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The State of the Art in Hydrogen Storage

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Abstract

The global renewable energy mix is set to change even further with the increasing demand for hydrogen. Hydrogen production levels are dramatically increasing, and it is becoming prevalent that the storage of hydrogen gas is much more complex than natural gas. There are many different hydrogen storage options being investigated, trialed, and used within the energy industry. On-land storage of hydrogen uses compressed pressure vessels for gas, cryogenic storage for liquid hydrogen, and the blending of hydrogen into natural gas to be stored in current pipeline systems. Underground storage options are found in depleted hydrocarbon reservoirs, deep aquifers, and salt caverns. The storage of hydrogen gas presents numerous challenges and opportunities as discussed in this paper, such as design and manufacturing, hydrogen embrittlement and behavior, structural integrity, standards and regulation, safety of high-pressure storage, subsea storage, and circular economy prospects in structural design. Various vessel compositions have been extensively explored to find the most suitable material combinations for pressure vessel designs, with Type IV being the most commonly used. However, significant opportunities remain to enhance vessel designs for more efficient hydrogen storage. Advancements could include improvements in storage efficiency, innovations in subsea and underground storage, and designs aligned with circular economy principles.

Keywords: hydrogen storage, composite materials, compressed gaseous hydrogen, structural integrity

1. Introduction

Renewable energy production is on the rise to address energy and environmental issues. However, renewables like wind and solar face local limitations and supply–demand inefficiencies. To overcome these challenges, suitable secondary storage systems are needed, and hydrogen is a promising option. Hydrogen gas is a clean alternative to natural gas and is abundant, making up 75% of the universe's mass. It offers endless potential as an energy source and can be produced through various methods.

Hydrogen, being the simplest form of all molecules, possesses the lowest energy content per unit volume. However, it holds the highest energy content among all fuels when considering weight. This high energy content makes hydrogen a valuable fuel in various applications like fuel cells and rockets. Hydrogen offers significant advantages, such as being emission-free, which addresses issues with fossil fuels, and having a heating value three times higher than petroleum. However, a key challenge in advancing fuel cell vehicles is hydrogen storage. Its low energy density makes it difficult to store enough hydrogen without the storage container becoming too large or heavy. As a result, research on hydrogen storage techniques, including pressurized tank storage, metal-based compound uptake, cryogenic liquid hydrogen storage, and underground storage systems, is crucial for the development of fuel cell vehicles. Consequently, the demand for hydrogen has grown more than threefold since 1975 [1] (Figure 1), and the potential uses of hydrogen range from industrial steel production, decarbonization of industries, transportation fuel for buses, cars, and airplanes to energy storage. Investment plans and governments worldwide have committed more than 70 billion USD in public funding to date [1].

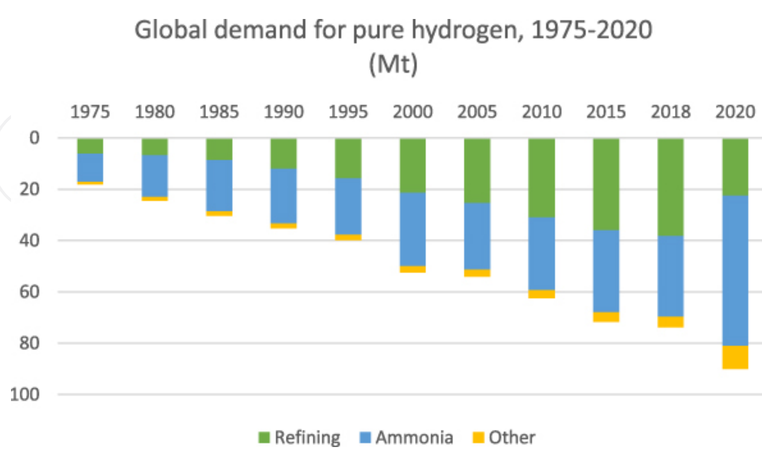

Figure 1. Global demand of pure hydrogen from 1975 to 2020.

This is because hydrogen as an energy source can help renewables contribute an even greater quota of energy than they are providing currently. This can be achieved using hydrogen to store renewable energy during a period of low demand phases. Hydrogen storage developments will combat the issues regarding the intermittency associated with renewable energy production, help balance gird supply and support the transport infrastructure. Hydrogen storage is prevalent in all aspects of the process from production to storage, to transportation, and to utilization.

Significant research is focused on utilizing mobile storage vessels and vehicle fuel cells for hydrogen. However, there are challenges in transforming the infrastructure for large-scale hydrogen use. Various hydrogen distribution pathways exist, including cryogenic liquid trucks, compressed tube trailers, and gaseous pipelines [2]. Tube trailers could be crucial during the initial phase of introducing liquid hydrogen into the energy mix, as they can accommodate smaller demand and avoid boil-off issues associated with liquid hydrogen storage.

Advanced materials for high-pressure gas storage vessels are witnessing rapid growth, making it one of the largest and most rapidly expanding markets. The purpose of this paper therefore is to review the current hydrogen storage options, including compressed gas storage, and highlight the opportunities and prospects for hydrogen storage using advanced materials to support the ever-growing demand.

2. *Types of storage*

Hydrogen storage systems that support renewable energy production can overcome intermittency problems and high-cost transmission, providing a stable source of base load energy [3] (Figure 2).

2.1. Storage vessels for hydrogen

Hydrogen in gaseous form offers the advantage of compact storage with retained energy effectiveness, and the technology is relatively simple. Increasing the pressure enhances the energy density per volume, allowing for efficient storage in a small space. However, this process can be volumetrically and gravimetrically inefficient as discussed in detail in the following sections [4].

2.1.1. Compressed gas storage

High-pressure gas cylinders are widely used for hydrogen storage, primarily because of their technical simplicity, rapid filling and release rates, cost-effectiveness, and well-established maturity of the method [5]. The high-pressure gas cylinder system has a life expectancy of around 20 years. Despite this storage method being the cheapest method (around 10,000 $ in capital), there are many drawbacks. Due to hydrogen being the lightest element in the world, issues arise with volumetric density, the tank pressures, and overall efficiency. Unfortunately increasing the pressure within the gas tank only provides slight benefits. In some cases, the

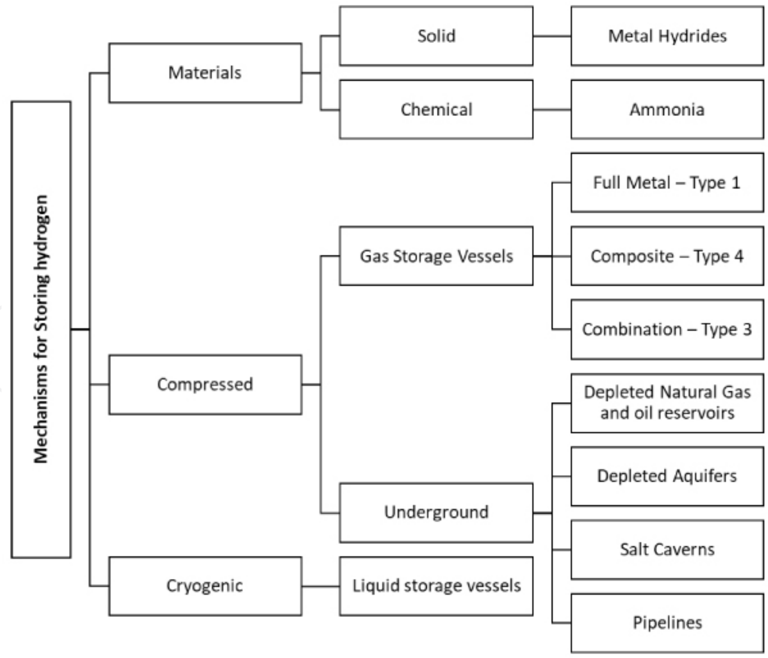

Figure 2. Mechanisms of storing hydrogen.

pressure increased by increasing the thickness of the walls of the pressure cylinder decreases the gravimetric density of hydrogen [6]. The pressure vessels necessitate a three-layer structure, comprising an inner polymer liner, a carbon fiber composite overwrap, and an outer aramid layer that resists mechanical and corrosion-related damages [7]. Compressing hydrogen can be achieved using conventional mechanical compressors of the piston type, with minor adjustments made to the seals to accommodate the higher diffusivity of hydrogen. The most optimized trade-off between cost-effectiveness and storage pressure for hydrogen cylinders is achieved at around 50–55 MPa. However, lighter weight composite cylinders can withstand pressures up to 80 MPa, enabling hydrogen to achieve a volumetric density of 36 kg/m^3 [8].

