occur in tanks at low temperature (-33,4°C) or in the existing propane infrastructure [22]. The main drawback of ammonia lies in the production process. It is mostly produced through the Haber-Bosch process, conducted at a high temperature and pressure, and requiring a specific catalyst to facilitate the process [34], [35].

Methane (CH4) is the “carbon-based carrier with the highest storage capacity” for hydrogen [22]. Production occurs through the Sabatier reaction [36], requiring pure CO2 as input. Despite this benefit, the CO2 used in the methanation process has to be purified before use. Besides, heat recovery should be applied. These extra steps result in higher costs due to higher energy and land requirements. In addition, recovering hydrogen from CH4 is hard and costly. It can be done through the Steam Methane Reforming (SMR) process, which produces so-called Grey Hydrogen and CO2 [37], or through the Catalytic Decomposition of Methane (CDM), a greener yet not commercially available option. These disadvantages make methane more viable as another energy carrier rather than as a medium for storing hydrogen [22].

2) Liquid Phase: Hydrogen can also be stored in compounds that are liquid at ambient temperatures [18]. Most well-known alternatives in this category are liquid organic hydrogen carriers (LOHCs) including Methanol and Formic Acid. LOHCs have a great capacity to store hydrogen, release little heat during production and are safe and abundant. The delivery of LOHCs to the end-users is rather simple as they are compatible with the technical characteristics of the existing fuel distribution infrastructure [18] [22]. The key disadvantage of LOHCs lies in high production costs, mainly due to the high temperatures and pressures, and catalysts needed [18].

Formic Acid (HCOOH) is an advantageous option because of its relatively high density, resulting in a considerable volumetric hydrogen storage capacity. It is associated with low flammability and toxicity, meaning that it is less likely to cause harm to living organisms and the environment. Compared with other liquid carriers, formic acid is rather easy to transport and store [38] . The problem is, it has limited applications, partly

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

due to its corrosive nature (requiring costly infrastructure adjustments), and partly due to the chemically unfavorable production process. In addition, it has a relatively low energy density when used directly as a fuel [39].

Methanol (CH3OH) also has a number of advantages: promising formation reaction rates, and a lower production cost. It can be used both as a hydrogen carrier (hydrogen is easily released from methanol) or directly as a fuel [40]. Methanol has a higher energy density as a fuel compared to Formic Acid, though lower than gasoline [39], [41]. The main disadvantage of methanol lies in its flammability (it burns with near-invisible flame) and toxicity [42], [43].

Another liquid hydrogen carrier is Syncrude, a mixture of long chain hydrocarbons showing similarities to crude oil [22]. Because of this characteristic, the existing infrastructure can be used for distribution. Syncrude can be produced from CO2 and hydrogen directly and indirectly [44]. However, the production process (Fischer-Tropsch synthesis [45]) is still complex and requires further improvement regarding reaction specifics.

3) Solid Phase: Hydrogen can react with other chemicals to form a solid via the process of absorption. Most common solid absorbents are Metal hydrides, divided into three groups: elemental, intermetallic and complex hydrides [20]. Metal hydrides are considered a safe medium for storing hydrogen due to the low operation temperatures and endothermic reaction [46]. Shortcomings that hinder large-scale application of this technology are e.g. relatively slow kinetics, high (hydrogen release) temperatures and low reversibility [47].

Adsorption technologies can be improved by surface modification and combining elements. Elemental hydrides are binary compound materials made of bonds between hydrogen and 1 other metal [48]. The most promising examples are magnesium hydride (MgH2) and aluminium hydride (AlH3). Intermetallic hydrides can be seen as an improved example of elemental hydrides with an extra element (largely rare earth and transition metals). The final compound takes the chemical formula of AxByHz [49]. These combinations improve hydrogen storage capacities, at the expense of higher material and thus investment costs. Finally, complex hydrides are formed through a reaction of two hydrides, for example, LiBH4, NaAlH4 and LiNH2 [22]. The highest storage densities are reached when boron (B) functions as the central atom. Hydrogen can be released under mild conditions, but hydrogen uptake - the amount of hydrogen that can be adsorbed or absorbed by a material per unit mass or volume - is a lot harder to achieve and requires significant costs and effort [50].

III. ANALYSIS OF CHARACTERISTICS

This section presents an analysis of the different hydrogen technologies with regard to the 4 comparison criteria. First, technological operational conditions are reviewed. Then technology efficiency, and safety. And lastly, economic projections.

A. Technical Operational Conditions

Operational conditions refer to the specifications regarding temperature, pressure and additive requirement needed for hydrogen storage, uptake and release. The simplest condition to maintain the operation is when hydrogen is stored at room temperature (about 21°C) and under normal pressure (1 bar), as this requires the least maintenance and safety measures.

