Elberry, Ahmed M.; Thakur, Jagruti; Santasalo-Aarnio, Annukka; Larmi, Martti

Large-scale compressed hydrogen storage as part of renewable electricity storage systems

Published in:
International Journal of Hydrogen Energy

DOI:
10.1016/j.ijhydene.2021.02.080

Published: 26/04/2021

Document Version
Publisher's PDF, also known as Version of record

Published under the following license:
CC BY-NC-ND

Please cite the original version:
Review Article

Large-scale compressed hydrogen storage as part of renewable electricity storage systems

Ahmed M. Elberry \textsuperscript{a,b}, Jagruti Thakur \textsuperscript{b}, Annukka Santasalo-Aarnio \textsuperscript{a,*}, Martti Larmi \textsuperscript{a}

\textsuperscript{a} Research Group of Energy Conversion, School of Engineering, Aalto University, Espoo, Finland
\textsuperscript{b} Division of Energy Systems, Department of Energy Technology, KTH Royal Institute of Technology, Stockholm, Sweden

HIGHLIGHTS

- Limitations and challenges of large-scale hydrogen storage.
- A coverage for all technologies for the compressed hydrogen storage.
- Reviewing the concerns of hydrogen blending into the natural gas infrastructure.
- Compares the technologies with respect to; storage time, losses, size, and cost.
- To evaluate the storage alternatives, a techno-economic chain analysis is required.

ARTICLE INFO

Article history:
Received 22 December 2020
Received in revised form
5 February 2021
Accepted 10 February 2021
Available online xxx

Keywords:
Hydrogen
Hydrogen storage
Geological
Storage vessels
Underground storage
Renewable energy

ABSTRACT

Storing energy in the form of hydrogen is a promising green alternative. Thus, there is a high interest to analyze the status quo of the different storage options. This paper focuses on the large-scale compressed hydrogen storage options with respect to three categories: storage vessels, geological storage, and other underground storage alternatives. In this study, we investigated a wide variety of compressed hydrogen storage technologies, discussing in fair detail their theory of operation, potential, and challenges. The analysis confirms that a techno-economic chain analysis is required to evaluate the viability of one storage option over another for a case by case. Some of the discussed technologies are immature; however, this does not rule out these technologies; rather, it portrays the research opportunities in the field and the foreseen potential of these technologies. Furthermore, we see that hydrogen would have a significant role in balancing intermittent renewable electricity production.

© 2021 The Author(s). Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Please cite this article as: Elberry AM et al., Large-scale compressed hydrogen storage as part of renewable electricity storage systems, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2021.02.080

* Corresponding author. P.O.Box 14300, 00076 AALTO, Espoo, Finland.
E-mail address: annukka.santasalo@aalto.fi (A. Santasalo-Aarnio).
https://doi.org/10.1016/j.ijhydene.2021.02.080
0360-3199/© 2021 The Author(s). Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Introduction

The interest in hydrogen storage is growing, which is derived by the decarbonization trend due to the use of hydrogen as a clean fuel for road and marine traffic, and as a long term flexible energy storage option for backing up intermittent renewable sources [1]. Hydrogen is currently used in industrial, transport, and power generation sectors; however, the use of hydrogen is mainly concentrated in the industrial sector (e.g., oil refining) [2,3]. It is expected that hydrogen demand will grow at a 5.48% compound annual growth rate (CAGR) over the period from 2019 to 2025 [4], while the global hydrogen energy storage market is expected to grow at a CAGR of 5.8% over the same forecast period [5].

Despite being used extensively in the industrial sector, the potential of hydrogen to support clean energy transitions has not been perceived yet [6]. Although batteries can efficiently store electrical energy, yet they are not economically feasible for large-scale and long-term storage, and they possess material limitations [7]. The potential of hydrogen storage for renewable energy sources (RES) is growing because RES capacity is expected to increase by 50% between 2019 and 2024, led by solar PV and on-shore wind [2,8].

Globally, the installed capacity of wind and solar power is growing exponentially [9], as shown in Fig. 1. Wind power is one of RES that is difficult to predict accurately [10], making its integration to the grid difficult, as it causes imbalances between peak demand and production, leading the system operator to dispatch the higher cost generators with high ramp rate needed to fulfill the demand. It also leads to technical challenges like transmission line congestions and disturbances in the electricity markets due to these imbalances in the generation [11]. With the forecasted growth of RES share in the energy mix and with the volatility of solar PV and wind power that affects energy security [10], the need for storage systems that can store energy for long term increases.

Hydrogen has the potential to turn out to be one of the lowest-cost electricity storage options throughout days, weeks, and even months [12], which makes it one of the most prominent options for renewable energy long-term storage [6]. Moreover, energy from RES can be transmitted through hydrogen and hydrogen-based fuels over long distances from areas with ample solar and wind resources, such as Australia or Latin America, to power-hungry cities thousands of kilometers away [6,13].

Hydrogen generated by electrolysis can also play a crucial role in incorporating large amounts of the surplus renewable
electricity, which otherwise curtailed. Also, without a new flexible demand option, high renewable curtailments will take place because of the shortage of time and spatial demand that fits the generation [14]. Although hydrogen is considered a clean fuel that produces zero emissions during use (except for water vapor) [15], its production is currently neither clean nor sustainable. It is accountable for around 830 million tons of CO₂ emissions per year [6]. Nevertheless, in the future, water electrolysis powered by RES would be a clean way to produce hydrogen, yet at the current market cost, this is still considerably more expensive than the route from fossil sources. To estimate the CO₂ emission from the full life-cycle of the technology, we need to also take into account emissions that are produced by the production of the electrolyzer’s equipment per se, particularly, the noble metal catalyst materials that have high CO₂ intensity due to the mining of these metals.

When hydrogen is produced, it can be stored as a compressed gas, liquid, or as a part of a chemical structure [16]. Hydrogen storage as compressed gas have challenges related to the high energy requirement because of hydrogen’s low specific gravity [17]. Furthermore, there are some material challenges pertaining to the materials of the storage tanks. Storing hydrogen in the liquid form requires a 64% higher amount of energy than that needed for high-pressure hydrogen gas compression, where hydrogen does not liquefy until −253 °C [18], and cooling that far is an energy-intensive process [19].

Hydrogen can be chemically stored by absorbing or reacting with other chemical compounds such as metals or “organic substances.” Metal hydrides are one of the most common types of hydrogen chemical storage that have the ability to store hydrogen at high densities that can exceed that of liquid hydrogen [20,21]. The challenges of storing hydrogen in a chemical form are mostly relative to the hydrogenation and dehydrogenation processes considering high temperature and pressure requirements which might be an obstacle to their application in large-scale energy storage applications [17,21]. On the other hand, some promising solutions are emerging that can offer unlimited storage size and time, like circular methanol, dimethyl ether, and liquid organic hydrogen carriers [22–24]. Several types of materials can be utilized in chemical storage, in-depth reviews of such materials can be found in Refs. [25–28].