In terms of storage vessel design and manufacture, this is dependent on the production capacity of the system and the technological development of the production process identified. As with the production vessels, storage of hydrogen also depends on the capacity and system used. In simple terms, the higher the gas pressure, the lower the storage volume needed. Currently, there are different types of pressurized fuel tanks developed for compressed gas, normally classified as Type I, II, III, and IV [9–12] . However, design limitations are experienced when using steel due to hydrogen embrittlement (cracking caused by hydrogen migrating into the metal) [13].

Type I tanks are known as monolithic pressure vessels and are full metal pressure tanks. They are made of standard aluminum or high strengthened steel, withstanding a maximum pressure of 17.5–20 MPa. These tanks are susceptible to fatigue, damage, and corrosion; therefore, their life is predictable. They possess very high compressional design strength and exhibit properties that provide high impact strength. The main drawback of this type is the heavy weight, meaning they are used for stationary purposes. Type I tanks are typically used for scuba diving and within the manufacturing industry.

Type II was the first model to be designed as a composite pressure vessel to be a lightweight alternative to Type I. Type II consists of glass-, aramid-, or carbon-fiber-reinforced composite (CFRC), which is hoop-wrapped on the vessel. This composite wrapping helps to retain the hoop stress. The retained stress is shared with the metal liner, which allows the metal wall to have a reduced thickness. The composite material does not possess the complete stress loads of the cylinder; therefore the metal liner is needed to withstand the pressure by retaining the required strength. These pressure tanks can withstand around 26.3–29.9 MPa. The advantage of using composite materials is the reduced weight of the cylinder; however, there are additional costs for manufacturing composites and certification. Fiber-reinforced composite (FRC) tanks have been widely used for water storage and offshore mostly for storing fluids such as diesel and lube oil. The literature shows that FRC tanks perform better than aluminum or steel tanks due to their low thermal conductivity, the contents of the composite tank remain cooler, and they have also shown to possess leak-free characteristics for a longer time in hydrocarbon pool fire [14]. The outer composite layer protects the tank from environmental damage; however, hydrogen embrittlement would still occur within the metal inner layer.

Type III vessel design consists of a metal liner (mostly aluminum alloy to prevent oxidation corrosion) and is overwrapped by a composite layer. This FRC overlay consists of a hoop and transverse wrap on the cylinder and mostly use glass, aramid, or carbon fiber. These pressure tanks can withstand an approximate pressure of 30.5 MPa and 70 MPa for aluminum alloy/glass-fiber-reinforced composites and for aluminum alloy/CFRCs, respectively. The advantage of this cylinder is its reduced weight with reduction in the thickness of the metal liner. The metal liner acts as a membrane to contain the pressurized gases. The composite overlay can only retain the stress of the compressed gas as the composite possesses a very high modulus of elasticity compared to the metal liner. This allows the composite overlay in taking the heavy load in the structure. Type III tanks have a higher percentage of composite material, which allows the cylinder to be even lighter than Type II and store minimal amounts of hydrogen [15]. Aluminum alloy layers play a fundamental role in the design and performance of composite high-pressure hydrogen storage vessels. Type III tanks are often used as medical oxygen cylinders in ambulances or in homes and within the aerospace and military sectors.

Type IV vessel consists of a plastic-lined pressure vessel, which is overwrapped with a composite material, and the structural strength and stiffness are provided by the composite. The function of the plastic liner is to contain the gas. The liner is made from high-density polyethylene (HDPE) to prevent corrosion and for better fatigue resistance and hydrogen embrittlement rate than metals. The modulus of elasticity for the plastic liner and the composite overwrap is spread in such a way that it ensures minimum fatigue on the plastic membrane. However, these plastic liners fail to provide a rigid supporting membrane to the composites. Therefore, this type of cylinder is more susceptible to impact damage. They are the lightest compared to the other vessels. Type III and Type IV tanks are considered the most appropriate solutions for transportation storage containers [15]. Gases, such as natural gas and air, are transported using these types of storage tanks as high pressure is required for transporting hydrogen (35–70 MPa) (Figure 3) [16], whereas natural gas and air only require up to 30 MPa. Conversely, these storage containers do not satisfy requirements in the automobile industry due to high cost and low performance.

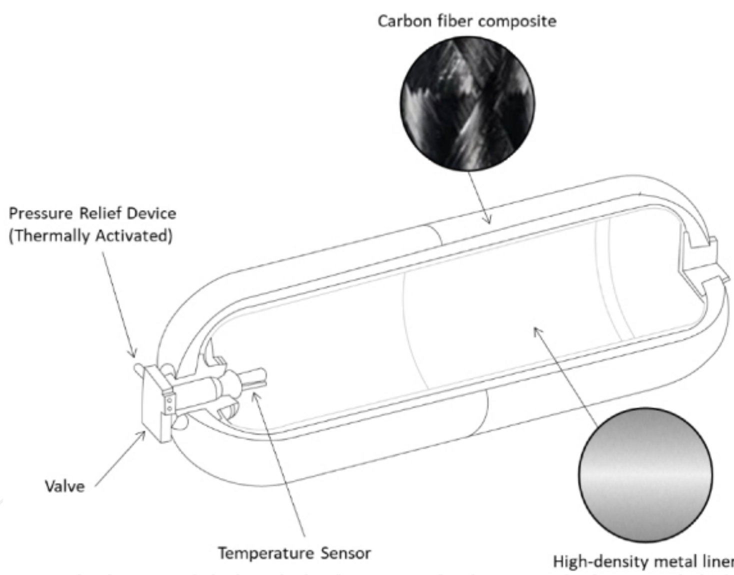

Figure 3. Type IV composite overwrapped hydrogen pressure vessel.

Developments of Type V composite tanks were recently introduced and have undergone successful testing [17]. The Type V design offers an all-composite construction with a liner-less design, with composite fiber wound over a sacrificial mandrel [18]. Compared to a Type IV composite vessel, the Type V is 10–20% lighter and similarly 100% load-bearing. However, very little research has been focused on Type V vessels. Hence further developments required commercialization of these pressure vessels.

In terms of the oil and gas sector, composite materials and tanks are nowadays used on offshore structures and floating production storage and offloading vessels due to their lightweight structural properties and high-pressure uses. These composite compressed cylinders range from 35–150 MPa as shown in Table 1 [19].

Table 1. Current applications of composites in offshore sector

Composite grids/gratings	Cable support systems
Handrails and ladder components	Modular paneling for partition walls
Aqueous piping system	High-pressure accumulator bottles
Water and fuel storage tanks, vessels	Flexible and floating risers, drill pipe
Low-pressure composite valves	Subsea structural components
Spoolable type thermosetting tubes	Boxes, housing, and shelters
Sump caissons and pull tubes	Tendons
Blast protection	Fire protection
Fire water pump casing and sea water lift pump casing	Offshore bridge connecting platforms

There is a need to continue exploring low-cost affordable manufacturing techniques coupled with the ability for mass production and a reduction in part number count and significantly improved structural integrity. Improvement of gas permeability may be achieved by using novel materials and nanocomposites in a composite tank (Table 2).

2.1.2. Liquefied hydrogen storage

When it comes to mobility-based hydrogen, storing and distributing hydrogen in liquid form is considered one of the most practical options from energy, technical, and economic standpoints. This method of storing hydrogen has been recognized as an ideal method in the transport sector and has become widely used in space technology for numerous years now [20]. Cryogenic tanker trucks offer the capability to transport larger quantities compared to tube trailers, meeting the requirements of expanding markets. In parallel, pipelines can be strategically positioned to transport hydrogen to high-demand regions as additional production capacities are established.

Liquefaction involves cooling a gas to convert it into a liquid, utilizing a combination of compressors, heat exchangers, expansion engines, and throttle valves. The Linde cycle or the Joule–Thomson expansion cycle is the most straightforward method for liquefaction processes. Liquid hydrogen has benefits such as its low molecular weight and high energy output. For this reason, it has become a part of advanced technology and is used as a propulsion fuel in aircraft and aeronautical vehicles [2]. Liquid hydrogen tanks are recommended for their ability to store 0.070 kg/L of liquid hydrogen, whereas its compressed gaseous form

Table 2. Comparison of pressurized fuel tanks with applications [9–12].