Table I & II present the operational conditions for storage (maintaining hydrogen in the medium) and for uptake and release (forcing hydrogen in and out of the medium) of hydrogen respectively. A ? refers to a lack of information. Remarks are added in italic.

TABLE I: Hydrogen Storage Parameters

Cat.	**Option**	***Pressure*** bar	***Temperature*** °C	***Add.***
FHG	Compressed H2 gas	350-700 [51]	normal [51]	No
	Glass struct.	1000+ [22]	-40 - 60 [23]	No
FHL	Liquid H2	1 [25]	-253 [20] [13]	No
FHS	MOFs (MOF-5)	1 [18]	cryogenic [18]	Yes [18]
	Carbon struct.	high [18]	cryogenic [18]	Yes [18]
	- AC	80 [29]	25 [29]	Yes [18]
	- G	100 [29]	25 [29]	Yes [18]
	- CN	120 [29]	27 [29]	Yes [18]
	Zeolites	?	room T [18] [52]	Yes [18]
	Adsorption (general)	40 [20]	-176 [20]	*Depend. on type sorbent*
CHG	Ammonia	normal / 8-10 [31] [5]	-33,4 / ambient [31] [5]	Yes [18]
	Methane	N.A.		
CHL	Syncrude	Similar to existing fuels [22]	Similar to existing fuels [22]	Yes [22]
	Methanol (LOHC)	1 [31] [5]	25 [31] [5]	Yes [22]
	Formic Acid (LOHC)	105 [20]	100-180 [20]	Yes [22]
CHS	Metal Hydr.	10-40 [53]	20 [53]	Yes [22]
	- Elemental	[20]	[20]	Yes [20]
	- Intermetal.	50 [20]	80 [20]	?
	- Complex	100 [54]	200 [54]	Yes [20]

From Table I it can be observed that there is no technology that enables storing hydrogen at room temperature and normal pressure. The least complicated way to store hydrogen are represented by the options with 2 optimal conditions: Compressed H2 Gas (normal temperature & no additives), Liquid H2 (normal pressure & no additives), Ammonia (normal pressure & temperature) and Methanol (normal pressure & temperature).

Methane is a special case. Methane storage and transport is a well established practice (natural gas). However, methane is almost never considered as a hydrogen carrier but rather as an energy carrier. This refers mainly to the relatively hard and costly process of hydrogen release, but also to the extra steps required to adequately store hydrogen in it.

Table II shows a wide variety of processes and associated conditions for hydrogen storage. Although comparing is difficult, one can observe that for both Compressed H2 Gas and Liquid H2 the hydrogen uptake and release processes are

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

unnecessary, making those options relatively beneficial. Once again methane is special in that it has an unfavorable hydrogen release process. Note that Syncrude is usually considered an end product and thus no hydrogen storage medium. In some cases - mostly for groups of hydrogen carriers like MOFs - there is still a lack of information.

TABLE II: Hydrogen Uptake & Release Parameters

		H2 Uptake		H2 Release		
Cat.	**Option**	***P*** bar	***T*** °C	***P*** bar	***T*** °C	***Add.***
FHG	Compr. H2 gas	N.A.	N.A.	N.A.	N.A.	N.A.
	Glass struct.	N.A.	N.A.	N.A.	N.A.	N.A.
FHL	Liquid H2	N.A.	N.A.	evap. [55]	evap. [55]	N.A.
FHS	MOFs *MOF-5*	1 [18]	cryog. [18]	?	?	?
	Carbon struct.	?	?	?	?	Yes
	- AC	30 [56]	-196 [56]	?	?	Yes [56]
	- G	113,5 [56]	room T ∼ 20 [56]	?	?	Yes [56]
	- CN	101 [56]	room T ∼ 20 [56]	?	?	Yes [56]
	Zeolites	∼100 [52]	350 [18]	1,5 [52]	?	Yes [18]
CHG	Ammonia	100-300 [22] [24]	400-500 [24] [31]	250 [57]	400-700 [31] [57]	Yes [22] [31] [24]
	Methane	<100 [58]	250-400 [22]	? [22]	? [22]	Yes [22]
CHL	Syncrude	10-40 [22]	200-250 *(LTFT)* [22]	?	?	?
	Methanol (LOHC)	40-60 [59]	∼140 [59]	25-50 [24] [22]	200-300 [24] [22]	Yes [31]
	Formic Acid (LOHC)	120 [60]	120 [60]	*depend. on CO2 recov.*	50-100 [20] [55]	Yes [60], *Ru-based*
CHS	Metal Hydr.	depend on type [22]	depend on type [22]	1.5 [54] *(compl. hydr.)*	<180 (compl.) [54] ≥300 (MgH2) [18] [20]	Yes [22]