In June 2019, the International Energy Agency (IEA) had released a report that identified geological storage, namely salt caverns, depleted natural gas or oil reservoirs, and aquifers as the best options for large-scale and long-term storage [6]. While salt caverns can reach high efficiency up to 98% without contaminating the stored hydrogen [29], the depleted oil and gas reservoirs contain contaminants that need to be eliminated if hydrogen would be utilized in high purity applications such as low-temperature fuel cells [30]. Still, if there is no high demand for hydrogen purity, this would be a possible option. For aquifers, hydrogen loss is also possible due to the reactions with rocks, fluids, and microorganisms [6]; however, this does not eliminate their potential as a storage option when these losses are accounted for [31].

Storing hydrogen over long periods is constrained by the hydrogen losses where, besides the fact that it is the most bountiful element in the universe, hydrogen is the lightest and smallest molecule as well, which implies that it needs to be rapidly contained before escaping to the Earth’s top atmosphere and then to space [32]. In addition to that, other technical and economic challenges are always associated with hydrogen storage in large-scale applications. Hence, the storage of large quantities of hydrogen over an extended period of time is a critical issue, and new measures are required to cope with the different hindrances when it comes to the wide deployment of hydrogen in energy storage applications.

Several studies were published recently on large-scale hydrogen storage [18,19,22–37]; however, these studies did not provide complete coverage to all the compressed gas hydrogen storage technologies; rather, their focus is almost exclusively on the geological storage. The novelty of this paper is to provide broader coverage for all the available technologies for the compressed hydrogen storage, including the mature and immature ones, along with providing a status quo of those technologies.

The paper is divided into five main sections, starting with a discussion on hydrogen compression in section 2. After that, the large-scale hydrogen storage alternatives are laid out in section 3 followed by discussion and conclusion in sections 4 and 5, respectively. These main sections have various subsections that reflect on the general theory of operation of the technologies, relative challenges, and the recent technological advances that can tackle those challenges.

**Methodology**

The extensive study of large-scale hydrogen storage is a mixed-method review that combines qualitative and state-of-the-art reviews. The qualitative review aimed to comprehensively describe the theory of operation and phenomena behind the different hydrogen storage technologies in fair details, along with the materials’ relative issues. The findings of the relative studies are then integrated and conceptually synthesized along with that tabular accompaniment whenever fits. The qualitative review is complemented by a state-of-the-art review that analyzed the current state of knowledge and the technological advances in the field.

The following portals were utilized to find the articles for this review: Google scholar, research gate, IEEE Xplore, ScienceDirect, SpringerLink, SpringerMaterials, Semantic Scholar, Google patents, Google books, KTH library, ASME Digital Collection, data and statistics of IEA and IRENA along with organizations’ websites such as Airliquide and the U.S. Department of Energy (U.S. DOE). “Hydrogen storage” and “large-scale storage” are the main keywords that were utilized during the research to screen and identify the compressed hydrogen storage technologies that can be currently used in large-scale storage applications.

In this paper, storing compressed gaseous hydrogen is discussed based on three main types of storage: a storage vessel with its different types, geological storage, and other underground storage alternatives, as shown in Fig. 2.
Hydrogen compression

A widely used process for processing gaseous fuels is compressing it to high pressure to achieve lower volume. The apparent distinction between hydrogen and other traditional fuels compression, such as natural gas, is the energy demand [38], where compressing hydrogen requires more energy because of its lower relative density [27]. Ni has stated based on thermodynamics and the equation of state of an ideal gas ($PV = nRT$) [39], that the volumetric storage density of hydrogen ($H_2$ - kg/m$^3$) at 25°C can be calculated as follows [19]:

$$\text{volumetric storage density of hydrogen} = 0.0807P \left( \frac{H_2}{m^3} \right)$$  \hspace{1cm} (1)

where $P$ is the storage pressure in bars. On the other hand, Makridis argued that unlike most gases that behave to a great extent in accordance with the ideal gas law, hydrogen dramatically deviates from the laws’ predictions [40] where hydrogen fills a bigger space than that predicted by the ideal gas law. This deviation can be compensated for by using a compressibility factor ($Z$) as follows [25]:

$$PV = nZRT, \text{ where } Z = \frac{n_{\text{ideal}}}{n_{\text{real}}} = \frac{m_{\text{ideal}}}{m_{\text{real}}}$$  \hspace{1cm} (2)

It can be seen in Fig. 3 that at ambient temperature and a pressure of around 300 bar, the compressibility factor ($Z$) is 1.2. This implies that a mass of hydrogen gas inside a container calculated by the ideal gas equation will be 20% greater than the actual mass [25].

Furthermore, the increase in hydrogen density is not linear with the pressure increase as shown in Fig. 4. For attaining 70 kg/m$^3$ density of hydrogen, the gas pressure needs to increase to up to 2000 bar [41], whereas methane can reach the same storage density at around 95 bar when the temperature is ambient [42].

There are two key components for the compressed hydrogen gas storage system: the storage means and the compressor used for reaching the storage pressure [43]. Due to properties of materials, investment costs, and safety issues, storing large quantities of compressed hydrogen gas at pressures exceeding 200 bar have many hindrances [43,44], which can be tackled with research and technology [45]. The work...
needed for compressing gasses is based on gas nature and the thermodynamics behind the compression process [40]. As can be seen in Fig. 5, hydrogen requires a significantly larger amount of energy to be compressed to the same pressure than helium and methane, which is mainly due to its extremely low density [46,47].

Compression work calculations are generally simplified by assuming either an adiabatic or isothermal compression process [41]. Under the adiabatic process assumption, the process occurs without transferring heat to the surroundings and at a constant entropy (Isentropic). In this case, the gas temperature varies without heat transfer occurrence between the gas and the surroundings [48]. Under the assumption of an isothermal process, the gas temperature stays constant during the compression process [49]. Under realistic conditions, theoretical isothermal and isentropic compression works acts as the boundaries for the compression work [41] and their difference for the case of hydrogen is presented in Fig. 6.

It can also be noted from Fig. 6 that the closer the process is to isothermal conditions, the lesser is the work required to compress hydrogen. Whereas a compressor that can compress gas isothermally does not exist under real conditions, it is possible to use multi-stage compression and cool down the compressed gas after each stage using cooling devices to make the compression as close as possible to the isothermal performance [49]. As a result, compressing hydrogen is usually performed in multi-stages [40]. The cooling energy required denoted as $q_k$ is added to the compression work which can be calculated with respect to the first law of thermodynamics as follows [25]:

$$w = h_2 - h_1 + q_k$$  \hspace{1cm} (3)

where $h_1$ and $h_2$ are the gas enthalpies before and after the compression, respectively.