	Type I	Type II	Type III	Type IV
Overview	Full metal pressure tanks Standard aluminum or high strengthened steel	Composite fiber that is hoop-wrapped on the vessel	Metal liner (mostly aluminum to prevent oxidation corrosion) and is overwrapped by a composite layer	Plastic-lined pressure vessel that is overwrapped with a composite material
Pressure	Withstanding a maximum pressure of 175–200 bar	Can withstand around 263–299 bar	Can withstand an approximate pressure of 305 bar for aluminum/glass, and 700 bar for aluminum/carbon fibers	Can withstand 350–700 bar
Advantages	Very high compressional design strength and exhibit properties that provide high impact strength	Provide optimum safety and are lightweight. Save up to 75% of the weight compared to metal cylinders. Very good behavior in fire and impact accidents, and are corrosion-free from inside and outside. Capable of large diameters while less costly than seamless metal liners. Low thermal conductivity; the contents of the composite tank remain cooler	Type III tanks have a higher percentage of composite material, which allows the cylinder to be even lighter than Type II Reduced weight with reduction in the thickness of the metal liner; composite overlay takes the heavy load	They are the lightest compared to other vessels

Table 2. (Continued)

	Type I	Type II	Type III	Type IV
Disadvantages	Susceptible to fatigue, damage, and corrosion Heavyweight	Additional costs for manufacturing and certification		High cost and low performance; more susceptible to impact damage as they are less robust; also prone to leakage due to the polymer lining not providing an impermeable barrier
Applications	Scuba diving Onsite industrial and manufacturing uses	Water storage Used offshore mostly for storing diesel, lube oil, etc.	Medical oxygen cylinders in ambulances and home oxygen therapy Aerospace and military	Transportation storage

can only store 0.030 kg/L [21]. Hydrogen storage is gravimetrically and volumetrically efficient, but further research is required to address challenges related to hydrogen uptake and release, high liquefaction rates leading to significant energy loss, hydrogen boil-off, and expensive tank costs.

It is recognized that liquid hydrogen is stored in cryogenic tanks at −251.95, which is roughly around −253 °C, and at ambient pressure [22]. Cryogenic vessels have been a common choice for storing and transporting industrial gases for over four decades. To liquefy hydrogen, the gas must be refrigerated at extremely low temperatures, necessitating highly efficient and well-insulated vessels. Modern developments in the manufacturing and design of cryogenic tanks have significantly reduced the thickness of the vessel walls, while the limiting of expensive material use (such as stainless steel) has reduced the overall vessel price. These design and manufacturing methods (cold stretching) have now been standardized through ISO 21900-1 [23]. To manage storage at −253 °C, high-efficiency insulated vessels and an external protective jacket are implemented in the vessel designs. In addition, perlite or superinsulation is employed to decrease the thermal conductivity within the space between the inner vessel and the outer jacket. This insulation can take the form of a powder structure or involve wrapping with layers of fiber or foam films [24]. Liquid hydrogen transportation via roads is carried out using trucks, which can exceed a capacity of 60,000 L. The method of transportation depends on the required quantities, which can be achieved through vacuum insulated containers or transferring the product to stationary vessels. For intercontinental transport, large ships are utilized to carry the liquid form of hydrogen, allowing for the accommodation of the size of the tanks used.

Energy efficiency concerns arise in both the liquefaction process and the thermal insulation of cryogenic vessels to minimize hydrogen boil-off. As mentioned previously, the rate of hydrogen boil-off from a liquid storage vessel, caused by heat leaks, is influenced by factors such as size, shape, and thermal insulation [25]. Boil-off losses due to heat leaks are proportional to the surface-to-volume ratio. Hence boil-off losses in hydrogen storage decrease as the tank size increases due to the surface-to-volume ratio. Spheres are the ideal shape for liquefied hydrogen storage, distributing stress and strain evenly, but large-sized spherical containers are expensive to manufacture due to complexity. Advanced insulating techniques are necessary to maintain low temperatures, making this method impractical and costly for small-scale applications [26].

In comparison with hydrogen gas, up to 40% of the energy content in hydrogen liquid can be lost whereas in gas there is only a 10% energy loss [27]. The reduction in temperature of hydrogen gas can be very time-consuming and highly energy intensive. The advantage of liquid hydrogen is that it has thrice the energy to mass ratio than in its gaseous form, making it the most energy dense fuel. Hydrogen in its liquid form can be very difficult to store over long periods due to product loss by vaporization and requires large bulky tanks due to insulation needs [4, 28]. Table 3 provides an overview on storage advantages and disadvantages in both liquid and gas forms. In its gaseous form, compressed hydrogen can be stored in high-pressure tanks.

2.1.3. Solid-material-based storage

Material-based hydrogen storage methods can significantly increase the density of hydrogen, surpassing the storage capacity of liquid hydrogen by more than two times. Metal-hydride-based energy storage offers a compact and efficient way to store hydrogen at ambient temperature and moderate pressure, providing an energy density approximately thrice higher than compressed or cryogenic storage. This is achieved through an extremely high volumetric density within the host lattice [29, 30]. Metal hydride storage systems are significantly more compact, being up to 18 times smaller than gaseous hydrogen storage systems, while holding the same amount of hydrogen. They possess the ability to absorb considerable amounts of hydrogen at a constant pressure due to phase transition properties.

The common design for metal hydrogen storage tanks is made up of stainless steel or aluminum and copper as shown in Figure 4. The tube portion of the tanks is stainless steel, along with end caps and filters. However, the spiral heat exchanger is made from copper. Paster *et al.* showed that the tanks are not filled with hydride

Table 3. Advantages and Disadvantages of Hydrogen in Liquid vs. Gaseous Form [21].

	Advantages	Disadvantages
Liquid references:	Can store more than gas per m^3	Requires conversion at either side of the storage process
	Easier to transport	The cooling process for liquefaction demands a substantial amount of energy, with energy consumption during liquefaction accounting for approximately 30% of the total hydrogen energy in practical applications
	Higher energy output	Chance of evaporation if not kept below its critical temp
	Low density as a liquid	Achieving thermal insulation for the vessel presents challenges, and the chosen design must meet strict criteria to effectively control evaporation losses of liquid hydrogen in the inner vessel and ensure the safety of the storage container, considering factors like anti-freezing capabilities and pressure-bearing capabilities
	Mature technology as a propulsion fuel in aircraft and rockets	High liquefaction rate that causes energy loss (25%–40%)
		High cost ($14.25/kg)
Gas references:	Does not need converting either side of the storage process	Very expensive materials to maintain tanks with 70 MPa
	Simple and mature technology	Volumetrically and gravimetrically inefficient
	Stored in smaller space	
	Low storage energy consumption	
	Low cost at not too high pressure	
	High speed of hydrogen release and inflation at room temperature	

powder as some space is required for expansion volume when the metal lattices expand during the absorption process [31]. It is suggested that 85% of the inner volume is the reaction volume, 12% of the free volume is for the expansion, and 3% is occupied by the internal heat exchanger [32].

Davids *et al.* [33] demonstrate that a metal hydride storage tank consists of a hydrogen storage alloy powder, heat exchange parts, and gas transport components. The container body is typically made of aluminum alloy or stainless steel. Metal

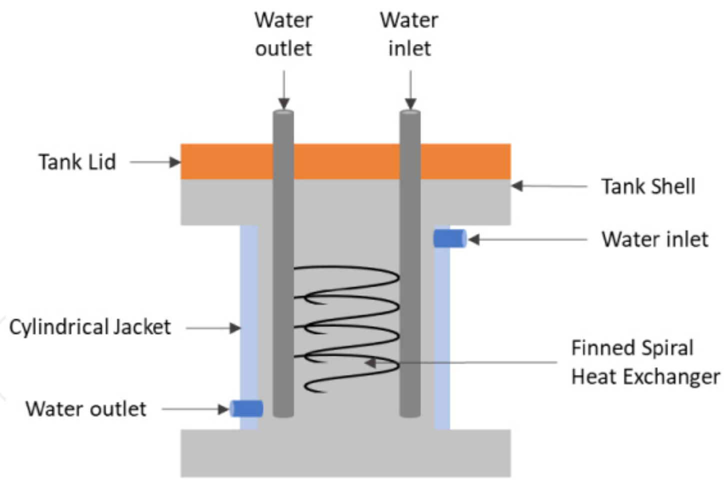

Figure 4. Schematic of the hydride tank used for hydrogen storage.

hydrides, formed through a reversible reaction between gaseous hydrogen and certain metals or alloys, hold great potential for hydrogen storage as solid-state materials. They offer exceptionally high volumetric hydrogen storage density, exceeding 100 gH/L in a given volume of solid-state material. These tanks, employing welded stainless-steel structures, can withstand hydrogen pressures of up to 185 bar at temperatures of 150 degrees and up to 500 ° of short-term heating when not pressurized [34].