B. *Technology Efficiency*

This section focuses on how far the different hydrogen storage technologies have progressed. This assessment is carried out considering various factors including: the scale of application, hydrogen content (in wt%), volumetric (in kWh/L) & gravimetric densities (in kWh/kg), round-trip & conversion efficiencies. Scale of application refers to the scale at which the technology currently is employed. It ranges from 1=large scale (e.g. energy grids), 2=medium scale, 3=small scale (usually laboratory scale), 4=very small scale (microscale) to 5=not realistic. The hydrogen content of a storage option describes what percentage of the weight consists of hydrogen. Volumetric and Gravimetric Density show the available energy per unit of volume or weight respectively. Volumetric Density can change depending on the applied pressure, whereas Gravimetric Density is a material property. Round-trip efficiency (or storage efficiency) is the percentage of energy input that can be retrieved again. Conversion efficiency is the effectiveness of the conversion - generally converting hydrogen in a compound - expressed as a percentage.

It is assumed that a desirable hydrogen storage technology should have widespread availability, high H2 content, high densities (especially volumetric), and high efficiencies. These factors are considered to determine the most favorable hydrogen storage technology. Results are summarized in Table III.

Table III shows that ammonia exhibits high scores across a majority of dimensions, with Methanol following closely behind. Thus, CHG appears to be the best performing category. One can also see that Liquid H2 has quite a high gravimetric density, but has rather low round-trip and conversion efficiencies. Likewise, methane has a high H2 Content but has a rather low volumetric density. On the other hand, most FHS technologies score very low regarding H2 Content. Note that there is a lack of data on some technologies including MOFs, carbon structures, zeolites, metal hydrides.

C. *Safety*

The safety level of different hydrogen technologies is evaluated based on the explosiveness and toxicity of the storage medium. The result is given in Table IV. A +/++ refers to reported high levels of explosiveness or toxicity. A - refers to the characteristic not being observed. A ? shows a lack of information. In the far right column important remarks regarding the safety of the storage options are reported.

Table IV shows that flammability is an issue for compressed hydrogen gas, liquid hydrogen, methane, methanol, and metal hydrides, followed by a lower level of explosiveness for ammonia and possibly syncrude. Toxicity is mainly a problem for ammonia, but also, albeit less extreme, for MOFs and methanol. The most promising options in this regard are thus carbon structures or formic acid for hydrogen storage as they both have no reported explosiveness and toxicity claims.

D. *Economic Projections*

The most prominent factor that determines the success of any technology finding its way in practice is its economic projection. Therefore, an estimated calculation of costs per technology option is provided in Table V. These relate to levelized costs of hydrogen storage (LCHS) solely. LCHS refers to the capital and operational cost of the hydrogen storage system expressed per unit of hydrogen stored. Other costs are considered beyond the scope of this paper. The values are calculated for storage of 1 ton of hydrogen, a realistic future objective. The results are shown in Table V. From an investment perspective, it is evident that technologies with lower investment and/or operational costs are preferred.

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

TABLE III: Technology Efficiency Parameters

Cat.	**Option**	***Scale*** -	***H content*** wt%	***Vol.Dens.*** kWh/L	***Grav.Dens.*** kWh/kg	***Round-trip Eff.*** %	***Conv. Eff.*** %
FHG	Compr. H2 Gas	1 [22]	13 [29]	1,32 [18]	33,3 [22]	95-98 [19]	72,4 [5]
	Glass struct.	4 [22]	10-14 [13]	?	?	?	?
FHL	Liquid H2	2-1 [13]	*Size dependent*	2,36 [22]	33,3 [22]	∼53 [5]	44,7 [5]
FHS	MOFs *(MOF-5)*	3 [13]	4,5 [18]	0,021 kg H2/L [18]	0,038 kg H2/kg [18]	?	?
	Carbon struct.	3 [13]	8 [13]	?	?	?	?
	- AC	3 [13]	5,5 [29]	?	?	?	?
	- G	3 [13]	4,48 [29]	?	?	?	?
	- CN	3 [13]	6,5 [29]	?	?	?	?
	Zeolites	3 [13]	9,2 [13]	?	?	?	?
CHG	Ammonia	1 [22] [31]	17,8 [18]	3,53 [31]	5,17 [31]	99,3 [5]	Haber-Bosch: 76 [5] NH3 to H2: 69 [57]
	Methane	5 [22]	25 [22]	0,0105 [61]	15,4 [61]	95 [5]	Methanation: 87,9 [5]
CHL	Syncrude	1 [22]	?	10 [62] *(crude oil)*	3,53 [63]*(crude oil)*	?	Power-to-fuel: 46-67 [64]
	Methanol (LOHC)	3 [22]	12,5 [22]	3,3 [22]	8,64 [63]	95 [5]	83,5 [5]
	Formic Acid (LOHC)	3 [22]	4,4 [13]	1,79 [22]	?	?	48 *(+Ru-catalyst)* [60]
	LOHCs	1-3 [22]	?	?	?	∼71 [65]	?
CHS	Metal Hydr.	4-3 [22]	max 12,6 [13]	*dependent on type*	0,50 [53]	∼78 [65]	?
	- Compl.	4-3 [22]	18,5 [66]	0,71 [18]	?	?	?
	- MgH2	4-3 [22]	7,66 [66]	5,55kg/100L [66]	?	?	?