Principally, a hydrogen compressor is the device in charge of increasing the gas pressure by reducing its volume. Hydrogen compressors can be of different types, and each type has its advantage and disadvantages, and its employment would be mostly based on the required pressure. The pros and cons along with the status quo of hydrogen compression technologies, are discussed in detail elsewhere [50].

### Compressed hydrogen storage

A thorough study of hydrogen storage means, along with identifying the limitations and barriers of the storage, is...
outlined in this section. Starting with section 3.1, which investigates storage vessels with their different types, followed by a discussion about geological storage in section 3.2 and end with section 3.3, in which the other underground technologies that have the potential to be utilized in large scale energy storage applications are outlined.

Storage vessels

Pressure vessels are commonly used in industrial, automotive, commercial, and aerospace applications, starting from a small bottle to massive storage tanks [51]. Their design, manufacture, use, and maintenance are regulated by different standards [52,53], with well-defined safety guidelines [54].

Some metals are subject to embrittlement1 caused by hydrogen adsorption and dissociation at surfaces of those materials [56], which reduce the strength and durability of the material [57]. Suitable materials that are mostly used for the pressure cylinders are austenitic stainless-steel,2 aluminum and copper alloys, which are known for their resistance and opposition to effects of hydrogen at ambient temperatures [58,59]. Many other materials such as alloy or high strength steels are prone to embrittlement, and their usage should be avoided in hydrogen storage applications [59].

For vehicle applications, the service pressure of hydrogen storage vessels is normally under 35 or 70 MPa [60,61]. Utilizing 70 MPa vessels will increase the volumetric storage density to about 38 kg/m³ compared to 23 kg/m³ at 35 MPa and with a negligible increase in the energy needed for compression [17]. However, the storage system gravimetric efficiency will decrease [62] due to the larger weight of the vessel resulted from the increased wall thickness that is required to sustain the tensile strength acted upon by the high pressure [59,63]. Overall, the decrease in the gravimetric density will be the penalty of increasing volumetric storage density.

This study focuses on stationary hydrogen storage, and therefore the gravimetric efficiency is not in focus, being more critical for mobile applications. But the tensile strength and material choice are still obstacles for stationary storages. Hydrogen gas is usually compressed to pressure values starting from 100 and up to 825 bars for large-scale storage [43,64]. Hence, materials choices are crucial, considering such high-pressure requirements. Considerable research has been carried out in this field, providing insights about the materials that are compatible with the high-pressure hydrogen gas. A comprehensive study on theory and design principles for pressure loading on hydrogen storage vessels along with the compatible materials can be found elsewhere [65].

The pressure vessels for hydrogen storage can be assorted into four types: Type I, II, III, and IV [33,66]. In General, the pressure vessels are constructed with a central cylindrical section, two spherical domes, and polar opening (s). They can also be polymorph or toroid in the case of composite vessels [51,67,68].

Type I pressure vessels are made of metals like carbon steel and low alloy steel; they are mostly used in industrial and commercial applications and are available with a net volume of 2.5–50 m³ at a pressure of 200/300 bar [25]. The type I vessels can stand 500 bar maximum pressure [33]. Although type I allows for good safety and strength properties, yet its high weight has led to the development of composite materials tanks, which is much lighter in weight [25,69].

Type II consists of a thick load-bearing metal liner (steel or aluminum) that ensures the gas tightness and prohibits its escape. This thick liner is partially wrapped with a fiber resin composite on the cylindrical part like a hoop-wrap [25,33,70]. This hoop reinforcement will lead to a better resistance for the metallic liner fatigue, where residual compressive stress3 can occur and get locked in the liner material, leading to an abatement in the maximum stress that the metal can handle before getting brittle (tensile stress) [51]. The steel liner and composite material equally share the structural load [72]. The pressure that type II vessel can withstand is not limited [33]. Reinforcing fibers and matrix are the basic components of composite materials; where the matrix binds the fibers together, allowing for load transfer between them and the matrix also shields the fibers against potential environmental and mechanical wearing [73].

Similarly, the Type III pressure vessel consists of a metal liner but thin and fully wrapped (axial and hoop wrapped) with a fiber resin composite of high-strength and stiffness that carry most of the pressure load acting on the vessel. In contrast, the metal liners carry only about 20% of the load [35,51]. Type III can withstand pressure up to 450 bar [33], and its weight is half of the type I weight, but its cost is twice that of type II [72]. Type IV vessel consists of a polymer liner or, in some rare cases, an ultra-thin metal liner that is fully wrapped with a fiber resin composite, where the polymer liner secures gas tightness. Only the vessel boss and its liner-junction are still made of metal. These kinds of vessels allow for a storage pressure up to 1000 bar [33]. In these types of vessels, the composites carry the structural load, and although they are the lightest of all vessels, their prices are relatively high [72].

Furthermore, a new type of vessels was introduced in 2010 by the Composites Technology Development Inc.; namely, type V, which is a linerless fully composite pressure vessel based on a fiber-reinforced shell. The first vessel of this type was 10–20% lighter and with a lower cost than composite based storage vessels (Type II to IV). However, Type V is costly to design and develop, and in addition to this, the maximum operating pressure and volume of type V that can be attained at this stage are limited which does not make type V a good fit for large-scale compressed hydrogen storage [72,74–76].

Typically, hydrogen storage systems comprise different components like valves, sensors, storage containers, etc. [77]. These components are made of different materials that can be

---

1 Embrittlement is the loss of the material ductility, which is the ability of material to be subjected to plastic deformation before becoming brittle [55].
2 Austenitic stainless steels are non-magnetic stainless steels which have large immunity to corrosion and also known for their formability [58].
3 Stress that is locked in a material during manufacturing. Where there are regions in materials that are under stress as they are pulled or pushed by the surrounding materials. These internal stresses are referred to as residual stresses because they exist within the material itself [71].
categorized to metallic, polymer, and composites parts, along with related issues to the main categorization, are as follows [33]:

- **Metallic parts**

  As mentioned before, hydrogen embrittlement (HE) is the main issue for metal components. The industry and academia have put a lot of effort into tackling the HE issues by examining the HE mechanisms in detail, manufacturing development of the alloys, component assembling, and assessing the materials’ mechanical testing [78]. A review of the most recent hydrogen embrittlement prevention techniques can be found elsewhere [79].

- **Polymer parts**

  Gas permeation is a common phenomenon for gasses in direct contact with polymers. It results from the absorption, diffusion, and desorption⁴ of gas molecules through complex physical and chemical processes. There is no consolidated theory that explains the gas permeation fully, but more details can be found in the following reference [82].

  However, it is believed that diffusion and accumulation of hydrogen through substances is the critical process behind gas permeation, which is more active in the case of hydrogen because of its small molecule size. Deformation occurrence is based on the cylinder’s maximum pressure and the pressure retained in the cylinder after the end of the emptying process. The speed of emptying the cylinder might also have an impact that needs to be far more investigated.