Metal hydrides consist of metal atoms forming a host lattice where hydrogen atoms get trapped in interstitial sites. Two fundamental bonding mechanisms have been identified for material-based solid-state hydrogen storage [35]. There are two mechanisms for material-based solid-state hydrogen storage. The first is chemisorption (absorption), where H_2 molecules are dissociated into H_2 atoms and integrated into the material's lattice, allowing for large storage in small volumes under low pressure and ambient temperatures. The second mechanism is physisorption (adsorption), where hydrogen atoms or molecules attach to the material's surface. Preferred material characteristics include high gravimetric and volumetric capacity, reversible hydriding, favorable equilibrium temperature and pressure properties, low sensitivity to gas impurities, and adequate stability within the formed hydride [36]. Hydrogen can be combined with various metals to form hydrides that release hydrogen upon heating [37]. Materials for hydrogen storage fall into two categories: hydrides (hydriding alloys, molecular hydride complexes, amine complexes, and hydrocarbons) and physisorbed high-surface-area materials (carbon fullerenes, nanotubes, metal organic frameworks, and aerogels). The uptake capacity of hydrogen in hydrides depends on temperature, pressure, and alloy composition [38]. Low-temperature hydrides can be found in iron titanium (FeTi), and magnesium-based hydrides (Mg_2Ni) work at a higher temperature [39]. The lifecycle of hydrides is considerably affected by the impurities present in the hydrogen being stored. Research shows [40] that after 500 cycles, a drop in almost 50% of the capacity is noticed; however, cycling pure hydrogen with magnesium hydride enables restoration. Material-based hydrogen storage methods operate at low pressures, and hydrides require additional energy for hydrogen release. The advantage lies in the reversibility of formation and decomposition reactions, allowing hydrides to be decomposed at moderate temperatures, potentially sourced from local and renewable heat sources like solar energy. Economically, this storage approach is cost-effective, with moderate storage vessel costs, low operating and maintenance expenses, and low purchased energy requirements per storage cycle [40].

Both absorption and adsorption methods have their pros and cons. Absorption requires thermal management to supply or remove heat for the reaction of splitting or recombining hydrogen molecules and forming chemical bonds with the material. The ability to recycle or reuse heat is crucial to system efficiency [35]. On the other hand, adsorption faces challenges in finding a light carrier with sufficient bonding sites and the need for low temperatures [41]. Despite these challenges, the advantages of the adsorption method include low operating pressures, inexpensive materials, and a straightforward storage system design. The success of hydrogen as a future fuel heavily relies on the optimal thermal design of materials suitable for reversibility [42].

2.2. Large-scale storage (underground)

The presence of geological formations deep underground covered by several hundred meters of rock allows for the use of high pressures up to 20 MPa. These facilities allow for large storage volumes and capacities, with low investment costs [43]. The principle behind geological hydrogen storage is the injection of hydrogen gas underground and its storage under pressure [44]. This will enable the hydrogen gas to be stored and removed when there is a need for it. Storage of hydrogen gas underground is advantageous because the reservoir has been well documented during the extraction of existing resources, and while it is stored underground, it is safe and secure since they are preserved to be less vulnerable to fire issues, and military and terrorist threats [45].

The underground storage of hydrogen if done properly can also aid in smooth urban planning because it does not affect planning of urban development [3]. Underground storage of hydrogen is also more economical compared to other pressurized composite and steel vessels for hydrogen storage; underground storage of hydrogen has great potential to reduce hydrogen storage costs.

It follows that the general trend seen in research is that a higher volumetric storage density is correlated with a high gravimetric storage density. However, surface hydrogen storage facilities in the form of tanks and pipelines have limited storage and discharge capacities; therefore large-scale storage solutions are realized underground [46]. The benefits of storing hydrogen on a large scale have been realized in engineering practices already, meaning in the future when the use, storage, and distribution of hydrogen is common practice, there will be well-developed set of codes and standards in place [46]. This highlights the many reasons for storing very large quantities of gas underground in geological formations.

The expenses of a large-scale hydrogen storage system can be categorized into three components: construction costs of the storage facility, operational costs of utilities, and maintenance costs [25]. Investment costs are influenced by storage density, with volumetric hydrogen storage density determining storage size and gravimetric hydrogen storage density determining the amount of storage material needed per unit weight of hydrogen stored.

There are limited similarities of hydrogen gas to natural gas, meaning adaptations are required due to the characteristics of hydrogen in high concentrations and under high pressures, especially when it comes to the use of metal pipelines, as hydrogen can cause hydrogen blistering, cracking, and hydrogen embrittlement [47]. This biggest difference can be seen within the permeability index differences between hydrogen and natural gas, suggesting that hydrogen has a permeability index five times higher than that of methane and natural gas [48]. Due to the nature of hydrogen gas, underground storage has been the favored option and there are several options within this concept. There are many advantages to underground storage of hydrogen gas; it is a safe alternative to on-land storage due to being less susceptible to fires and general attacks. Traditional surface tanks require extensive areas to store the same amount of gas as underground storage facilities [48]. The latter have minor surface installations, making integration within the current landscape and infrastructure easier. Economically, underground storage offers cost advantages, as construction expenses are significantly lower for facilities of similar capacities compared to surface installations.

2.2.1. Depleted hydrocarbon reservoirs

Many depleted hydrocarbon fields and reservoirs have been converted into hydrogen storage facilities due to the success of natural gas storage. These structures have been around for long geological time periods, validating the tightness of reservoirs, and the already completed exploration and production phase allows for the parameters to be readily outlined. These reservoirs can be at various depths, optimally up to 2000 m [48]. The reservoir rocks have high porosity and high permeability with inclusion of roof rocks to provide a seal for the deposits. The geology of the reservoir formations is well recognized to have a high capacity for storage. In terms of hydrogen, these fields can hold a similar amount compared to the hydrocarbon that was previously stored. There is a high availability of deposits, and the existing infrastructure can be adapted for specific hydrogen gas storage. Depleted hydrocarbon reservoirs can be found in large capacities; however, their suitability for hydrogen storage is questioned. Despite the remaining natural gas being utilized as cushion gas, the ability for it to mix with pure hydrogen dilutes the hydrogen concentration on output [47].

The literature states that this storage method allows for a maximum of two cycles of injection and withdrawal a year, making it suitable for seasonal storage [49]. Due to the fine matrix of pores in depleted hydrocarbon reservoirs, the regular movement of the gas within causes large flow resistances; therefore minimal cycles at low production rates are more suitable. Other limitations that have been identified are in the reactions that take places within the deposits [46]. There can be some contamination of the hydrogen gas with accumulated trapped hydrocarbon residue, and undesirable reactions producing gases such as hydrogen sulfide (H_2S) and methane (CH_4) causing a loss of hydrogen. From an economic perspective, this is the lowest cost option in terms of underground hydrogen storage as there is no need for exploration and construction. However, there are more costs in the conversion of depleted oil fields than natural gas storage.

2.2.2. *Deep aquifer*

Deep aquifer storage facilities are very similar to hydrocarbon reservoirs; however, they are a layer of water-bearing permeable rock. When converting aquifer storage facilities to suit hydrogen gas, several conditions need to be met (Table 4). For example, the top of the aquifer requires sealing by an impermeable layer of rock; a dome-shaped structure is required to hold the injection of gas in a defined space, and there needs to be adequate pore space with high permeability. Each aquifer is judged on an individual basis to assess the suitability of hydrogen storage. However, the advantage of aquifer storage is that there is no chance of contamination of hydrogen with hydrocarbon residues. These storage installations also vary in depth, however optimally up to 2000 m with high storage capacity [48]. The geological tightness of the structures is initially unknown, which causes a risk of gas leakage, and they only have the current ability for a maximum of two cycles of injection and withdrawal per year [50]. Economically, this storage option is the highest costing in terms of construction and operation due to the amount of exploration and assessment that is required on an individual basis to create suitable storage for hydrogen in its pure form. However, on withdrawal it is highly unlikely that hydrogen will be in its pure form due to residual gas, contaminants, and mixing. Deep aquifer storage facilities have also been recognized in the potential for carbon capture and storage (CCS) within Europe; however, there are no existing examples of this being executed [51].

2.2.3. Salt caverns

Within Europe, there are well-recognized salt cavern formations for the storage of natural gas and future hydrogen storage. In the United Kingdom, there is a fully functioning salt cavern for hydrogen storage in Teesside 350–450 m deep. In the United States, Clemens Dome, Spindletop, and Moss Bluff are all built at a depth of above 800 m. The Teesside salt caverns store 1 million m^3 of pure hydrogen, and in this instance, hydrogen with 96% purity and 4% CO_2. These salt caverns are at

Table 4. Large-scale hydrogen storage overview: geological and man-made [47, 49].

