Advanced Energy Conversion Materials
https://ojs.wiserpub.com/index.php/AECM/

UNIVERSAL WISER PUBLISHER

Review

Hydrogen: Safety, Storage, and Transportation, Perspectives, and Measures

Mubbashar Mehmood[1], **Ali O. M. Maka**[2*]

[1]Department of Mechanical Engineering, School of Engineering and Physical Sciences, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, United Kingdom
[2]Libyan Centre for Desert Research and Development of Desert Communities, Murzuq, Libya
E-mail: Ali_makh@lcdrd.ly

Received: 18 March 2025; **Revised:** 29 May 2025; **Accepted:** 4 June 2025

Abstract: Reducing greenhouse gas emissions is a target for many industries to achieve the United Nations Sustainable Development Goals' energy objectives and to reach Net Zero. Hydrogen has been identified as a potential energy carrier with almost zero emissions. However, there are challenges in safety during the storage and transportation of hydrogen. This paper provides an insight into various storage technologies and transportation methods, along with their limitations and potential applications. Highly compressed hydrogen requires high-pressure storage tanks that necessitate special materials and enhanced safety measures to prevent leakage or explosion. Liquid hydrogen requires cryogenic temperatures (-253.0 °C) and requires super-insulated tanks to minimise heat loss and reduce the boil-off ratio. Currently, the most viable solution for storing hydrogen safely is the absorption process, which utilizes Metal Hydride (MH) tanks. In addition to transporting hydrogen using tanks and cylinders, it can also be transported via pipelines. API X65 material can be used to transport hydrogen in the subsea. However, more research is required on the material for safely storing hydrogen in cylinders and innovative sensors to detect any leakage immediately.

***Keywords*:** safety of hydrogen, hydrogen storage, hydrogen transport, sustainable energy

Abbreviations

CH_2	Compressed Hydrogen Gas
LH_2	Liquid Hydrogen
MH	Metal Hydrides
MgH_2	Magnesium Hydride
$TiMn_2$	Titanium Manganese
TiFe	Titanium Iron
$LaNi_5$	Lanthanum Nickel

DOI: https://doi.org/10.37256/aecm.6220256783

1. Introduction

The global energy crisis is causing an imbalance between demand and supply. There has been a surge in energy costs in the post-pandemic era in Europe [1]. Moreover, we must reduce our reliance on fossil fuels to reduce our carbon footprint. The world is shifting towards green and sustainable energy resources to meet demand, which may help mitigate climate change and achieve net zero by 2050 [2]. Hydrogen is a key element in achieving these targets and a sustainable alternative energy resource. Hence, many decarbonization attempts include the hydrogen industry as an essential to attaining net-zero emissions goals [3-6].

John Bockris introduced the concept of the hydrogen economy in 1972 [7]. Hydrogen is the first element in the periodic table, making it the simplest and lightest element. It is the most abundant element, having 75% of the universe's mass. At room temperature, this is a colourless, odourless substance with a density $1/14^{th}$ that of air, making it disperse rapidly when released [7]. Due to its clean-burning nature, non-toxic properties, and ability to quickly disperse in case of leaks, it is safer than current fossil fuels [7]. Its production through electrolysis from renewable sources can significantly reduce greenhouse gas emissions, positioning hydrogen as a key player in providing clean and green energy, while also enhancing energy security [7].

Since hydrogen is environmentally valuable and sustainable, utilizing it as a substitute fuel is an efficient approach to bring about this shift. However, the primary barriers to its usage continue to be the large-scale production of hydrogen and efficient H_2 distribution and storage [8]. It is important to note that hydrogen is non-poisonous and creates no pollution [9], but it is highly combustible and notably has a higher flame propagation rate than other fuels [10]. It takes 80-90 percent less time to burn as compared to other fuels [11]. So, there are some limitations in its storage and transportation techniques, and there is a need for safer, more efficient, and cost-effective methods for hydrogen deployment on a large scale.

Figure 1 shows an overview of hydrogen production from renewable energy resources (wind and solar photovoltaic), ways of storing it in the form of compressed gas, Liquid Hydrogen (LH_2), in metal hydride tanks, in the metal organic framework (MOF), and in salt caverns [12]. Storage of hydrogen in the form of a compressed gas (CH_2) needs high pressure, while Liquefaction of Hydrogen (LH_2) at a cryogenic temperature (-253 °C) also requires a large amount of energy. Absorption-based storage using Metal-Organic Frameworks (MOFs) has gained significant interest in recent years for hydrogen storage. MOFs are composed of metal ions or inorganic clusters coordinated with organic ligands. However, their practical application is limited by the requirement for extremely low absorption temperatures (around-196 °C) [13-14].