  The cylinder’s structure and, principally, the polymer liner and the boss junction are prone to high and low temperatures ranging from 85 to –60 °C depending on the standards throughout the filling and emptying processes. The assessment of liner deformation impact on the cylinder lifetime and risk leakage can be provided by further tests that ought also to provide recommendations on the suitable operating conditions. All in all, materials should be carefully selected accordingly to avert the deformation of materials that can lead to a leak risk [33].

- **Composites**

  As mentioned before, a composite material is based on the unification of two different materials with a variety of different compositions, of which fiber-reinforced composites are the most common for hydrogen storage tanks [83]. This material consists of fibers that are held together by the resin, and the most common options for these both components are discussed [25,33]:

  - **Fibers**

    - Carbon fibers: has exceptional mechanical properties and chemical resistance, which make them perfect for pressure vessels. One of the drawbacks is their high cost.
    - Glass fibers: low stiffness compared to the other reinforcement fibers, but have the advantage of low cost [84]. Typically, glass fibers are not the main load-carrying material in high-pressure hydrogen tanks. It can be combined with carbon fibers for enhancing composite structure toughness as well as deducing the total cost [51].
    - Aramid fibers: has a better mechanical property compared to glass fiber. They are organic fiber with high tensile strength and damage resistance [85]. The principal drawbacks are the high cost and vulnerability to high temperatures and environmental corrosion [41].

  - **Resins**

    Polyester, epoxy, phenol resins can be used. However, the high mechanical properties of the epoxy resins and their resistance to temperature and corrosion make them a perfect candidate for manufacturing pressure vessels [33,51].

    An important sequel to the material’s discussion is an issue that was highlighted in the literature related to the handling of the tanks. Further studies are needed to identify the consequences of mechanical impacts or a fall of the cylinders during handling and transportation, which may lead to damages in the composite material and the polymer liner [33,86,87]. The authors in the literature have also stated the development of bonfire⁵ tests is crucial for understanding the composite vessels’ behavior in the case of fire. Valenciaia and Ruban also reported that bursting or leaking of the composite cylinders during a fire is due to the heat transfer through the wall rather than pressure increase as in the metallic pressure vessels. The heat transfer leads to the loss of tightness or the degradation of the mechanical properties of the wall, which results in the burst [33,89].

    Zheng et al. classified storage vessels for high-pressure hydrogen gas into three types: stationary, vehicular, and bulk transportation [90]. This study focuses on large-scale hydrogen storage; hence, this study discusses in detail only stationary tanks. The carbon fiber prices are quite high, where for type IV storage system with a storage capacity of 5.6 H-kg at 700 bar costs about 14.19 $/Kwh⁶ of which more than 50% accounts for carbon fibers costs [91]. Thus, vessels of type III and IV that are fully wrapped with composite materials are too expensive and create another challenge for any potential future cost reductions in contrast to steel or aluminum vessels [92]. As a result, Type III and Type IV vessels are not economically viable for large scale applications where low-cost hydrogen storage is required [43].

    Stationary vessels that are mainly used for large-scale applications like hydrogen refilling stations and energy storage are of Type I and II tanks [90,93], which are based mainly on metals. In our work, we present five alternatives for storage vessels that could be utilized in large-scale storage applications (see Fig. 7).
Seamless hydrogen storage vessel

Seamless hydrogen storage vessels are made from high strength seamless tubes, and they are commonly utilized in hydrogen fuel stations. The inner diameter of this kind of vessel is limited to 6.1 m, and their maximum overall length is based on the largest pipe length (usually ≤ 12 m) or the available pipe weight. Thus, seamless hydrogen storage vessels have a limited volume. Nevertheless, for storing large quantities of hydrogen, seamless vessels can be used in multi-vessel assemblies, which are denoted as cascade storage, where the seamless vessels are assembled through valves and interconnection piping manifolds, leading to more hydrogen leak points.

This vessel type volume is only 0.411m³ despite the maximum operating pressure of 650 bar, implying that a large number of vessels are required for large-scale storage. On the other hand, the maximum operating pressure can be increased by using steel with higher strength. On the other hand, it has been found that when using a higher tensile strength steel (≥ 800 MPa) at high-pressure hydrogen, the hydrogen embrittlement effect increases significantly, possibly leading to physical and mechanical damage of the steel’s properties. Moreover, hydrogen storage vessels are difficult for Online Safety Monitoring as they are not capable of neither collecting leaked hydrogen automatically nor arresting crack propagation [45,90,95,96].

Multifunctional layered stationary hydrogen storage vessels

To overcome the above issues, the multifunctional steel layered hydrogen storage vessel (MSLV) was developed. The basic structure of MSLS is based on two main components: a flat steel ribbon wound cylindrical shell and two double-layered hemispherical heads where the cylinder shell is composed of three shells; inner, layered, and a protective shell. The inner shell is based on cladding steel sheets, layered by the layer shell that is made from flat steel ribbons, while the layer shell is wrapped by the protective shell, which is made from steel sheets. On the other hand, the hemispherical head is composed of inner and outer heads in which the inner one is made up of double-layered steel sheets made from low-alloy steel and austenitic stainless steel. In this way, austenitic stainless steel would be the inner layer that is in direct contact with the high pressure. Like the outer layer of the inner head, the outer head is made from low alloy steel [45,97].

From the positive characteristics of MSLV is the feasibility for manufacturing large-scale hydrogen storage vessels operating at high pressure without restrictions on size, either for shell and length thickness or internal diameter. As the inner diameter increases, the manufacturing process becomes more manageable, resulting in better manufacturing efficiency. Moreover, a reduction in associated costs is attainable in comparison with seamless pressure vessels [45].

MSLV is not prone to hydrogen embrittlement issue, which was solved by using hydrogen compatible materials for components that are in direct contact with hydrogen. The cladding layer material of the steel sheets used in the inner shell is made from type 316 L stainless steel, which is compatible with hydrogen at ambient temperature and high pressure. The rest of the metals used in the cylinder (incl. outer shell) have tensile strengths that are far below 800 MPa. Thus, even in the case of hydrogen leak occurrence from the inner shell, hydrogen embrittlement can hardly take place [45,90].

Unlike seamless storage vessels, the structure of MSLVs allows for an online safety monitoring system. The system is equipped with sensors and other devices that are capable of detecting hydrogen leakage points and vent it through an escape pipe to prevent any potential fire (Burst Resistant or Self-Protected). It has been proven that the flat steel ribbon wound shell is not significantly affected by the sudden brittle fracture damage, and the stalemate would be a gas leakage and no burst under any condition [45].

Although theoretically, there is no restriction on MSLV design parameters, the manufacturing of MSLVs is restricted by the available winding machines capacities [97]. The Chinese national standard (GB/T 26466-2011) identified the design specifications as follows: the maximum operating pressure is 100 MPa, the inner diameter is up to 15 m, and the maximum length is 30 m [98].