Type	Depleted hydrocarbon reservoirs
Storage media	Reservoir rocks characterized by substantial porosity and permeability, accompanied by intact roof rocks serving as effective seals without any fractures.
Pressure/temperature	The maximum pressure at the site frequently surpasses the initial reservoir pressure, enabling the storage of larger quantities of gas than initially contained in the deposit.
Access	The presence of deposits in natural geological formations with favorable geological and mining conditions provides opportunities for gas storage. Existing infrastructure on the deposit can be modified and utilized for gas storage purposes. Typically, one to two cycles of gas injection and withdrawal occur each year. A limited number of boreholes are needed for gas injection and withdrawal, along with additional observational boreholes for monitoring purposes.
Reuse	Since the early 1990s, depleted oil wells have been utilized for natural gas storage. The social implications associated with the use of existing or purpose-built underground storage structures hold significant importance for the local communities involved.
Advantages	Depleted natural gas deposits offer the lowest storage costs compared to storing gas in oil fields. In addition, underground storage provides enhanced safety measures with reduced susceptibility to fires, leading to lower costs compared to above-surface storage options. Moreover, suitable geological structures for gas storage are widely available across many countries, covering large areas.
Limitations	Converting existing boreholes for hydrogen storage may pose feasibility challenges. The availability of appropriate technology and equipment is crucial for constructing and operating the storage system. The reactivity of hydrogen with liquid hydrocarbons restricts the practicality of utilizing depleted oil fields for storage purposes.

Table 4. (Continued)

Type	**Deep aquifer**
Storage media	Reservoir rocks characterized by substantial porosity and permeability, accompanied by intact roof rocks serving as effective seals without any fractures.
Pressure/temperature	Pressure fluctuations occur during the gas injection and withdrawal processes.
Access	The presence of deep aquifers with well-established favorable geological conditions, typically located in proximity to end users, offers opportunities for gas storage. These aquifers do not have existing infrastructure on the deposits. Typically, one to two cycles of gas injection and withdrawal occur each year. A limited number of boreholes are required for gas injection and withdrawal, along with additional observational boreholes for monitoring purposes.
Advantages	Thus far, there have been no documented instances of exclusively storing pure hydrogen in aquifers; most recorded cases involve a mixture of hydrogen and methane gases, typically in a 50/50 ratio.
Limitations	The feasibility of repurposing existing boreholes for hydrogen storage may present challenges. The availability of appropriate technology and equipment is essential for constructing and operating the storage system. However, it is worth noting that the costs associated with adapting boreholes for hydrogen storage tend to be higher compared to storage in salt caverns or hydrocarbon deposits.
Type	**Salt caverns**
Storage media	Thick salt formations are considered highly suitable for salt cavern storage.
Pressure/temperature	Rock salt exhibits exceptional gas tightness even under high pressures, making it suitable for operations at depths of nearly 2000 m. Operational pressures typically range from 60 to 180 bar. When caverns are located at shallower depths, a smaller volume of cushion gas is required to be permanently present in the cavern. However, reducing the pressure in the cavern leads to compression, limiting the amount of gas that can be injected into it.
Access	The presence of salt deposits with well-established favorable geological and mining conditions provides opportunities for gas storage. These deposits do not have existing infrastructure. There is a potential for multiple cycles of gas injection and withdrawal, ranging up to 10 cycles per year. Typically, one borehole is required for each cavern used for storage.
Limitations	The convergence leading to the compression of the cavern. The presence of adequate technology and equipment for constructing and operating the storage system. The accessibility of water for leaching the cavern. Higher expenses compared to utilizing depleted hydrocarbon fields.

Table 4. (Continued)

Type	Pipes and pipelines
Storage media	Combination, often metal alloys (steel).
Pressure/temperature	Operate typically at 10–20 bar but can reach up to 2 MPa, dependent on size, diameter, and length.
Access	Decommissioned pipelines will have more difficulty being accessed than new pipelines being put in.
Reuse	Decommissioned pipelines are becoming more and more common; however, adaptations are required to transform the metal pipelines into suitable porous media for the control of hydrogen flow; difficult to access as pipelines are buried and costs to remove are high.
Advantages	Pipelines act as storage and transportation methods for gas. The storage of energy through a gas network experiences much less loss (<0.1%) than in a power network (8%). When blended with natural gas, the natural gas leakage rate reduces slightly due to the higher mobility of hydrogen molecules.
Limitations	Material choices and durability; metal pipes can degrade when exposed to hydrogen over long periods, especially when the hydrogen is in high concentrations (20%+) and high pressures. Hydrogen leakage is a limitation due to the permeation rate for hydrogen, as it is four to five times higher than that of methane. Leakage occurs mainly through threads or mechanical joints at a rate thrice higher than methane.

depths of 400 m with a pressure of around 5 MPa. The literature [46, 47] proves that the characteristics of salt caverns as hydrogen storage can vary significantly across individual installations. Salt caverns can be at various depths, optimally up to 1500 m; this depth and the properties associated with salt rock provide a stable tightness of geological formation [48]. Similarly to other underground storage installations, each storage facility requires one borehole for the injection and withdrawal of gas. However, in the case of salt caverns, there is a possibility of multiple cycles of injection and withdrawal of gas per year. Therefore this method of storage can be used for more than seasonal storage [52]. There are many limitations to this storage method; there is a possibility of impurities within the gas caused by undesirable reactions between hydrogen and interbeddings other than rock salt [53]. The literature [54, 55] proves that despite it being undesirable, it is inevitable that impurities occur in underground hydrogen storage. Within the HyUnder Study [56], five European countries were investigated (Figure 5), suggesting that the numbers of salt caverns required for 2050 targets are as follows: Germany = 74, Netherlands = 43, Spain = 24, United Kingdom = 21, and Romania = >1. The storage capacity of individual caverns, located in eligible areas within Europe, is estimated based on thermodynamic considerations and site-specific parameters [57].

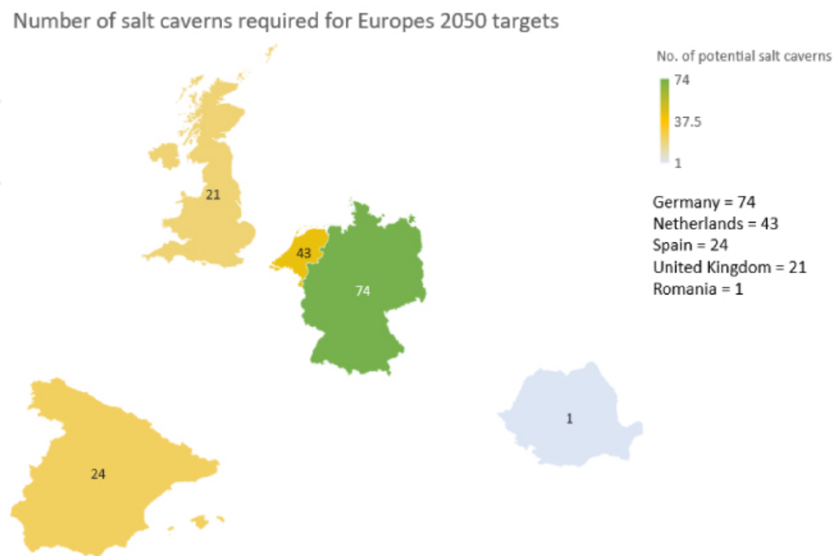

Figure 5. Map showing number of salt caverns required for meeting European 2050 targets.

2.2.4. Pipelines

Understanding the implications of hydrogen on pipeline joints and downstream components within the gas grid is crucial to meet the requirements of gas grid operations through the pipeline distribution network. This includes evaluating valves, regulators, and springs to assess the long-term effects of hydrogen on their functional properties. It may be necessary to replace components with new materials or apply hydrogen-resistant coatings. Standardization of testing and inspection protocols for materials research is essential to evaluate the influence of hydrogen blending on pipeline materials and enable transmission through existing pipelines. Hydrogen embrittlement has a more significant impact on high-pressure transmission networks compared to low-pressure distribution networks.

The use of decommissioned oil and gas assets such as pipeline bundles will create a significant increase in overall storage capacity. Pipeline bundles are an economically attractive solution for high-pressure, high-temperature field development by incorporating advanced design and fabrication techniques. However, issues with pipeline storage can be found in the materials used. Hydrogen does not react well with metal pipelines, causing hydrogen embrittlement and hydrogen-induced cracking and blistering; therefore alternative materials need to be utilized.

Over 75 pipeline bundles are installed in the North Sea and Norwegian sea regions, with the majority installed from Wick, Scotland, with the potential to be included in the UK National Grid HyNTS Programme (Hydrogen in the National Transmission System) [58, 59]. The natural gas network serves as a permanent storage of hydrogen through blending it into natural gas. Pipeline energy storage offers several advantages, with minimal energy loss ($<0.1\%$ compared to 8%) in the gas network. However, using buried pipes for hydrogen storage presents challenges like material durability, hydrogen leaking, and safety concerns. Hydrogen, being odorless and colorless, lacks detectable smell like natural gas, which has an odorant added for safety. Although nontoxic, hydrogen is highly flammable, posing a serious fire risk in surface storage systems. The material durability of metal pipes can degrade over time when exposed to pure hydrogen, leading to the use of carbon steel pipelines with protective coatings to prevent corrosion. The diameter of these pipelines can vary from 5.1 to 152.4 cm, with operating pressures typically between 0.42 and 0.84 MPa, but in specific cases, it can reach up to 13.9 MPa.