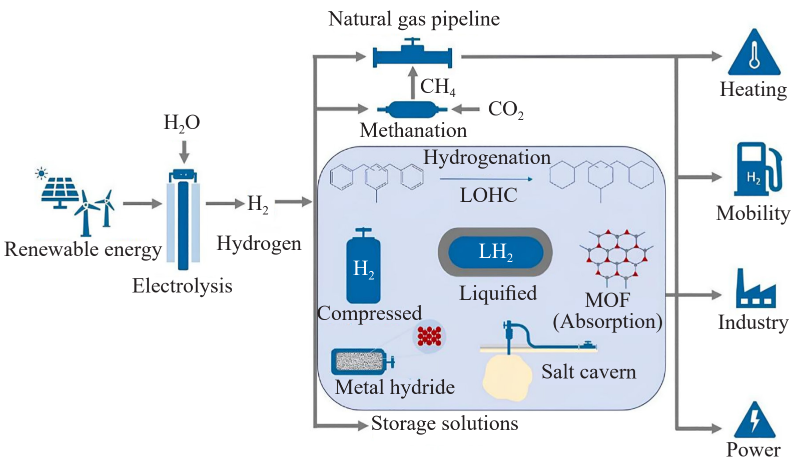

Figure 1. Overview of hydrogen production using electrolysis, storage, and industrial applications [12]

Another method of hydrogen storage involves chemical reactions with Liquid Organic Hydrogen Ccarriers (LOHCs), although releasing the hydrogen typically demands high temperatures [14]. For large-scale storage, salt caverns and natural gas pipelines are viable options. In the case of pipelines, hydrogen can be injected directly or stored as methane after undergoing methanation. These pipelines also offer the added benefit of facilitating hydrogen/natural gas transportation [12]. Another technology to store hydrogen is using Metal Hydrides (MH), which uses an absorption and desorption process. The benefits of this method are high energy densities and increased safety [15-16]. Figure 1 also shows practical applications of hydrogen in heating, transport, industry, and the energy sector [12].

These technologies for producing hydrogen are developing quickly, however, industry challenges need careful consideration. This paper critically analyses the environmental characteristics of different techniques for safely storing and transporting hydrogen. For this review work, the data has been searched using Google Scholar, ScienceDirect, and Scopus, mainly for papers published after 2020. However, there are some papers from previous years to understand a concept. Its significance is highlighted in the hydrogen storage and processing challenges; those factors are vital to considering the breakthrough of the technologies. The paper is organized as follows: Section 1 presents an introduction; Section 2 summarises the storage techniques and challenges, which include compressed hydrogen tanks, liquid hydrogen tanks and metal hydride tanks. Challenges related to CH_2, LH_2, and the MH are given in Sections 2.1, 2.2, and 2.3, respectively. The transportation of hydrogen is highlighted in Section 3. Section 4 discusses the safety measures of hydrogen at various stages, and Section 5 provides the conclusion.

2. Storage techniques and challenges

The natural gas reforming process used to produce hydrogen does not seem environmentally clean. The hydrogen economy depends on the non-fossil fuel techniques of producing hydrogen, which is mostly based on wind/solar energy utilisation, and currently, significant development is taking place to improve production and storage [8].

Figure 2 gives us a summary of storing hydrogen in different ways. It can be broadly categorized as (i) compressed hydrogen storage, either in the form of vessels or underground/geological storage, (ii) liquid hydrogen, (iii) hydrogen stored through the absorption process in the metal hydride tanks. Hydrogen can be stored in the tanks at ambient temperature, but at high pressure from 350 to 700 bar. Hydrogen liquefaction requires cryogenic temperatures (-253 °C). Hydrogen storage in the metal hydride tanks is possible using the absorption and desorption process [17]. Commonly used metal hydrides are Magnesium Hydride (MgH_2), Titanium Iron (TiFe), Titanium Manganese ($TiMn_2$), and Lanthanum Nickel ($LaNi_5$) [12]. Amongst these, MgH_2 is the most economical and readily available metal hydride with the added advantage of recyclability [12]. More details about the metal hydride storage tanks are given in Section 2.3.