TABLE IV: Safety Assessment

Cat.	**Option**	***Explosive***	***Toxic***	***Remarks***
FHG	Compressed H2 gas	++ [67]	- [68]	Asphyxiant [68]
FHL	Liquid H2	++ [67] [27]	- [68]	Frostbite [27] [67]
FHS	MOFs	? [69]	+ [69] [70]	Many forms [69] [70]
	Carbon structures	- [71] [72]	- [71] [72]	Weakly explosive / health hazard [73]
	Zeolites	? [74]	?/- [74]	Little info
CHG	Ammonia	+ [75]	++ [75]	Corrosive / Environmental hazards [75]
	Methane	++ [76]	- [76]	
CHL	Syncrude	+? [77]	-? [77]	Based on crude oil [22] / Health and environmental haz.
	Methanol (LOHC)	++ [78]	+ [78]	Health hazard [78]
	Formic Acid (LOHC)	- [79]	- [79]	Corrosive [79]
CHS	Metal Hydr.	++ [80] [81]	? [81]	Taken as a group

TABLE V: Economic Projections

Cat.	**Storage Option**	***Costs*** $/ton	***Remarks***
FHG	Compressed H2 gas	1810 [82]	Compression + Storage
	- Salt caverns	1610 [22]	LCHS
	- Above ground	140-330 [65]	
	Glass structures	?	No info available
FHL	Liquid H2	1686-1905 [22] [57]	Liquefaction / Liquefaction + Storage
FHS	MOFs	490000 [18]	
	Carbon structures	?	No info available
	Zeolites	?	No info available
CHG	Ammonia	3510 [65]	LCHS Air Seperation Unit [5]
	Methane	?	No info available
CHL	Syncrude	1523 [64]	Calculated from €/lDE
	Methanol (LOHC)	2250 [65]	LCHS
	Formic Acid (LOHC)	23160 [60]	Levelized costs (ecFA + LCO2), described as Scenario 3 in article by Kim et al. (2022), containing production and transportation
	GENERAL LOHC	1200 [65]	LCHS
CHS	Metal Hydrides	700 [65]	LCHS

It should be noted that the values listed in Table 5 are not complete. Costs related to chemical processes (hydrogen uptake and release) and material costs are not included. Moreover, most technologies require some development as the costs are still quite high. This especially counts for MOFs and Formic Acid. Costs are relatively low for Metal Hydrides and above-ground Compressed H2 Gas storage.

IV. CONCLUSION

This paper provides a comprehensive overview of the existing and emerging hydrogen storage technologies. Special attention is given to non-economic characteristics: technical operational conditions, technology efficiency and safety.

The technical operational conditions show that Compressed Hydrogen Gas storage is the most promising technology. It stores free hydrogen, requiring no additional chemical reactions for uptake and release of hydrogen. Hydrogen is stored at normal temperature without additives. On the downside, it requires an elevated pressure of 350-700 bar, raising safety concerns.

The technologies are also assessed based on scale, energy

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

content, and efficiency. In this regard, ammonia is the most suitable technology. The technology is readily available at a large scale, and especially suitable for transport. It has a high hydrogen content (17,8 wt%), high storage efficiency (99,3%), medium conversion efficiencies (ranging from 25% to 76%) and a relatively high volumetric density (3,53 kWh/L).

The level of safety is assessed based on flammability and toxicity. From this point of view, Carbon structures and Formic Acid are most suitable because neither are flammable nor toxic. However, Formic Acid is corrosive, negatively impacting its storage possibilities. Powdered carbon structures exhibit low explosive potential and are classified as irritants and suspected carcinogens.

Lastly, regarding economic projections, it is difficult to draw any conclusion. This is because research in this field is relatively new. As a result, there is limited clarity and data availability which makes the assessment prone to error. This aspect can be further investigated in the future.