3. Challenges, opportunities, and prospective

Hydrogen storage technologies, although promising, have inherent drawbacks, and there are significant challenges in finding a suitable storage system [60]. Table 5 outlines the challenges and opportunities the hydrogen storage developments are facing. The optimal storage medium should enable high energy densities both volumetrically and gravimetrically, rapid fuel uptake and release, operate under room temperatures and atmospheric pressure, ensure safety during use, and achieve balanced cost-effectiveness. For future technology to move to mass production, low-cost manufacturing process, safety and maintenance routines, and the standards that govern the safe use of vessels will need improvements for compressed hydrogen storage technology.

3.1. Compressed gas pressure vessel manufacturing process

The choice of manufacturing process is based on the form and complexity of the product, the tooling and processing costs, and the required properties for the product. Filament windings were originally used in pressure vessel production and chemical and water tanks. Before the development of filament winding, dry wire winding of rocket motors was used; however, this required reinforcement [61]. Several applications are now used in rotor shafts for helicopters, high-pressure pipelines, fuselages for aircrafts, wing sections, and all types of structural applications [62].

Table 5. Summary of opportunities and challenges for hydrogen storage.

Challenges	Opportunities
Safety of high operating pressures	Circular economy prospects in structural design
Poor efficiency	Small/portable storage tanks
Cost challenges	Pipeline blending
Hydrogen embrittlement	Subsea storage
Hydrogen-induced cracking and blistering	Repurposed decommissioned oil and gas assets
	Further research into liquefaction boil-off prevention
	Further research into improving hydrogen embrittlement relief

Filament windings have been the simple base for manufacturing pressure vessels. However, these are the most challenging in terms of design. Pressure vessels with filament-winding composites are used for many engineering applications (excluding military) [63]. The filament-winding process is a high-speed procedure in the construction of tubes and various other round components. Filament winding is a technique to produce reinforced composite materials with great resistive properties, and it is recognized as cost-effective. During the filament-winding process, the fiber is permeated with resin and wrapped on a mandrel with cylindrical shape [64]. The curing is performed at a specific time and temperature as the speed of the horizontal carrier controls fiber orientation [62]. Although the mandrel can be part of the design, the wound composite is removed from the mandrel after curing. In summary, FRCs are developed using a renewable polymer for a starting point, as it has exceptional characteristics preferred in engineering applications because of the low cost, high strength, and low environmental impact [65].

3.2. Materials, design, and manufacturing

Although compressed natural gas storage is a well-established technology, it is widely acknowledged that no single hydrogen storage method fully meets all the criteria set by manufacturers and end users. Enhancements are required in areas such as weight, storage volume efficiency, conformable shapes, system integration, and cost reduction to fulfill these criteria. Consequently, new design methodologies must focus on delivering a higher strength-to-weight ratio, optimized safe structures, high integrity and reliability, improved manufacturing process monitoring, smart fault detection, and versatile shapes (e.g., above 35 MPa). Furthermore, the development of maintenance routines and standards for the safe use of cylinders has not kept pace with the advancements in carbon fiber compressed cylinder storage technology.

In high-pressure applications, vessels rated at 5,000 psi (34.47 MPa) or higher, categorized as Type III and Type IV vessels, are the most feasible choice. Incorporating high-fatigue-resistant FRC materials significantly enhances a pressure vessel's corrosion resistance, overall safety, and service life (extending up to approximately 30 years). However, this improvement comes at a higher cost. Lately, filament windings have been found to be most favored. However, designing the pressure vessels using such a method is difficult, slow, and remains expensive due to sophisticated manufacturing and quality assurance. Therefore, there is a need to develop low-cost mass production methods or more reliable hydrogen tanks capable of meeting future demand.

The design of hydrogen gas compressors can be difficult due to the ability of hydrogen to degrade materials (hydrogen embrittlement and high-temperature hydrogen attack). Hydrogen embrittlement is a phenomenon where hydrogen penetrates metal, resulting in reduced ductility and tensile strength, causing mechanical damage to the material. It causes brittle fractures; these cracks are always intergranular. Certain metals are more susceptible to embrittlement than others, such as high-strength materials. It is assumed that hydrogen embrittlement is caused by hydrogen atoms when they do not combine fully into hydrogen molecules [66]. There are two types of hydrogen embrittlement: internal, which is a result of pre-existing hydrogen already inside the metal; hydrogen environment embrittlement, where hydrogen is from the external environment.

For liquid hydrogen to be stored at critical low temperatures, a number of considerations are required: the changes in mechanical characteristics, expansion and contraction phenomena, and the thermal conduction of various materials. Metallic materials in general decrease in ductility and toughness when the temperature is lowered. When it comes to steel, the toughness drops drastically in a narrow temperature range and becomes brittle.

The Charpy impact test is utilized to assess the brittleness of materials under cold temperatures [67]. The testing method involves breaking materials with a U-shaped notch at the center, and the absorbed energy is calculated by measuring the strength. Tests are conducted at different temperature settings, including submerging the test piece in a bath to lower the temperature. For critical temperatures of liquid hydrogen, insulation is required for the test piece, and the temperature rise during impact testing must be monitored. It should be noted that hydrogen embrittlement susceptibility can only be detected in slow strain tests and not through the Charpy impact test.

The literature suggests that as the temperature decreases, the crystallinity rises, impacting about 50% of the surface at the transition temperature and 100% within the brittleness range [68]. Additional concerns at low temperatures involve potential cold transmission by unaffected metal parts, like stainless steel contraction. To mitigate these issues, appropriate insulation is required to minimize thermal conductivity and account for specific heat at low temperatures.

Liquid hydrogen offers advantages over its gaseous form, as highlighted by [27], stating that transportation of hydrogen is more cost-effective in its liquid state. Boil-off during storage, transportation, and handling of liquid hydrogen can consume up to 40% of its available combustion energy. Spherical designs experience a significant decrease in boil-off rate as the tank size increases, while cylindrical tanks with a constant diameter do not show substantial decreases in evaporation rate with size. The NASA has developed an integrated refrigeration and storage method for space travel, demonstrating the ability to maintain liquid hydrogen with zero boil-off indefinitely [26].

3.3. Structural integrity due to structural impact failure

Composite materials have become essential for large-pressure vessels, but they are vulnerable to damage from impact loading due to their relatively low toughness. A common safety concern in composite overwrapped pressure vessels (COPVs) is the failure caused by low-velocity impacts during operation, repair, and other processes, compromising vessel integrity and leading to hazardous situations. This impact damage can be seen as delamination or cuts in the overwrap or cracks in the resin. There are two different levels of impact damage recognized notably: Level 1 and Level 3 [69]. Level 1 damage is only a slight damage, where a very small area of the fiber glass is frosted, and can be serviced. However, Level 3 damage causes a large area of delamination of fibers, frosting, or other such structural damage, requiring the cylinder to be replaced. Impact testing is utilized to examine dynamic disfigurement and failure methods of materials. Low-velocity affected systems can be characterized using plate-on-plate, pole-on-plate, plate-on rod, and pole-on-pole tests. Two kinds of plate-on-plate tests have been proposed: wave generation tests and thin-layer high-strain-rate tests. The plate-on-plate tests are additionally characterized as nonrecovery or recuperation tests.

Research endeavors aimed at enhancing the resistance of composite structures to impact damage, with a specific focus on mitigating delamination effects [70]. Olsson explained that broadly, the loading experienced by composites can be categorized into low-velocity impacts and high-velocity impacts [71]. The type of impact plays a crucial role in the initiation, propagation, and overall effects of damage. The most critical damage mode affecting the burst strength of COPVs is fiber damage, while damage caused by delamination does not significantly impact the burst pressure

[72]. Research on thick epoxy/graphite COPVs, specifically focusing on impact-induced damages concluded that surface fiber damage, particularly in pressure vessels with hoop winding on the outer layer, is the main contributing factor leading to a decline in the burst strength of the pressure vessel [73].

Drop weight impact test is the most common test for composite materials. Studies show that the damage resulting from the drop weight test is divided into clearly visible impact damage and barely visible impact damage [74]. To perform the test, a mass is released from the desired height to impact the sample, where the machine can be noninstrumented or instrumented. The spread of damage caused by repetitive low-velocity impact (drop weight or ballistic impact) is a severe issue in many composite materials [75]. Furthermore, several impacts may occur during the fabrication, maintenance processes, and operation. In addition, damage from the low-velocity impact is not easily detected by the naked eye. The study on impact-related issues highlights that the primary cause of the decline in burst strength in thick graphite/epoxy composite vessels is external fiber damage, especially in pressure vessels with hoop winding on the outer layer. This is due to impact-related issues [62, 76]. Further investigation into the effects of impactor shape, size, and internal pressure revealed that the key factor leading to reduced burst pressure is fiber damage within the hoop layers. Additionally, it was determined that compressive stress-induced buckling is responsible for the occurrence of fiber damage.