MSLVs can be manufactured with design pressures ranging from 200 to 980 bar and with volumes ranging from 0.5 to 25 m³ [45,90,99]. The costs of MSLVs are less than the U.S. DOE target cost in reference to the corresponding storage pressures [90,99]. The approximate costs for storing hydrogen at 860, 430, and 160 bar are 600, 450 and 350 $/kg – H₂ [99], respectively.

---

7 No welding is required during the manufacturing process and the vessel is seamless.
8 The manifold is set of pipes and/or valves aimed to organize and control the fluid flow [94].
Steel–concrete composite pressure vessels

Cylindrical pressure vessels are subjected to axial and hoop stresses, which act on the longitudinal and circumferential directions [100,101], as shown in Fig. 8. The hoop stress on a cylindrical vessel can be calculated as follows [101]:

\[ \sigma_h = \frac{Pr}{t} \]  

where \( P \) is the internal pressure, \( r \) is the internal radius, and \( t \) is the wall thickness.

The hoop stress is a function of the wall thickness. Therefore, as the wall thickness decreases, the hoop stress increases.

Oak Ridge National Laboratory has developed steel-concrete composite pressure vessels, consisting of an inner steel vessel encased in a concrete shell [102]. The concept behind such vessels is to allow for the hoop stresses to be equally shared between the inner steel vessel shell and the concrete shell. As such, hydrogen can be stored in large-diameter steel vessels under high pressure without the need to use large shell thickness, which is very hard to be produced by steel mills, very expensive, and impractical [102].

Furthermore, cost savings can be accomplished by making the internal steel shell out of layered construction rather than a solid wall. This also allows for venting the permeating hydrogen out of vent holes to the ambient, which in turn enhances the safety and helps in protecting the steel shell from hydrogen damage. The steel layer shell is made from SA-724 material with a tensile strength of 655 MPa [102], and for the inner liner, type 304 stainless steel with a tensile strength of 43.1 MPa [102] is used. This implies that hydrogen embrittlement potential is eliminated. Moreover, the inner vessel layered design allows leaking before bursting, which helps in averting catastrophic failures [102,103].

A mock-up vessel has been fabricated with a design pressure of 431 bar and an approximate volume of 2.2 m³ and now it has been cycled with hydrogen to prove its reliability [102]. On the other hand, Oak Ridge National Laboratory has already finished the design for a vessel of size 1.000 kg at 875 bar with cost below $700/kg – H₂ and hydrogen leak rate of 50kg H₂/year [103].

Hydrogen storage in wind turbine towers

NREL has proposed storing hydrogen in wind turbines tubular towers under patent no. US 7471,010 B1 [104]. The idea behind that invention is to store a large amount of compressed hydrogen gas inside the wind turbine tubular tower (in-tower storage) at a pressure between 10 to 15 bars, limited by the tower’s crossover pressure \[ \sigma_h \] [105]. The conceptual design is to store the hydrogen as close as possible to the lower part of the tower. While the ladder and power transmission lines that exist at that part will be moved to the tower exterior, and the power transmission lines shall be then protected by a conduit [104]. It was found that a 940 kg of hydrogen can be stored at an optimum pressure of 11 bar in a 1.5 MW wind turbine of height of 84 m with a cost of $88/kg – H₂ [105,107]. Furthermore, the fatigue damages resulted from stresses imposed by the storage’s internal pressure are expected to be negligible compared to the frequent aerodynamic stresses. Nevertheless, issues such as hydrogen embrittlement, corrosion induced by hydrogen, and the tower’s fatigue life are under investigation [108].

Utilizing natural gas metallic vessels

There is a potential for utilizing the metal pressure vessels that are used for natural/town gas storage in hydrogen gas storage [43,109]. There are three main types of such vessels, namely, pipe storage, gas holders, and spherical pressure vessels. Gas holders can store large amounts of gas; however, constrained to low operating pressure levels that are around the atmospheric pressure levels [110,111]. Few hydrogen gas holders currently exist; one of them is at Hochst Industrial Park in Germany, holding net volume gas of 10K m³ at 1.07 bar which is equivalent to about 898.8 Kg – H₂ net mass capacity [111]. Provided that electrolyzers produce hydrogen at relatively elevated pressures, which is expected with polymer electrolyte membrane (PEM) electrolyser in the future [111,112], therefore, gas holders are not a viable option for seasonal energy storage. Nevertheless, they can be utilized in other applications, where low-pressure hydrogen is produced [109].

Spherical pressure vessels could hold up about 300K m³ of gas at a pressure of 20 bar, which is equivalent to 26964 kg – H₂. Such vessels have lower capital and operating costs in comparison with gas holders [109]. Tietz et al. have performed a comprehensive study of spherical vessels and found no evidence of their use for hydrogen storage applications [111]. Therefore, there are no available data about neither economic nor technical parameters for hydrogen gas storage in spherical vessels.

---

9 The crossover pressure is the critical pressure where failure crosses from loss to bursting. For most of wind turbines, the crossover pressure is between 10 and 15 bar.

10 This cost is in 2004 dollars which is equivalent to about $121. \n 3 \n 11 The net mass capacity was calculated using hydrogen density at STP which is equal to 0.0899 kg/m³.

12 Geometric volume is about 15 755 m³.
Pipe storage is one more alternative for storing compressed hydrogen gas. A storage volume of 12K m³ at pressures range 1.5–100 bar can be achieved in pipe storage facilities. The building of pipe storage mainly comprises of civil construction and welding activities where the storage pipes are commonly placed just a few feet under the ground, which requires a hole excavation for the pipes. Pipes are welded together, forming a storage pipe that is extended for up to several hundred meters. Burying the pipes below the ground provides protection for the pipes against environmental and mechanical impacts. However, coatings and other measures are applied to protect the pipes from corrosion. Although burying the pipes underground allows for land area utilization, there are considerable limitations to avoid pipes damage caused by the above-ground activities, which may include, for example, agricultural activities and therefore create a risk for hydrogen leakage. Hence, the land must be leased, bought, or legally obtained in any way [109,111,113].

For decades, pipe storages have been used for storing natural gas. One example was a natural gas pipe storage facility that was built in Switzerland at the end of 2013 with a storage volume of 6112 m³ and a net volume capacity of 720 K m³ at a maximum operating pressure 100 bar [111,113,114]. The conversion of this total volume to hydrogen results in a total mass of 64714 kg, equivalent to 2156 MWh of energy, and the related costs were 376.4 €/kg – H₂ [111,113]. It is with this in mind that storage in the GWh range is attainable with this kind of technology [103,105,107]. Tietz et al. reported the storage efficiency for the spherical pressure vessels and pipe storage as 94.9% and 97.1%, respectively. Where the storage efficiency can be defined here as the ratio of retrieved work from the storage to the input work used for storing [111].