REFERENCES

[1] M. A. Bhuiyan and E. Ibragimova, "Hydrogen energy and decarbonisation: Evidence from regions of the world," in *Clean Energy Investments for Zero Emission Projects*. Springer, 2022, pp. 127–138.

[2] C. Acar and I. Dincer, "Review and evaluation of hydrogen production options for better environment," *Journal of cleaner production*, vol. 218, pp. 835–849, 2019.

[3] R. L. L. Steinmetz and S. B. Fong, "Water legislation in the context of lithium mining in argentina," *Resources Policy*, vol. 64, p. 101510, 2019.

[4] E. Taibi, R. Miranda, W. Vanhoudt, T. Winkel, J.-C. Lanoix, and F. Barth, "Hydrogen from renewable power: Technology outlook for the energy transition," 2018.

[5] V. Dias, M. Pochet, F. Contino, and H. Jeanmart, "Energy and economic costs of chemical storage," *Frontiers in Mechanical Engineering*, vol. 6, p. 21, 2020.

[6] P. Moriarty and D. Honnery, "Prospects for hydrogen as a transport fuel," *International Journal of Hydrogen Energy*, vol. 44, no. 31, pp. 16 029–16 037, 2019.

[7] F. Ausfelder and A. Bazzanella, "Hydrogen in the chemical industry," *Hydrogen science and engineering: materials, processes, systems and technology*, pp. 19–40, 2016.

[8] S. E. Hosseini and B. Butler, "An overview of development and challenges in hydrogen powered vehicles," *International journal of green energy*, vol. 17, no. 1, pp. 13–37, 2020.

[9] I. Dincer, "Green methods for hydrogen production," *International journal of hydrogen energy*, vol. 37, no. 2, pp. 1954–1971, 2012.

[10] A. V. Abad and P. E. Dodds, "Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges," *Energy Policy*, vol. 138, p. 111300, 2020.

[11] M. Khan, T. Al-Attas, S. Roy, M. M. Rahman, N. Ghaffour, V. Thangadurai, S. Larter, J. Hu, P. M. Ajayan, and M. G. Kibria, "Seawater electrolysis for hydrogen production: a solution looking for a problem?" *Energy & Environmental Science*, vol. 14, no. 9, pp. 4831–4839, 2021.

[12] P. Tseng, J. Lee, and P. Friley, "A hydrogen economy: opportunities and challenges," *Energy*, vol. 30, no. 14, pp. 2703–2720, 2005.

[13] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12 254–12 269, 2019.

[14] W. J. Lampert, A. B. Bianchi, W.-S. Chen, and S. S. Torbaghan, "Economically optimal operation of a power-to-hydrogen/gas unit as a balancing services provider," in *2022 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 2022, pp. 1–5.

[15] A. M. Oliveira, R. R. Beswick, and Y. Yan, "A green hydrogen economy for a renewable energy society," *Current Opinion in Chemical Engineering*, vol. 33, p. 100701, 2021.

[16] J. O. Abe, A. Popoola, E. Ajenifuja, and O. Popoola, "Hydrogen energy, economy and storage: review and recommendation," *International journal of hydrogen energy*, vol. 44, no. 29, pp. 15 072–15 086, 2019.

[17] A. Chapman, K. Itaoka, K. Hirose, F. T. Davidson, K. Nagasawa, A. C. Lloyd, M. E. Webber, Z. Kurban, S. Managi, T. Tamaki *et al.*, "A review of four case studies assessing the potential for hydrogen penetration of the future energy system," *International journal of hydrogen energy*, vol. 44, no. 13, pp. 6371–6382, 2019.

[18] I. Hassan, H. S. Ramadan, M. A. Saleh, and D. Hissel, "Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 149, p. 111311, 2021.

[19] A. M. Elberry, J. Thakur, A. Santasalo-Aarnio, and M. Larmi, "Large-scale compressed hydrogen storage as part of renewable electricity storage systems," *International journal of hydrogen energy*, vol. 46, no. 29, pp. 15 671–15 690, 2021.

[20] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," *International journal of hydrogen energy*, vol. 44, no. 23, pp. 11 901–11 919, 2019.

[21] S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 457–469, 2015.

[22] P. Preuster, A. Alekseev, and P. Wasserscheid, "Hydrogen storage technologies for future energy systems," *Annual review of chemical and biomolecular engineering*, vol. 8, pp. 445–471, 2017.

[23] M. Prewitz, M. Gaber, R. Müller, C. Marotztke, and K. Holtappels, "Polymer coated glass capillaries and structures for high-pressure hydrogen storage: Permeability and hydrogen tightness," *International journal of hydrogen energy*, vol. 43, no. 11, pp. 5637–5644, 2018.