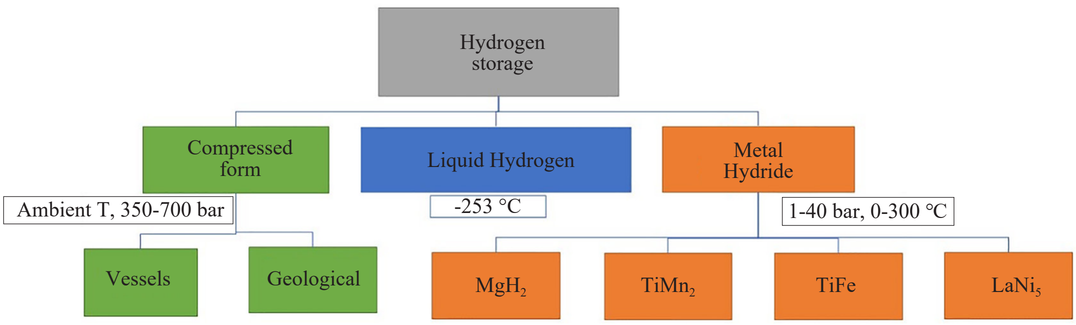

Figure 2. Methods of storing hydrogen in different forms

2.1 *Compressed hydrogen tanks*

Hydrogen can be stored by compressing it with a pressure of 350 to 700 bar. One of the potential applications of these compressed Hydrogen cylinders is in Fuel Cell Vehicles (HFCVs). Through a chemical reaction, hydrogen reacts with oxygen and generates electricity to run the electric motor [18]. Using compressed hydrogen cylinders, by 2020, there were about 30 k Fuel Cell Vehicles (FCV) with only 400 hydrogen stations worldwide. The plan is to have two to five million more FCVs, and thousands of fuel stations are required by 2030 to be filled with hydrogen in compressed form [19].

Storing hydrogen at high pressure also increases the temperature of the vessel. To ensure the tank's integrity, it is important to monitor the temperature variations [20]. The process by which hydrogen atoms or molecules diffuse or absorb into the material's surface is called hydrogen permeation. The selection of the material for hydrogen tanks is critical, and the phenomenon of hydrogen permeation must be considered [21]. Moreover, materials having high strength can result in having more weight in the tank, which will reduce the efficiency of H_2-powered automobiles [22]. Hydrogen has a small energy density by volume, so big tanks are required to store a good amount of hydrogen; this impacts the design, efficiency, and mileage range of automobiles running on hydrogen [23]. High-pressure tanks are costly, especially when made from advanced composites [24]. Since hydrogen is inflammable, hydrogen tanks need periodic inspections and maintenance to ensure safety, which will add to the cost [25].

Type III and Type IV are commercially available hydrogen tanks that work under a nominal pressure of 70 MPa. The thermal behaviour of these tanks during the cycling process (fast filling, holding, and emptying) has been monitored, and a correlation was found between internal and external temperatures at different cycling conditions. As shown in Figure 3, 8 thermocouples have been placed inside the tank at different locations with various Resistance Temperature Detectors (RTD) for outer surface temperature monitoring [16]. T1 to T6 are inside temperatures of tanks at different locations, whereas T7 is the front temperature and T8 is the rear temperature of the tank.