Low-velocity and reduced energy impact tests were conducted on CFRP circular laminated plates to investigate the impact of sampling dimensions and boundary constraints on dynamic behavior and material damages [77]. Two different diameters and constraints were studied. Numerical simulations of the impact response using a finite element (FE) program were compared to experimental results [78]. The examinations revealed that both dimensions and boundary conditions significantly influenced the response and damages, with greater target stiffness resulting in better energy absorption and more extensive delamination [63].

COPVs can experience various types of low-velocity impacts during their production, operation, and maintenance processes. Consequently, assessing the residual burst pressure becomes crucial to ensure the safety of COPVs. It is essential to consider the impact damage results during the design phase and develop an efficient analysis system to anticipate both the impact damage and the recurring burst stress of COPVs [79]. In a study involving graphite/epoxy bent cylindrical panels, an impact machine capable of measuring load was used to impact the center of the panels. Load, deflection, and stress were measured over time for six symmetrical lay-up configurations, using impact forces ranging from 0.5 to 4.5 ft-lb. Damages were observed in all panels at specific impact forces. The extent and location of the damages were determined through C-scans and optical microscopy of panel samples. Random samples indicated that both delamination and transverse splitting contributed to internal damage.

To predict panel deflections and stresses, an internal nonlinear FE code was employed. The analysis yielded accurate results in predicting the deflection of [0/90] 3s panels and indicated the presence of transverse failure stresses in the central area of the panel. The deflections indicated that the panel boundary exhibited characteristics between simple supported and clamped conditions, with satisfactory agreement achieved when considering hinged support at each edge [80]. Authors studied a damage model to investigate intraluminal damages [81]. The Hashin criteria were used to predict composite damage, and the cohesive area model considered delamination. The initial damage significantly reduced the rigidity of the cylinder, and the damage gradually spread until reaching the time of maximum deflection.

Composite tanks for hydrogen storage have also been found to have an extensive application in the oil and gas industry as they exhibit excellent fatigue characteristics and good resistance to extreme temperatures and wear [19]. These composite tanks have been tailored to meet specific applications, which have greater advantages such as high axial strength and stiffness, low thermal conductivity, and low coefficient of thermal expansion.

A numerical analysis was conducted for Type III tanks, which is a filament-wound pressure vessel overwrapped with metal liners exhibiting plastic behavior [82]. The results from this research showed that there is a remarkable drop in the principal axis by the metallic liner in both hoop and helical wound layers of the fiber epoxy composite. Alternative studies focused on the possible variations in winding angles and predicted the behavior of filament-wound structures, which included continuous change in fiber angles over the dome area by three-dimensional FE methods [83]. The experimental results obtained by the strain gages fixed to the outer side of the tank matched the FE results. In the study focused on creating a new generation of filament-wound composite pressure vessels, incorporating an HDPE liner and thermosetting resin as the matrix, researchers identified failures in specific cross-ply internal layers [84]. Numerical analyses were also conducted on Type IV tanks, revealing that modifying the hoop winding angle in various sections could lead to an approximate 5% reduction in composite use [85]. The studies also indicated that the required composite weight to meet design requirements increases with the amount of stored hydrogen. Implementing an end cap was found to reduce the thickness of the helical layers, resulting in approximately 10% reduction in composite weight.

Additionally, the study focuses on a thermomechanical model of Type IV hydrogen high-pressure storage vessels, investigating the effects of dome thickness, thermal dependencies of mechanical and thermal properties, and damage analysis. The research analyzes the vessel's behavior, considering the influence of damage and temperature through isothermal calculations at different temperature levels [86]. The study observed variations in stress distribution when considering temperature gradients, with the insulation liner being affected by increasing temperatures.

Furthermore, the behavior of composite pressure vessels made from linear low-density polyethylene and HDPE under burst testing was investigated [87]. Based on burst pressure, a combination of FE analysis and experimental methods determined the required vessel thickness and appropriate stacking sequences. However, SEM analysis revealed that the composite maintained its dimensional integrity fully [88].

3.4. Standards and regulations of structural design

Unlike natural gas, there are currently not many standards and regulations for the structural design of gaseous hydrogen storage tanks. There are a number of standards for storage, transportation, and general hydrogen developments published by the International Organization for Standardization (ISO), Compressed Gas Association (CGA), National Fire Protection Association (NFPA), American Society of Mechanical Engineers (ASME), American National Standards Institute (ANSI), Standardization Administration of China (SAC), European Committee for Standardization (CEN), and Japanese Industrial Standards Committee (JISC) as seen in Table 6 [34]. These cover general design and safety, receptacles, pipelines, and hydrogen embrittlement. There are significantly more standards surrounding hydrogen embrittlement than any other aspects of hydrogen storage vessels.

Initial inspections and testing are completed at the time of manufacture, and it is the responsibility of the manufacturing organization to comply with the applicable design standards. This process is conducted under the supervision of a notified body chosen by the manufacturer. Pre-fill inspections take place at dedicated filling centers, where skilled personnel follow appropriate procedures using specialized equipment. After the initial inspection is successfully completed, cylinders are authorized for filling and transportation according to the specified period outlined in the inspection protocols.

A series of impact experiments or drop tests need to be performed to test the ability of vessels to withstand internal and external loads, as in the Standard

Table 6. A brief overview of ISO and BS Standards available and under development in 2024.

Number of standards	Title	Status	Review date	Source
EN 10229:2000	Evaluation of resistance of steel products to hydrogen-induced cracking	Published	Under review in 2023	[89]
EN ISO 11114-4:2017	Transportable gas cylinders—Compatibility of cylinder and valve materials with gas contents—Part 4: Test methods for selecting steels resistant to hydrogen embrittlement	Published	Under review in 2023	[89]
EN ISO 15330:1999	Fasteners—Preloading test for the detection of hydrogen embrittlement—parallel bearing surface method	Published	Reviewed in 2012	[89]
ISO 10587:2000	Metallic and other inorganic coatings—Test for residual embrittlement in both metallic coated and uncoated externally threaded articles and rods—Inclined wedge method	Published	Under review in 2025	[89]
ISO 11114-4:2017	Transportable gas cylinders—Compatibility of cylinder and valve materials with gas contents—Part 4: Test methods for selecting steels resistant to hydrogen embrittlement	Published	Under review in 2023	[89]
ISO 11623:2015	Gas cylinders—Composite construction—Periodic inspection and testing	Published	Will be replaced by ISO/FDIS 11623	[89]
ISO 15330:1999	Fasteners—Preloading test for the detection of hydrogen embrittlement—parallel bearing surface method	Published	Reviewed in 2017	[89]

Table 6. (Continued)

Number of standards	Title	Status	Review date	Source
ISO 16111:2018	Transportable gas storage devices—hydrogen absorbed in reversible metal hydride	Published	Under review in 2023	[89]
ISO 16573-1:2020	Steel—Measurement method for the evaluation of hydrogen embrittlement resistance of high strength steels—Part 1: constant load test	Published	Under review in 2025	[89]
ISO 19881:2018	Gaseous hydrogen—Land vehicle fuel containers	Published	Will be replaced by ISO/AWI 19881	[89]
ISO 24431:2016	Gas cylinders—Seamless, welded and composite cylinders for compressed and liquefied gases (excluding acetylene)—Inspection at time of filling	Published	Reviewed in 2022	[89]
ISO 2626:1973	Copper—Hydrogen embrittlement test	Published	Reviewed in 2019	[89]
ISO 7539-11:2013	Corrosion of metals and alloys—Stress corrosion testing—Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking	Published	Reviewed in 2018	[89]
ISO 9587:2007	Metallic and other inorganic coatings—Pre-treatment of iron or steel to reduce the risk of hydrogen embrittlement	Published	Will be replaced by ISO/WD 24251-1	[89]
ISO 9588:2007	Metallic and other inorganic coatings—Post-coating treatments of iron or steel to reduce the risk of hydrogen embrittlement	Published	Will be replaced by ISO/WD 24251-1	[89]
ISO/AWI 19881	Gaseous hydrogen—Land vehicle fuel containers	Under development		[89]

Table 6. (Continued)