[24] J. Zheng, H. Zhou, C.-G. Wang, E. Ye, J. W. Xu, X. J. Loh, and Z. Li, "Current research progress and perspectives on liquid hydrogen rich molecules in sustainable hydrogen storage," *Energy Storage Materials*, vol. 35, pp. 695–722, 2021.

[25] Z. Yanxing, G. Maoqiong, Z. Yuan, D. Xueqiang, and S. Jun, "Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen," *International Journal of Hydrogen Energy*, vol. 44, no. 31, pp. 16 833–16 840, 2019.

[26] A. T. Wijayanta, T. Oda, C. W. Purnomo, T. Kashiwagi, and M. Aziz, "Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review," *International Journal of Hydrogen Energy*, vol. 44, no. 29, pp. 15 026–15 044, 2019.

[27] A. Products and Chemicals, "Liquid hydrogen: Safetygram 9," https://www.airproducts.com/-/media/airproducts/files/en/900/900-13-082-us-liquid-hydrogen-safetygram-9.pdf, 2014.

[28] D. Broom, C. Webb, K. Hurst, P. Parilla, T. Gennett, C. Brown, R. Zacharia, E. Tylianakis, E. Klontzas, G. Froudakis *et al.*, "Outlook and challenges for hydrogen storage in nanoporous materials," *Applied Physics A*, vol. 122, no. 3, pp. 1–21, 2016.

[29] M. Mohan, V. K. Sharma, E. A. Kumar, and V. Gayathri, "Hydrogen storage in carbon materials—a review," *Energy Storage*, vol. 1, no. 2, p. e35, 2019.

[30] A. Halder and D. Ghoshal, "Strategies for the improvement of hydrogen physisorption in metal-organic frameworks and advantages of flexibility for the enhancement," *Journal of Molecular and Engineering Materials*, vol. 10, pp. 2 240 003–2735, 2022.

[31] M. Aziz, A. T. Wijayanta, and A. B. D. Nandiyanto, "Ammonia as effective hydrogen storage: A review on production, storage and utilization," *Energies*, vol. 13, no. 12, p. 3062, 2020.

[32] A. Afif, N. Radenahmad, Q. Cheok, S. Shams, J. H. Kim, and A. K. Azad, "Ammonia-fed fuel cells: a comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 822–835, 2016.

[33] C. Smith, A. K. Hill, and L. Torrente-Murciano, "Current and future role of haber–bosch ammonia in a carbon-free energy landscape," *Energy & Environmental Science*, vol. 13, no. 2, pp. 331–344, 2020.

[34] J. Humphreys, R. Lan, and S. Tao, "Development and recent progress on ammonia synthesis catalysts for haber–bosch process," *Advanced Energy and Sustainability Research*, vol. 2, no. 1, p. 2000043, 2021.

[35] T. Kandemir, M. E. Schuster, A. Senyshyn, M. Behrens, and R. Schlögl, "The haber–bosch process revisited: On the real structure and stability of "ammonia iron" under working conditions," *Angewandte Chemie International Edition*, vol. 52, no. 48, pp. 12 723–12 726, 2013.

[36] L. Guerra, S. Rossi, J. Rodrigues, J. Gomes, J. Puna, and M. T. Santos, "Methane production by a combined sabatier reaction/water electrolysis

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.

process," *Journal of environmental chemical engineering*, vol. 6, no. 1, pp. 671–676, 2018.

[37] L. Chen, Z. Qi, S. Zhang, J. Su, and G. A. Somorjai, "Catalytic hydrogen production from methane: A review on recent progress and prospect," *Catalysts*, vol. 10, no. 8, p. 858, 2020.

[38] S. Chatterjee, I. Dutta, Y. Lum, Z. Lai, and K.-W. Huang, "Enabling storage and utilization of low-carbon electricity: power to formic acid," *Energy & Environmental Science*, vol. 14, no. 3, pp. 1194–1246, 2021.

[39] X. Yu and P. G. Pickup, "Recent advances in direct formic acid fuel cells (dfafc)," *Journal of Power Sources*, vol. 182, no. 1, pp. 124–132, 2008.

[40] A. Kumar, P. Daw, and D. Milstein, "Homogeneous catalysis for sustainable energy: hydrogen and methanol economies, fuels from biomass, and related topics," *Chemical reviews*, vol. 122, no. 1, pp. 385–441, 2021.

[41] L. Sileghem, A. Ickes, T. Wallner, and S. Verhelst, "Experimental investigation of a disi production engine fuelled with methanol, ethanol, butanol, and iso-stoichiometric alcohol blends," Argonne National Lab.(ANL), Argonne, IL (United States), Tech. Rep., 2015.