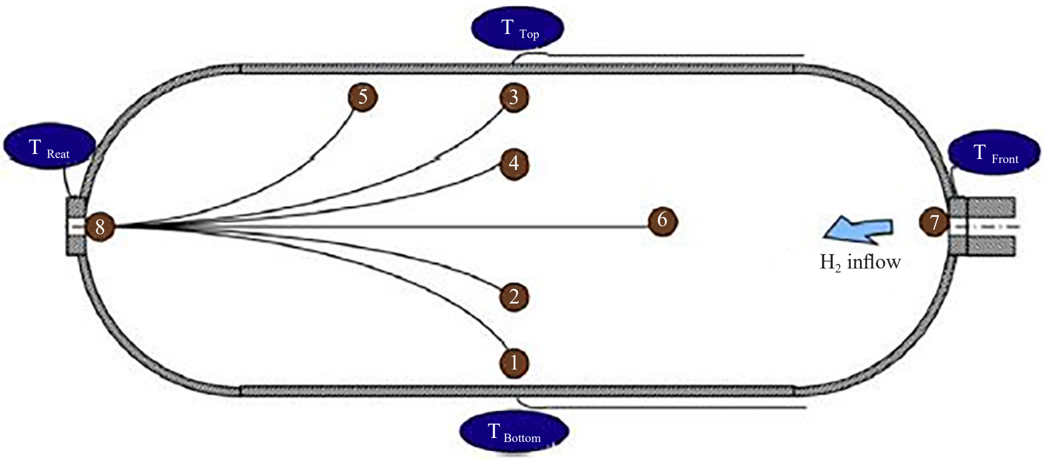

Figure 3. Schematic of temperature measurement in the tested tanks [16]

Figure 4 shows the temperature and pressure variations of three tested tanks along with the time it takes for filling, holding and emptying (Type IV 19-liter, Type IV 29-liter, and Type III 40-liter). The filling of all tanks on average takes 4-5 minutes, whereas the sum-up of holding and emptying time is 50 to 55 minutes. Furthermore, Figure 4 shows that the total time (filling, holding, and emptying) for Type IV-19 liter is 54 minutes, Type IV-29 liter is 60 minutes, and Type III-40 liter is 57 minutes [16].

There is a jump in the temperature during the filling phase as visible in Figure 4, then a decrease in the holding and emptying phase. The tank's average gas temperature has been taken as the average of TC1 to TC6. The temperature of TC7 and TC8 has not been considered for calculation since they are influenced by the outside boundary. The average temperature during the filling phase is $\Delta T_{Av} = T_{Av}$ (end of filling) − T_{Av} (start of filling). It has been observed that ΔT_{Av} for Type IV gas cylinders is higher than ΔT_{Av} for type III cylinders [16]. It is to be noted that the average temperature for a type IV 29-liter tank is touching 90 °C, which is higher than the maximum temperature allowed under the International Organization for Standardization (ISO) safety code (85 °C). This higher average temperature for type IV cylinders is a safety concern, and hence, additional efforts are required to guarantee the safety of the cylinders [26].