Number of standards	Title	Status	Review date	Source
ISO/AWI TR 15916	Basic considerations for the safety of hydrogen systems	Under development		[89]
ISO/AWI TR 19884-2	Gaseous Hydrogen—Cylinders and tubes for stationary storage—Part 2: Material test data of class A materials (steels and aluminum alloys) compatible to hydrogen service	Under development		[89]
ISO/AWI TR 19884-3	Gaseous Hydrogen—Cylinders and tubes for stationary storage—Part 3: Pressure cycle test data to demonstrate shallow pressure cycle estimation methods	Under development		[89]
ISO/CD 19884-1	Gaseous hydrogen—Cylinders and tubes for stationary storage—Part 1: General Requirements	Under development		[89]
ISO/FDIS 11623	Gas cylinders—Composite cylinders and tubes—Periodic inspection and testing	Under development		[89]
ISO/TR 15916:2015	Basic considerations for the safety of hydrogen systems	Published	Will be replaced by ISO/AWI TR 15916	[89]
ISO/TR 20491:2019	Fasteners—Fundamentals of hydrogen embrittlement in steel fasteners	Published	Under review in 2024	[89]
ISO/TS 10839:2022	Polyethylene pipes and fittings for the supply of gaseous fuels—code of practice for design, handling and installation	Published	Under review in 2027	[89]
ISO/WD 24251-1	Prevention of hydrogen assisted brittle fracture of high-strength steel components—Part 1: Fundamentals and measures	Under development		[89]
BS EN 17533:2020	Gaseous hydrogen. Cylinders and tubes for stationary storage	Published	Under review in 2025	[90]

Table 6. (Continued)

Number of standards	Title	Status	Review date	Source
BS EN 2831:1993	Hydrogen embrittlement of steels. Test by slow bending	Published		[90]
BS EN 2832:1993	Hydrogen embrittlement of steels. Notched specimen test	Published		[90]
BS ISO 14687:2019	Hydrogen fuel quality. Product specification	Published	Under review in 2024	[90]
BS ISO 26142:2010	Hydrogen detection apparatus. Stationary applications	Published		[90]

EN 14427 [91]. Additionally, ISO 11119-3 covers the construction of composite gas cylinders in part three of the standard specification of cylinders, and test methods such as burst test and drop test are listed. The EN 12245 standard is applicable for the transportation of fully wrapped composite cylinders and can be employed both numerically (using advanced 3D FE modeling) [90] and for experiments on the low-velocity impact of the pressure vessel (filament-wound) manufactured by winding glass fiber with vinyl ester resin over a polyethylene liner [91]. The ISO 11439:2013 standard focuses on cylinder types I, II, III, and IV, accounting for the high pressure when storing natural gas for automotive vehicles. Moreover, the standard includes cylinders made of steel (except for stainless), aluminum alloy, or even nonmetallic cylinders and different designs for a specific servicing condition (ISO 11439:2013–2018).

3.5. Safety risks due to high operating pressures

It is recommended that high operating pressures should be limited to −235 °C and operating pressures should be limited to values less than 5 MPa for cryogenic temperatures or elevated temperatures (up to −235 °C) [92]. The operating pressure should be reduced to 35 MPa for room temperature applications. With higher pressure comes higher safety risks, and the safety of these pressurized cylinders can be a concern in highly populated areas. Highly pressurized hydrogen does not react well with oxygen at ambient pressures and temperatures, causing unwanted reactions and ignition. With increased pressure, the likelihood of leaks is higher, and the ranges of flammability widen. Hydrogen gas is odorless; therefore sensors are required to detect leakages. The safety of high operating pressures has also been linked to wide flammability and sensitivity to ignition and detonation [93].

The rupture of the laminate leads to the burst effect on a composite tank, where the internal pressure and extra loads predominate. The most critical failure mechanism in burst effect is the rupture of the laminate [94]. One of the main issues that a composite pressure vessel can face is the risk of hydrogen embrittlement of steel due to premature cracking. It can occur because of the hydrogen atoms' dissolution and trap. Consequently, the risk of vessel burst is high [15].

Researchers developed a specific continuum damage mechanics model to simulate the burst behavior of hyperbaric pressure vessels, utilizing the fixed directions damage approach [95]. This model links the damage directions to the composite orthotropic axes through tensor function representation theory. Moreover, the same methodology allowed for the prediction of burst pressure and pressure mode in Type IV pressure vessels [95].

Additionally, they conducted experiments to analyze the burst failure of filament-wound pressure vessels made of T800 graphite/epoxy. By using a degenerated finite shell element that considered the winding angle variation and thickness along the meridional line of the cylinder, they successfully predicted the vessel's damage propagation under applied load. The experimental burst pressure measurement aligned with the theoretical approach [96].

3.6. Subsea storage and pipeline blending

The use of large hydrogen storage systems submerged underwater has the potential to address the gap between renewable energy production and intermittent energy supply. There is a significant demand for large-scale storage methods suitable for pure hydrogen, and the utilization of composite materials offers the possibility of storing substantial amounts of hydrogen for varying durations. Submerging the composite vessels below sea level allows energy storage close or even connected to the renewable energy source powering electrolysis. Subsea storage solutions allow for the efficiency and pressure of the tank to be adapted to the different depths of water.

Blending hydrogen into the natural gas pipeline network presents an opportunity to advance the adoption of hydrogen as a clean energy source worldwide [97]. However, this approach also brings challenges, notably in material selection for future pipelines due to hydrogen embrittlement in the current steel pipeline network, which hinders the increase in the ratio of natural gas to hydrogen [98]. There is an opportunity for demonstration projects of large-scale hydrogen pipelines at high pressures as existing steel pipeline networks may already suffer from stress corrosion, poor quality welds, and mechanical damage, making the conditions unsuitable for hydrogen. There is also an opportunity to investigate the behavior of varied concentrations of hydrogen–methane mixture under different conditions, such as high/low pressure and temperature [99].

3.7. Efficiency, cost, and circular economy prospects in structural design

The US Department of Energy (DOE)'s study on hydrogen and fuel cells, noted that there is yet to be a method of energy conversion step, from production, storage, and utilization [100]. The energy required to compress hydrogen to 700 bar and deliver it to a vehicle can vary from 5% to 20% of the hydrogen's lower heating value, while PEM fuel cells achieve an efficiency of around 60%. It is suggested that hydrogen demands almost as much energy to produce as it delivers, with an efficiency percentage of approximately 60%. Nevertheless, hydrogen can efficiently store large amounts, increasing its density.

The cost of large-scale storage vessels is a topic of significant discussion, with particular attention on the expenses arising from the substantial amount of robust materials necessary for the structure [101]. Currently, researchers are actively involved in developing cost-effective carbon fiber solutions that can meet the essential stress, strain, and safety criteria for high-pressure storage tanks. The key to successful implementation lies in adhering to thickness limitations for the tank to achieve the desired volumetric capacity objectives. The literature proves that a circular approach has been taken on board in several hydrogen storage systems, with the reuse of underground hydrocarbon storage and the repurposing of buried pipelines to ensure suitability for hydrogen [102]. However, there is little to no literature on the end of life for hydrogen storage. Designing products for end-of-life scenarios is vital to facilitate material recovery and reuse, aiming to minimize waste generation [103].

4. Conclusion

With the increasing demand for hydrogen, it is important that large-scale storage develops. The literature shows that there are numerous types of underground storage methods to store hydrogen. Adapting previous underground gas storage systems has the lowest costs due to the lack of exploration and construction needed. However, man-made salt caverns allow for a significantly higher number of cycles of removing hydrogen a year, allowing for seasonal storage. Salt caverns are also a popular choice in Europe, with the United Kingdom storing 1 million m^3 of pure hydrogen. In terms of surface hydrogen storage, the use of liquefied hydrogen is the storage and transportation in cryogenic tanks. However, there are issues with evaporation rates.

In conclusion, the existing literature has highlighted the significant impact of composite damages on the behavior and residual strength of composite pressure vessels. These damages, including fiber and matrix fractures, as well as delamination, should be duly considered in impact examinations. The enhancement of glass fibers to composite materials increases the tensile strength, chemical resistance, and insulating properties of the composite pressure vessel. Moreover, the addition of polymer-based resins raises toughness as well as tightness of the composite pressure vessel. There are many issues demonstrated within the literature for hydrogen storage, a main one being hydrogen embrittlement of storage vessel materials. This becomes more of an issue with the use of cryogenic tanks due to the low temperatures affecting the ductility and toughness of metallic materials.

Author's contribution

Reynolds, Jemma: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.
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Njuguna, James: Writing – original draft, review & editing, Visualization, Supervision, Project administration, Data curation, Conceptualization, Funding acquisition.

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Abbreviations

CCS	carbon capture and storage
PEM	proton exchange membrane
HDPE	high-density polyethylene
CFRP	carbon-fiber-reinforced polymer
COPV	composite overwrapped pressure vessel

FRC	fiber-reinforced composite tank
FE	finite element
SEM	scanning electron microscopy

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