It should be noted that the storage parameters and costs mentioned above were estimated by the authors of those publications. Furthermore, considering hydrogen’s different thermodynamic characteristics, material, and safety issues, estimating such parameters from natural gas spherical vessels would be far from being accurate. For obtaining accurate parameters, a lot of research and development (R&D) is needed for investigating the feasibility of such alternatives. Except for pipe storage, it can be presumed that a little R&D is needed as hydrogen pipelines already exist in some industries such as the chemical and Petro industries. Inasmuch as there are no considerable differences between hydrogen pipelines and natural gas storage pipes [113], it is believed hydrogen pipeline storage could be achieved with a fast timetable.

Finally, it is worth mentioning that NPROXX, which is one of the leading companies in manufacturing Type IV pressure vessels for high-pressure hydrogen storage, is currently developing a new vessel that can store more than 1000 Kg of hydrogen at a pressure of 500 bar [116]. In light of the storage time, compressed hydrogen gas storage is a closed system. Therefore, storing hydrogen gas for extended periods with no losses is attainable as long as the appropriate materials and dimensions are considered [25].

The theory of operation behind geological storage is to inject hydrogen gas underground and storing it under pressure, where it can be later withdrawn whenever needed. Underground storage systems are advantageous in many regards; first, they provide secured and safe storage since they are not likely prone to fires and less vulnerable to potential threats by military or terrorist elements. Secondly, underground storage can be smoothly integrated with the urban plan of cities with the least modifications. Furthermore, unlike geological storage, surface tanks will need to occupy a large ample of surface land to store the same amount of gas. Finally, the geological storages are the best option to store a large amount of hydrogen economically as compared to other present alternatives [117]. There are five types of geological storage: depleted natural gas & oil reservoirs, aquifers, salt caverns, abandoned mines, and rock caverns (see Fig. 9).

The underground stored gas is divided into a cushion and working gas. Cushion gas is the base gas of the underground storage reservoir aimed at keeping the pressure at an adequate level that would maintain the gas deliverability; the rate at which the gas can be delivered out of the reservoir which can be expressed as mass, volume or energy per a unit of time [118,119]. Therefore, cushion gas is intended to stay permanently in the reservoir and since it mostly gets trapped inside the geological structure, it also becomes non-recoverable; it can be considered as the minimum charge level of the storage as in batteries [120,121]. On the other hand, working gas is the actual storage capacity that can be repeatedly charged and discharged [122,123]. It should be noted that there is a possibility to extract part of the cushion

---

13 The reported cost in the literature was 376.4 €/kg in 2013 Euros which is equivalent to 400.5 €/kg in 2020 Euros [115].
gas from the underground storage using specific technologies; however, this partial recovery of the cushion gas would be largely limited to the extensivity of the potential damage to the underground formation that would result from the extraction process [124].

The geological storage system typically includes injection and withdrawal wells and a confining layer. The injection and withdrawal wells are the devices responsible for getting the hydrogen in and out of the underground geological formations [125,126]. On the other hand, the confining formation acts as a sealer to the gas so that it does not leak throughout the boundaries of the reservoir [127,128].

For depleted natural gas & oil reservoirs, the gas is injected below in the depleted reservoirs through the injection wells [129]. The primary factor of the confining layer is cap rocks which seal the top of the reservoir. These rocks are natural rocks that possess unique characteristics, of which the most important is their impermeability that ensures the gas’ tightness [130]. Cap rocks are often salt or shale[14] rocks that initially existed naturally in the depleted reservoirs contributing to the prevention of gas’ escaping [113,131]. Conversion of depleted to underground hydrogen storage reservoirs is likely to require a low budget (1.23 USD/kg)[15] [117]. The main reason behind this is that the reservoir already exists and is equipped with all the needed facilities and tools. Furthermore, no geological tests or studies are needed for examining storage behavior since they already exist [117,132].

Another advantage is the existence of residual gas even after the depletion, which can act as cushion gas. On the other hand, there are concerns about the potential contamination of hydrogen because of the residual hydrocarbon [30] where despite these residual gases are in equilibrium with the rocks in the reservoir, the continuous injection of hydrogen will alter this equilibrium [133]. However, it is uncertain to what extent will the residual gas mix with hydrogen [129]. Furthermore, the conversion of the depleted reservoirs to underground storage facilities is not always attainable due to limitations posed by different factors such as the reservoir’s depth, structure, and hydrogen dissolution and diffusion into the surrounding, which are discussed in detail elsewhere [113,129,131,134]. This emphasizes that depleted reservoirs need to meet specific criteria to be eligible for storing hydrogen gas. Despite being one of the most common underground gas storage (UGS) types [124], depleted reservoirs have not been utilized for storing hydrogen before.

Similar to depleted reservoirs, there is no experience in storing hydrogen in aquifers, except for some cases where gases with 50–60% of hydrogen content have been stored in aquifers by some companies (e.g., Gaz de France) [135]. Aquifers are an underground geological structure of rocks that holds groundwater; the rocks are porous and permeable, where water can easily move among them [136]. A dome-shaped formation must be created to hold the gas by displacing the water sideways and downward. The porosity of aquifers’ rocks makes it unsuitable for gas storage, which is why a layer of impermeable rocks needs to be added to form the confining layer with the groundwater, together acting as a sealer to the gas [137,138]. The tightness of an aquifer needs to be identified and thoroughly studied through various tests that are expensive in nature. This makes aquifers more expensive (1.29 USD/kg) [117] than depleted reservoirs that have such parameters known already.

Although hydrocarbons residues do not exist in the case of aquifers, there are concerns about potential hydrogen contamination and loss due to reaction with minerals and microorganisms that exist there [137,139]. Another drawback of aquifers is the high cushion gas requirements, which implies that a vast amount of gas will be trapped permanently in the aquifer without the possibility of being recovered later [117]. There are also other environmental concerns regarding the potential land subsidence and underground water contamination [140,141]. The latter concern applies to all the types of underground gas storages as underground water can be one of the deep layers that contribute to the overall sealing of these storages [113,131].

For salt caverns, there are already cases for implementing them to store hydrogen in the United States, Britain, and Germany. Salt caverns are formed by leaching[16] the salt out of a salt dome or a salt bed. Naturally, salt possesses special properties that allow for tight and stable gas storage—making salt caverns one of the best options for underground gas storage. Furthermore, salt caverns require a lower cushion gas compared to the other geological storage options [142]. The amount of required cushion gas in salt caverns is based on its depth; salt caverns at lower depths allow for lower cushion gas requirements [117,143]. However, it is the most expensive alternative (1.61 USD/kg), which can be attributed to the cost accompanied with salt leaching [117,144,145].