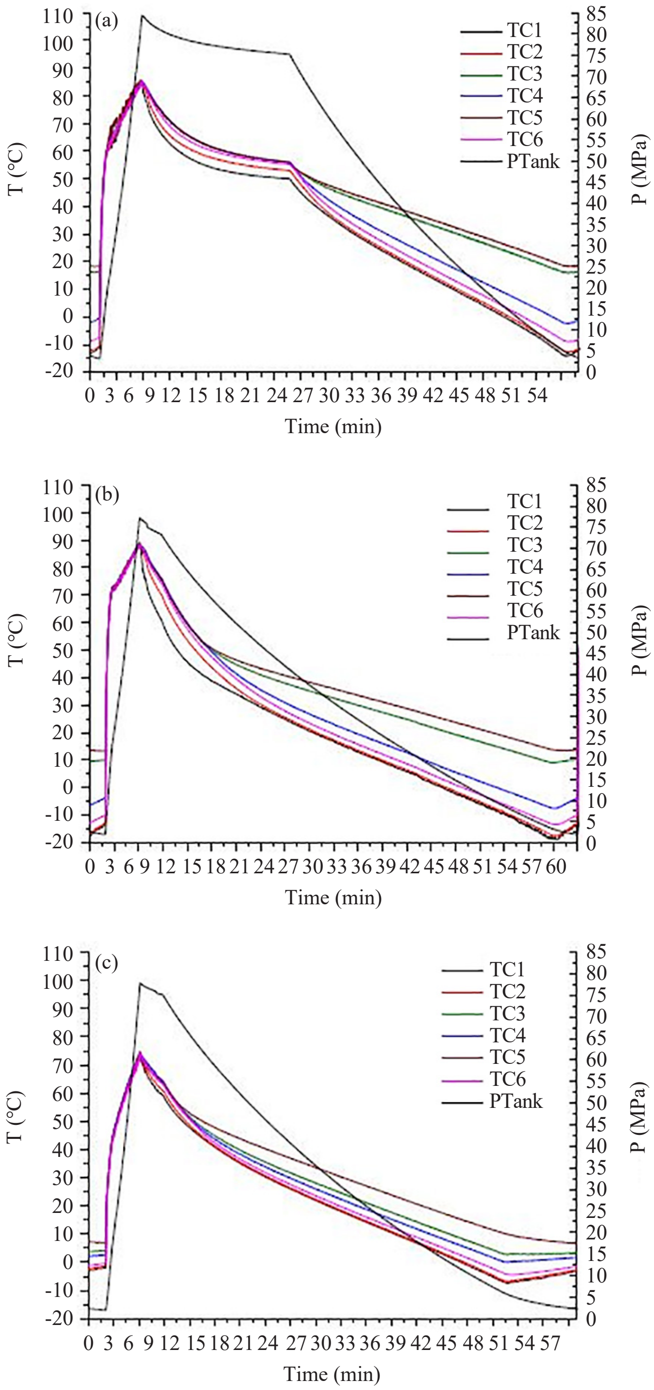

Figure 4. Pressure and temperature variations of (a) Type IV19 liter. (b) Type IV 29 liter. (c) Type III 40 liter hydrogen storage tank during the emptying phase [16]

For compressed hydrogen gas, an important thing to consider is the cost of a compressor. If we reduce the operating pressure, the cost of hydrogen storage in a compressed tank can be reduced. Modeling of hydrogen compressors is also a dynamic component. Its modeling can also be expressed as:

$$\text{Power} = Z\dot{m}RT_n\left(\frac{1}{\eta}\right)\left(\frac{k}{k-1}\right)\left(\left(\frac{P_{\text{outlet}}}{P_{\text{inlet}}}\right)\left(\frac{k-1}{nk}\right)-1\right). \tag{1}$$

Where the power is in KJ/s and is dependent on a mean compressibility factor during the entire compression period (Z), $\dot{m}$ is the mass flow rate in kg-mole/s, R is the universal gas constant, and T is the inlet gas temperature in Kelvin. The power demand is for the calculation of the required compression power over several stages. The value of Z is set to 1.07, inlet gas temperature (T) is constant with a value of 15 °C. η is set to be 0.89 and the ratio of specific heats (k) is 1.4. However, the compressor's inlet and outlet discharge pressure are denoted by P_{inlet} and P_{outlet} [27].

2.1.1 *Geological storage*

Hydrogen can be stored in depleted oil systems since there is already available space due to the depletion of natural resources [28]. One gigantic, depleted gas field can store enough H_2 that may suffice for the World. For example, the Lemen field, North Sea, has a storage capacity of 833 TWh, which is sufficient to fulfill the entire seasonal demand [29]. Moreover, hydrogen can be stored at high pressure in salt caverns, providing a big storage capacity. There is less risk of leakage using this method. Hydrogen can also be stored in aquifers, which are porous rocks containing water. H_2 can be infused into porous layers with overlying caprock acting as a seal to prevent leakage. This is a less common method than hydrogen storage in salt caverns and depleted reservoirs [29].

2.2 *Liquid hydrogen (LH_2) storage*

LH_2 storage is a more secure and compact technique of hydrogen storage. This method can overcome the drawbacks of compressed hydrogen storage technology [30]. To be in a liquid state, hydrogen must be cooled to 20.3 K (-253.0 °C) and pressurized to 250-350 atm [5]. Super-insulated cryogenic pressure tanks are required to minimize heat loss and increase the vessel's performance [7]. Another important parameter to be considered for the efficiency of liquid hydrogen transport is the Boil-Off Ratio (BOR), which varies with the storage capacity [31]. The term boil-off ratio is associated with the gases stored in liquid form, such as liquid hydrogen, liquid oxygen, etc. It can be defined as the percentage of the total volume of the liquid that evaporates per unit of time. It determines the storage system's efficiency in retaining the stored substance's liquid state [32]. Equation 2 describes the Boil-off ratio as given below:

$$\text{BoR} = \left(\frac{\text{Volume of liquid evaporated per unit time}}{\text{Total volume of liquid stored}} \right) \times 100. \tag{2}$$

Different Liquid Hydrogen (LH_2) storage technologies reveal that the BOR of modern tanks can have a rate of as low as 0.1% per day. Minimizing or reducing boiloff is important in LH_2 storage. Zero boiloff is an evolving concept in the aerospace industry [32]. The relationship between tank size and BOR indicates that larger tanks have less BOR due to a smaller surface-to-volume ratio, which is advantageous for LH_2 transport [31].