[42] K. Y. Ignatiev and A. Yurin, "Development prospects of hydrogen fuel air independent power plants."

[43] S. E. Plotkin, "Assessment of pngv fuels infrastructure: infrastructure concerns related to the safety of alternative fuels." Argonne National Lab., IL (US), Tech. Rep., 2000.

[44] R. Gao, C. Zhang, K.-W. Jun, S. K. Kim, H.-G. Park, T. Zhao, L. Wang, H. Wan, and G. Guan, "Transformation of co2 into liquid fuels and synthetic natural gas using green hydrogen: A comparative analysis," *Fuel*, vol. 291, p. 120111, 2021.

[45] G. P. Van Der Laan and A. Beenackers, "Kinetics and selectivity of the fischer–tropsch synthesis: a literature review," *Catalysis Reviews*, vol. 41, no. 3-4, pp. 255–318, 1999.

[46] B. Sakintuna, F. Lamari-Darkrim, and M. Hirscher, "Metal hydride materials for solid hydrogen storage: a review," *International journal of hydrogen energy*, vol. 32, no. 9, pp. 1121–1140, 2007.

[47] N. Rusman and M. Dahari, "A review on the current progress of metal hydrides material for solid-state hydrogen storage applications," *International Journal of Hydrogen Energy*, vol. 41, no. 28, pp. 12 108–12 126, 2016.

[48] M. B. Ley, L. H. Jepsen, Y.-S. Lee, Y. W. Cho, J. M. B. Von Colbe, M. Dornheim, M. Rokni, J. O. Jensen, M. Sloth, Y. Filinchuk *et al.*, "Complex hydrides for hydrogen storage–new perspectives," *Materials Today*, vol. 17, no. 3, pp. 122–128, 2014.

[49] U. Häussermann, H. Blomqvist, and D. Noréus, "Bonding and stability of the hydrogen storage material mg2nih4," *Inorganic chemistry*, vol. 41, no. 14, pp. 3684–3692, 2002.

[50] J. Jeong, V. K. Bhosale, and S. Kwon, "Ultrafast igniting, low toxicity hypergolic hybrid solid fuels and hydrogen peroxide oxidizer," *Fuel*, vol. 286, p. 119307, 2021.

[51] O. of Energy Efficiency Renewable Energy, "Physical hydrogen storage," https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage, october 2022.

[52] M. O. Ozbek and B. Ipek, "A theoretical investigation of cu+, ni2+ and co2+-exchanged zeolites for hydrogen storage," *ChemPhysChem*, vol. 23, no. 20, p. e202200272, 2022.

[53] A. Geueke, "How powder metal hydrides solve safety and size challenges for hydrogen storage," https://news.pminnovationblog.com/blog/how-low-pressure-hydrogen-storage-tanks-increase-safety-and-efficiency, october 2022.

[54] M. Baricco, M. Bang, M. Fichtner, B. Hauback, M. Linder, C. Luetto, P. Moretto, and M. Sgroi, "Ssh2s: Hydrogen storage in complex hydrides for an auxiliary power unit based on high temperature proton exchange membrane fuel cells," *Journal of Power Sources*, vol. 342, pp. 853–860, 2017.

[55] J. W. Makepeace, T. He, C. Weidenthaler, T. R. Jensen, F. Chang, T. Vegge, P. Ngene, Y. Kojima, P. E. de Jongh, P. Chen *et al.*, "Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress," *international journal of hydrogen energy*, vol. 44, no. 15, pp. 7746–7767, 2019.

[56] S. ullah Rather, "Preparation, characterization and hydrogen storage studies of carbon nanotubes and their composites: A review," *International Journal of Hydrogen Energy*, vol. 45, no. 7, pp. 4653–4672, 2020.

[57] Z. Abdin, C. Tang, Y. Liu, and K. Catchpole, "Large-scale stationary hydrogen storage via liquid organic hydrogen carriers," *Iscience*, vol. 24, no. 9, p. 102966, 2021.

[58] K. Elen, "Expert talk: Hoe kan omzetting van co2 bijdragen aan de klimaatdoelstellingen?" https://www.energyville.be/pers/expert-talk-hoe-kan-omzetting-van-co2-bijdragen-aan-de-klimaatdoelstellingen, august 2022.

[59] S. A. Al-Saydeh and S. J. Zaidi, "Carbon dioxide conversion to methanol: opportunities and fundamental challenges," *Carbon dioxide chemistry, capture and oil recovery*, vol. 41, 2018.