In light of abandoned mines, they can be converted into high-pressure gas storage facilities. However, there are a lot of question marks about their gas tightness and the difficulty of testing it. At the moment, using abandoned mines for storing gases is not as commonly practiced as other geological alternatives [34,113]. Regarding rock caverns that are constructed by conventional mining technologies, they are not usually eligible for holding gases tightly enough under high pressure. However, they can be sealed up using a range of different methods such as natural groundwater and stainless-steel lining, which can act as a permeability barrier [113,146–148]. One project of this kind—hard rock caverns for natural gas storage—currently exists in Sweden, in which the lining is steel with maximum storage pressure of 200 bar [43,113]. It is believed that hydrogen might also be eligible to be stored in this type of storage.

Some selected examples for the investigated geological storage alternatives are listed in Table 1. Although the storage options shown in Table 1 originally store natural gas (except for salt caverns), the authors have recalculated the equivalent parameters for hydrogen for ease of comparison [113]. As can be seen in Table 1, there are apparent differences in what type of pressures these storages can withstand, which is mostly

---

[14] A shale is a fine-grained rock that disintegrates to mud upon exposure to water. It is impermeable and is able to prohibit the gas to flow through it [131].

[15] Costs for geological storage here are levelized costs.

[16] Leaching: dissolving solid minerals (e.g. salt) using pressurized water.

based on the geological nature of the area and the kind of seal/lining utilized. Even when the same seal/lining is used, slight differences in the pressure range can still be noticed, as the case for the salt caverns in Clemens and MOSS Bluff in Table 1, where both rock caverns have sealing of rock salt but different pressure ranges. Furthermore, the differences in the ratios of cushion and working gases among the different alternatives are noticeable.

Geological storage may have many challenges that include but not limited to Refs. [113,117,149]:

- Cost of compression needed for injection or withdrawal which (depends on the initial $H_2$ pressure)
- Geological requirements
- Potential chemical reactions with hydrogen that can result in gas contamination or loss
- The pipelines’ material durability (e.g., hydrogen embrittlement)
- Design concerns of the location, depth, and the exact volume of the well
- Legal and social obstacles regarding country regulations (e.g., land use and caverns construction regulations), public acceptance, and environmental concerns.

Overall, there is no experience in storing pure hydrogen in geological storage facilities except for salt caverns, which is also still considered a limited experience [156]. For the wide utilization of geological storage, actions need to be taken to evaluate the potential hazards and the hydrogen behavior upon storage in such facilities to prove its viability. Moreover, addressing the geological characteristics and environmental challenges should be a priority along with the legal and social obstacles.

**Other underground technologies**

In this section, two other interesting underground storage technologies that can be utilized in large-scale hydrogen storage are discussed; the Underground storage of a blend of natural gas and hydrogen, and the Underground methanation reactor.

**Blending hydrogen into natural gas pipelines**

In this technology, pure hydrogen produced through a process based on renewable resources is injected into natural gas’ pipelines or underground storage facilities. This technique can also be used to store the surplus power produced by renewable sources. No CO$_2$ emissions result from hydrogen upon combustion; therefore, adding hydrogen will decrease the amount of natural gas burned by replacing it while keeping the same energy value. This will result in what is known as decarbonizing or greening the natural gas (reducing its CO$_2$ emissions) [151]. Furthermore, the effect of utilizing this blend in heat and electricity generation imitates the added value of increasing renewable sources in the electricity mix [152]. Moreover, hydrogen can be recovered from the blend when needed through various techniques that vary in efficiency [36].

Despite the benefits of hydrogen injection into the natural gas network, there are also drawbacks that limit the amount of hydrogen (%) that can be injected. Hydrogen embrittlement is one of the main issues concerning pipelines safety and leaking risk. However, these issues become less of a concern at low hydrogen percentages. Furthermore, because high-pressure make hydrogen embrittlement more pronounced, hydrogen percentage should decrease with the increase of the pressure of the gas pipeline or network. For example, its percentage should be lower in the transmission network (high-pressure) than distribution ones (low-pressure) [151,153–155].

In addition to that, some countries utilize natural gas in the household (e.g., Cooking), which triggers even more challenging issues related to the odor and color of a pure hydrogen flame. As hydrogen can leak without being detected; therefore, odorizing hydrogen might be needed to make it more detectable, especially that hydrogen’s risk of ignition is higher than that of natural gas. Adding colorant should also be considered considering the pale color of pure hydrogen flame that might be entirely invisible [156,157].

Adding hydrogen to natural gas will increase the pressure drop across the gas network. Whereas, because of hydrogen’s low energy density, the amount of energy delivered through the network will decrease. This makes it imperative to increase the flow rate for delivering the original amount of energy; with increased flow rate, larger pressure drops, and losses will take place [158]. As a result, it is recommended to consider these pressure drops while planning future networks [159].

Considering the utilization of hydrogen blend in industrial and power generation applications that involve combustion of the blend, new burners have been designed to be more flexible with the new combustion characteristics. However, because the hydrogen comes from intermittent renewables, the hydrogen percentage will vary with time, which will result in further issues that are being investigated currently [151,160]. On the other hand, the testing of the first hybrid hydrogen
turbine has been accomplished and will come into service by 2021 in Italy; the turbine will be fueled by natural gas blended with up to 10% of hydrogen [161].

On the whole, there are concerns about the percentage of hydrogen that can be injected into a natural gas network/pipeline. At hydrogen blend percentage, less than 5–15%, fewer concerns are involved that vary with respect to the composition of the natural gas and other site conditions. For a 15–50% blend, more serious issues arise, for example, modifying the end-user equipment to be compatible with the new blend fuel. Safety and material concerns, along with more challenges, arise at over 50% blends [152]. As shown in Fig. 10, Germany has the highest allowable hydrogen blend percentage, up to 10% [162]. Overall, the issue of the safe percentage range is controversial; however, many studies agreed on a blend percentage that is up to 15–20% hydrogen [151,156].

A plan to create a hydrogen transport network throughout Germany—the world’s largest hydrogen grid—has been presented by the German gas pipeline operators. The network grid is to be 1200 km, of which 1100 were initially natural gas pipelines and only 100 km would be newly built [163]. This reflects on the relative hydrogen compatibility with the existing infrastructure and gives insights into how the existing infrastructure can be modified accordingly.

**Underground methanation reactor (UMR)**

This technique is based on the reaction of hydrogen and carbon dioxide in an aquifer or depleted gas reservoir, where the methanogenic bacteria that are normally present there catalyzes the Sabatier’s reaction (Equation (4)).

$$4H_2 + CO_2 \rightarrow \frac{1}{2}CH_4 + 2H_2O$$ \hspace{1cm} (5)

This reaction usually takes place at high temperatures in the presence of a catalyst (nickel); however, in the presence of the methanogenic bacteria, it occurs at a much lower temperature. This saves money considering relatively expensive catalysts (compared to bacteria) and the high temperature required [164–167].