The liquefaction of hydrogen involves a Mixed Refrigerant (MR) cycle for precooling i.e. Joule-Brayton (J-B) cycle and ortho-para. In a study of this MR cycle refrigeration, operating pressure has been measured, and energy and exergy analysis have been determined. The energy analysis shows that the Coefficient Of Performance (COP) and Specific Power Consumption (SPC) of the system are 0.2485 and 4.994 kWh/kgLH_2, respectively. However, the exergy analysis of this mixed precooling refrigeration cycle, J-B unit and for the integrated system are 41.62, 47.87 and 49%, respectively [33]. It is clear from this data that the system is inefficient since COP < 1, which indicates that the system requires more energy input than it delivers as output. Therefore, a significant amount of energy is being lost within the system.

Another important challenge in the liquefaction of hydrogen is the attainment of cryogenic conditions and providing thermal insulation to reduce energy loss. Thermal insulation can be obtained by employing inner materials such as vapour-cooled shields, glass bubbles, high vacuum, and Multi-Layer Insulation (MLI) [8]. However, more work is required to reduce energy loss and improve the system's efficiency.

2.3 *Metal hydride tanks*

The storage of hydrogen gas in compressed and liquid form has some challenges. Due to its higher energy density, it has good potential for chemical energy storage. When hydrogen interacts with certain metals, it forms metal hydrides and absorbs the metals, changing its phase to solid during absorption. For desorption, you need to heat it, and then it returns to a gas state.

Notably, energy storage systems on a scale of small to medium have demonstrated the effectiveness of metal hydride hydrogen storage and compression methods. Many factors influence the selection standards of metal hydride materials for compression applications and hydrogen storage. These include the hydride formation and decomposition cycles that need to be reversible within the particular temperatures of operation and hydrogen pressure limit for the given application [17].

TiFe-based alloys are composed of Titanium and iron, which are inexpensive and abundant. Absorption of hydrogen atoms can typically take place from room temperature to 100 °C and a pressure of 10-20 bar. The storage capacity of TiFe-based alloys is 1.5-1.8 wt% hydrogen [34]. On the other hand, $TiMn_2$-based alloys have a hydrogen storage capacity of 1.5 to 2.5 wt%. The exact storage capacity depends on the composition and processing techniques. Absorption normally takes place between 10-30 bar at room temperature; however, desorption takes place either by increasing the temperature (100 °C and 300 °C) or lowering the pressure [35].

Lanthanum Nickel ($LaNi_5$) based alloys have excellent absorption and desorption properties that make them an ideal candidate for applications in fuel cells and other storage systems. Absorption normally takes place at a pressure of 1-10 bar at an ambient temperature, and desorption takes place between temperatures of 50-100 °C. Hydrogen storage capacity is 1.4 wt%. $LaNi_5$ has fast kinetics, meaning absorption and desorption take place quickly [35].

Magnesium hydride (MgH_2) has high hydrogen storage potential, low cost, and is abundant. This has the highest hydrogen storage capacity of 7.6 wt%, which is the highest amongst metal hydrides. Absorption takes place from 5-10 bar at a temperature of around 300 °C, whereas desorption takes place between 300-400 °C. However, the hydrogenation and dehydrogenation processes are slightly slower than other metal hydride alloys [12].

Table 1. Summary of all storage technologies with storing conditions, safety, and transport [18, 24, 36-42]

Feature	Compressed Hydrogen (CH_2)	Liquid Hydrogen (LH_2)	Metal hydrides
State	Gas	Liquid	Solid (via absorption)
Storage pressure	350-700 bar	Cryogenic conditions	1-30 bar
Storage temperature	Ambient	20 K (-253 °C)	Ambient temperature to 300 °C (Varies with the type of hydrides)
Energy density (by volume)	Lower (25-30 kg/m^3)	Higher (50 kg/m^3)	Higher (50-175 kg/m^3)
Energy efficiency	Less energy efficient to compress	More energy is required to liquefy	Depends on the type of metal hydride. $LaNi_5$ has fast kinetics and less energy required for absorption/desorption
Typical applications	Hydrogen FCVs	Aerospace, large-scale transport	Residential to industrial
Storage equipment	High-pressure tanks	Cryogenic tanks	Metal tanks
Long-distance transport	Less efficient	More efficient	Depends on the type of metal hydride
Advantages	Refuelling speed is higher, stable technology, not have a complex vessel structure	H_2 is purer in this state, with higher volumetric density	Not a requirement to have high pressure, which reduces initial cost, safer than compressed and LH_2
Drawbacks	Safety concerns due to high pressure and thermal management is also required	More energy in liquefaction, safety and thermal insulation concerns, high cost and time-consuming	Depending on the type of metal selected, high cost due to high operating temperature for releasing H_2