[60] C. Kim, Y. Lee, K. Kim, and U. Lee, "Implementation of formic acid as a liquid organic hydrogen carrier (lohc): Techno-economic analysis and life cycle assessment of formic acid produced via co2 utilization," *Catalysts*, vol. 12, no. 10, p. 1113, 2022.

[61] K. Mazloomi and C. Gomes, "Hydrogen as an energy carrier: Prospects and challenges," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3024–3033, 2012.

[62] B. E. Layton, "A comparison of energy densities of prevalent energy sources in units of joules per cubic meter," *International Journal of Green Energy*, vol. 5, no. 6, pp. 438–455, 2008.

[63] J.-P. Rodrigue, "Energy density of some combustibles (in mj/kg)," https://transportgeography.org/contents/chapter4/transportation-and-energy/combustibles-energy-content/, 2020.

[64] R. Peters, N. Wegener, R. C. Samsun, F. Schorn, J. Riese, M. Grünewald, and D. Stolten, "A techno-economic assessment of fischer–tropsch fuels based on syngas from co-electrolysis," *Processes*, vol. 10, no. 4, p. 699, 2022.

[65] Z. Abdin, K. Khalilpour, and K. Catchpole, "Projecting the levelized cost of large scale hydrogen storage for stationary applications," *Energy Conversion and Management*, vol. 270, p. 116241, 2022.

[66] Y. Kojima, "Hydrogen storage materials for hydrogen and energy carriers," *International Journal of Hydrogen Energy*, vol. 44, no. 33, pp. 18 179–18 192, 2019.

[67] NCBI, "Pubchem compound lcss for cid 783, hydrogen," https://pubchem.ncbi.nlm.nih.gov/compound/Hydrogen#datasheet=LCSS, october 2022.

[68] C. S. Technologies, "Asphyxiation: Occupational health hazards," https://www.chemscape.com/resources/chemical-management/health-hazards/asphyxiation, october 2022.

[69] H. U. Escobar-Hernandez, R. Shen, M. I. Papadaki, J. A. Powell, H.-C. Zhou, and Q. Wang, "Hazard evaluation of metal–organic framework synthesis and scale-up: A laboratory safety perspective," *ACS Chemical Health & Safety*, vol. 28, no. 5, pp. 358–368, 2021.

[70] Niklas, "How toxic are mofs?" https://blog.novomof.com/blog/how-toxic-are-mofs, september 2019.

[71] G. C. Corporation, "Activated carbon msds," https://generalcarbon.com/activated-carbon/activated-carbon-msds/, october 2018.

[72] J. Silberman, M. Galuska, and A. Taylor, "Ncbi - activated charcoal," https://www.ncbi.nlm.nih.gov/books/NBK482294/, july 2022.

[73] NCBI, "Pubchem compound lcss for cid 5462310, carbon," https://pubchem.ncbi.nlm.nih.gov/compound/Carbon#datasheet=LCSS, october 2022.

[74] S. E. Lehman and S. C. Larsen, "Zeolite and mesoporous silica nanomaterials: greener syntheses, environmental applications and biological toxicity," *Environmental Science: Nano*, vol. 1, no. 3, pp. 200–213, 2014.

[75] NCBI, "Pubchem compound lcss for cid 222, ammonia," https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia#datasheet=LCSS, october 2022.

[76] ——, "Pubchem compound lcss for cid 105026, carbon-13," https://pubchem.ncbi.nlm.nih.gov/compound/Carbon-13#datasheet=LCSS, october 2022.

[77] Whiting, "Safety data sheet," https://whiting.com/wp-content/uploads/Crude-Oil-Sweet-SDS.pdf, 2013.

[78] NCBI, "Pubchem compound lcss for cid 887, methanol," https://pubchem.ncbi.nlm.nih.gov/compound/Methanol#datasheet=LCSS, october 2022.

[79] ——, "Pubchem compound lcss for cid 284, formic acid," https://pubchem.ncbi.nlm.nih.gov/compound/Formic-Acid#datasheet=LCSS, october 2022.

[80] E. Rivard, M. Trudeau, and K. Zaghib, "Hydrogen storage for mobility: a review," *Materials*, vol. 12, no. 12, p. 1973, 2019.

[81] C. chemicals, "Metal hydrides, flammable, n.o.s. — noaa," https://cameochemicals.noaa.gov/chemical/19107, october 2022.

[82] NREL, "Hydrogen station compression, storage, and dispensing technical status and costs (nrel/bk-6a10-58564)," https://www.nrel.gov/docs/fy14osti/58564.pdf, may 2014.

Authorized licensed use limited to: Wageningen UR. Downloaded on December 06,2023 at 14:27:56 UTC from IEEE Xplore. Restrictions apply.