Panfilov was the first to introduce the UMR in 2010 [164,168]. He suggested that UMR can be achieved either by injecting hydrogen into an aquifer/depleted gas reservoir that is storing CO₂ or through directly introducing CO₂ into radioactive waste’s underground stocks. In which the degradation of containers produces pure hydrogen. The resulting methane then could be added to the natural gas network, which can provide one big storage that can be accessed by renewable sources that are close to the natural gas grid. However, Strobel et al. have studied the UMR’s potential and concluded that currently, there are concerns regarding the production rate of CH₄ and the efficiency factor where neither of them could be accurately determined so far. On the other hand, simulation studies have portrayed the potential of UMR as a storage option in terms of capacity and conversion [168].

**Discussion**

This paper provides a holistic view of the technologies that have the potential to be employed for large-scale hydrogen storage to be used as a part of renewable electricity storage. The analysis was based on reviewing more than 140 Scientific papers and reports that covered compressed hydrogen storage, different technologies, and their challenges from different perspectives. The study discusses the ten most feasible large-scale storage technologies for compressed hydrogen. However, there are key questions and notions that are not clearly represented in the existing literature such as, storage time, storage losses, lifetime, and charge and discharge rates of the storage technology.

From all the technologies that have been investigated throughout the study, some technologies were shortlisted for a more thorough analysis. This does not rule out the other
technologies; rather, it portrays the technologies that have available data as well as a higher potential to store pure hydrogen at present. Table 2 shows the results of the analysis for the shortlisted technologies, which is based on four specific criteria: storage size, cost, and the technology maturity for both hydrogen and natural gas. The technology maturity for natural gas (NG) has been considered since, according to Kruck et al. there is no substantial difference between the hydrogen and natural gas storage facilities [113]. Hence, the experience of storing NG would be an asset for assessing the proposed hydrogen storage technologies. As mentioned before, compressed hydrogen gas storage is a closed system, so extended periods of storage with no losses are attainable as long as the appropriate materials and dimensions are considered. However, the higher the storage pressure, the higher leakage possibility and the less the storage time, which implies that the geological storage would have a higher storage time due to its relatively low storage pressure when compared to pressure vessels.

It can also be seen in Table 2 that geological storage has the highest storage capacities, followed by underground pipe, pressure vessels, and Wind turbine tower storages, respectively. It should be noted that the pressure vessels and turbine tower capacity is per unit. This implies that a multi-vessel assembly (cascade storage) is one option, but on the other hand, this will possibly lead to a larger number of hydrogen leak points. Hence, more losses and lower storage time.

A closer look to the literature on costs reveals a number of gaps and shortcomings; the costs represented in the literature are not sufficiently explained and cannot be considered as conclusive. Whereas some studies reported the costs without labeling them as capital costs per kg – H$_2$ or levelized capital costs [37,117], which is substantially different. Only a few studies clearly stated that the costs were levelized capital costs; however, some details related to the number of years based on which the costs were levelized nor the interest rates were not available [37,44].

Table 2 also highlights that there is always a trade-off with the storage option, and the selected technology will reflect on the users’ needs for the storage. The results imply that the geological storage can prove to be one of the most feasible options for a very large size hydrogen storage with extended times, considering its technological and economical characteristics. Also, it must be considered that the costs vary with the size, so the geological storage would not be the economically optimum alternative in every case; rather, the smaller the storage size, the higher cost the geological storage would be. In fact, the geological nature and availability vary from one place to another, which can greatly affect the costs as well; for example, salt caverns storage has no potential in some countries, such as Finland or Sweden, due to the absence of the salt deposits there [134].

**Conclusion**

As renewable energy production is expected to have a significant increase, the balancing of the electricity grid cannot be managed with purely mechanical or electrochemical storages. Also, for the next decades, the three energy sectors: electricity, heat, and transport will emerge, and hydrogen will work as an important energy vector in this transition. The question is how large scales of hydrogen can be stored safely and cost-efficiently. This review introduces for the first time all the large-scale storage options for compressed hydrogen and provides highlights for their strengths and limitations. This will contribute to the dialogue if hydrogen can work as a future energy vector.

Evaluating the viability of one alternative cannot be easily concluded as various factors can tilt the scale in favor of one technology over another. For example, the cost and efficiency can change for one technology based on the required size only, such as geological storage; the lesser the size, the more costly and unrealistic option it would be. Furthermore, geological nature and viability are crucial factors for some technologies. Therefore, a techno-economic chain analysis needs to be performed specifically for each case study, which would identify influential factors that should include but not limited to:

- The distance that hydrogen will be transported and for how long the hydrogen will be stored
- The hydrogen required output pressure
- The kind of geological storage which will be used, and how much losses are expected, which differ from one place to another depending on the geological nature of the place
- Regarding geological storage, how accurate are the losses that were assumed based on natural gas to that of hydrogen, the lightest gas on Earth
- The application of hydrogen energy storage, would it be for fueling cars, ships, or power storage?

The knowledge of these factors shall help the decision-makers to analyze and identify the trade-offs among the different factors concerning the different technologies based

---

Table 2 - Results of the assessment of the shortlisted hydrogen storage technologies.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Compressed</th>
<th>Wind turbine tower</th>
<th>Pressure vessels</th>
<th>Underground pipes</th>
<th>Geological storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage size (GWh)</td>
<td>Up to 0.031 per km tall WT</td>
<td>0.034</td>
<td>2.05</td>
<td>&gt;10-100 depends on the site nature</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology maturity NG</td>
<td></td>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology maturity H$_2$</td>
<td></td>
<td></td>
<td>Exist but not on large scale</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please cite this article as: Elberry AM et al., Large-scale compressed hydrogen storage as part of renewable electricity storage systems, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2021.02.080
on case by case requirements that can include specific technical parameters such as discharge or storage size.

On the other hand, most of the technologies discussed in this study are immature and under development, which means that the research is still ongoing. Furthermore, the infrastructure and facilities behind some of the technologies are massive, which would require significant resources and costs. As a result, stepping in from the industry sectors is required to achieve absolute certainty about these technologies. The findings of this study signal the need for additional research to understand more about the economic aspects and some crucial technical parameters for implementing this system as a part of renewable electricity production. Also, critical studies to understand the key tenets of adding hydrogen storage to an energy system with regards to its effects on CO₂ emissions and energy costs are required.

Declaration of competing interest

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

Acknowledgement

The authors would like to acknowledge the support of this research from The Academy of Finland through Grant 326346 for profiling funding 5 for Energy Storage. Ahmed Elbery would like to acknowledge Fortum and Neste foundation for the personal grant provided by the foundation for this research.

REFERENCES


Please cite this article as: Elbery AM et al., Large-scale compressed hydrogen storage as part of renewable electricity storage systems, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2021.02.080