Table 1 summarises three key hydrogen storage technologies with their advantages, disadvantages, and applications. High pressure is a safety concern for CH_2 tanks; however, more energy is required for cryogenic tanks for the liquefaction of hydrogen, and thermal losses remain a concern for LH_2. On the contrary, it is evident that metal hydride tanks do not need high temperatures and pressure to store hydrogen. Moreover, this option is much safer than hydrogen in the compressed or liquid form and has applications ranging from residential to industrial.

3. Transportation of hydrogen

Hydrogen is considered the best energy carrier, but there are challenges in its transport due to insufficient infrastructure and resources. Hydrogen can be transported using methods discussed in the previous section i.e., in the form of compressed gas, liquid tanks, or through MH tanks. Among those, a metal hydride tank is the safest form of transporting hydrogen, as it doesn't require high temperatures or pressures. However, the process of desorption, which releases hydrogen from MH tanks, requires high operating temperatures, which can be costly.

Another way of transporting H_2 is through pipelines over long distances. Europe is planning to widen its existing natural gas pipeline to accommodate hydrogen transport demand, but there are challenges in converting the natural gas pipeline/infrastructure and using it for hydrogen transport [43].

Around the globe, investigations are conducted to discover new materials for subsea pipelines for safe hydrogen transportation. X65 steel is a material that has been manufactured using thermochemical controlled processes and can be used for long-distance offshore pipelines. Benefits of using this material include (i) lower risk of hydrogen-assisted cracking at pressures < 100 bar when gas contaminants are absent; (ii) Fracture toughness is minimal under dry hydrogen [44].

Two API 5L X65 pipeline materials have been used to investigate which is better for hydrogen transportation. One is Quenched and Tempered (QT) pipeline steel, material A, and the other is vintage hot rolled pipeline steel, material B [43]. Hydrogen permeation tests and Mechanical fracture tests were performed to check which material performs better. It was noted that Material B exhibits higher subsurface hydrogen concentrations than Material A under the same charging conditions [43]. However, material A has lower fracture toughness under the same charging conditions. It is important to note that these results may vary by changing the charging method and/or charging conditions.

Critical fracture toughness can be observed using the Crack Tip Opening Displacement (CTOD). It is an important parameter in evaluating the structural integrity of materials exposed to hydrogen environments. CTOD can be influenced by hydrogen embrittlement [45]. At a 17 bar hydrogen pressure, materials A and material B have CTOD ranging from 0.49 mm to 0.56 mm.

It is to highlight that the charging methods and charging conditions are important parameters for hydrogen storage and fuel cell technology. This may involve Compressed Hydrogen gas, Liquid hydrogen, metal hydrides, chemical hydrides, and absorption in porous materials. The charging conditions depend on the charging methods, requirements, and target applications, which may vary with temperature, pressure, safety, and control.

4. Safety of the hydrogen

There are unique safety hazards and challenges related to hydrogen storage, transport, and usage. There have been catastrophic incidents in the past related to hydrogen release or rupture of hydrogen tanks that have led to several casualties [46]. Hence, strict compliance with safety norms, and strong legislation are needed for its safe incorporation into the energy sector. It is important to mention that the safety of hydrogen comprises the stages of storage, transport, and utilization.

• **Storage Safety:** Hydrogen can be compressed and stored at high pressure (350-700 bar). This storage at high pressure may cause risks of leaks and explosions. Therefore, robust safety measures are required to prevent accidents [36]. Conversely, there is a risk of embrittlement since metals can become brittle when they are in contact with hydrogen, and this can cause tank failures [47]. The material for hydrogen tanks must withstand high pressure and resist embrittlement. Advanced composites can be one option, but they are expensive [45]. It is important to note that the type-IV compressed hydrogen tank's average temperature during filling, holding, and emptying phases reaches 90 °C which is higher than the ISO safety code (85 °C). Isolation systems are needed to guard against leaks and maintain structural integrity. Furthermore, the cryogenic storage method stores hydrogen at cryogenic temperatures (-253 °C), which requires super-insulated material for tanks.

Metal hydride tanks require high temperatures (up to 300 °C) with a pressure of up to 30 bar for the hydrogenation process. At these temperatures and pressures, there is a risk of overheating, thermal degradation of the material, risk of leakage, and combustion/explosion. Depending upon the type of metal hydride, a higher temperature is required for dehydrogenation, which again causes risks of thermal degradation and leakage risks that may lead to an explosion or combustion [12].

• **Transport Safety:** Hydrogen can either be transported using tanks and cylinders or for long distances, normally through pipelines. Based on the type of storage tank/cylinder, safety procedures are required to prevent leaks during filling, transport, and usage [43]. Since hydrogen has an extremely low density and fast diffusion rate, it is easier to get leaks. Moreover, hydrogen is odorless and colorless; therefore, it is not easy to detect hydrogen leaks, and we can't add agents to generate a taste that can pollute the gas [46]. However, some optical fibre sensors can be used to detect the leakage of hydrogen [46].

• **Usage Safety:** The utilization of hydrogen in several applications; thus, fuel cells in vehicles and other applications are designed with various safety arrangements, containing robust casing, leak detection systems, and venting mechanisms. Moreover, it is utilized in the industry sector, so industries using hydrogen need to adhere to strict safety criteria to manage dangers related to pressures, potential leaks, and high temperatures.

Since hydrogen is highly flammable and has a vast flammability range, about (4-75% in air). Therefore, that might ignite with a very low energy source, and it can establish explosive mixtures [48]. One such incident happened in a chemistry laboratory at a University in North China in 2015, where the researcher died due to an explosion, however, some other staff members were safely evacuated. The explosion happened in a high-pressure hydrogen cylinder, which was 2-3 m away from the research worker in the laboratory. The reason for this incident was the leakage of hydrogen from the cylinder, which was ignited by the tert-butyllithium [49].

These risks can be reduced by an adequate protocol for safety training and education. In order to prevent hydrogen leakage during storage and transportation, most things are dependent on the choice of material used for cylinders, or choice of hydrogen sensors that can be attached with the cylinder to detect a leakage can be attached to detect leakage. A recent study demonstrated the operation of a Pd-alloy hydrogen sensor, which provides an immediate response to hydrogen gas. The response time of this sensor is approximately 0.85 s for 1 mbar of hydrogen with an accuracy of 2.5%. The sensor is also robust against aging and temperature [50].

5. Conclusions

Considering United Nations Sustainable Development Group (UNSDG) goal number 7, the World needs a sustainable and clean energy resource for the future. There is great potential in green hydrogen as an energy carrier; however, it faces challenges and limitations in its storage, transport, and safe usage. This work presents a review of current trends in the storage and transportation of hydrogen.

Hydrogen can be stored in a compressed form at pressures of 350 to 700 bar; however, high-pressure storage tanks require special composite materials and are expensive. Storing hydrogen in its liquid form requires cryogenic conditions (20.3 K), which necessitate a significant amount of energy and cost. However, hydrogen can be stored using an absorption process, where it solidifies with the metal to form metal hydrides and then released using a desorption process. The latter option is a more viable solution and is safer than compressed or liquid hydrogen.

In addition to being transported through tanks and cylinders, hydrogen can also be transported through pipelines. The work is underway if the natural gas pipeline can be used to transport hydrogen. Quenched and tempered steel (Material A) and hot-rolled pipeline steel (Material B) have been used to test which material performs better in subsea hydrogen concentration for transporting hydrogen. It is evident from the experiment that Material B has a higher hydrogen concentration than Material A.

Considering safety aspects, further research is required on materials to identify methods for minimising hydrogen leakage from the cylinder and to develop new sensors capable of detecting hydrogen within nanoseconds. There is a need to develop new algorithms to optimise different liquefaction cycles, improving the coefficient of performance and reducing the boil-off ratio. Although magnesium hydride is the most potential metal hydride, further development is necessary on the molecular scale to improve the stabilisation of the nanostructure and coupling with hydride materials.

Conflict of interest

The authors declare no competing financial interest.

References

[1] Ari A, Arregui N, Black S, Celasun O, Lakova D, Mineshima A, et al. *Surging Energy Prices in Europe in the Aftermath of the War: How to Support the Vulnerable and Speed Up the Transition Away From Fossil Fuels*. International Monetary Fund Working Paper. USA. 2022.

[2] Costa L, Moreau V, Thurm B, Yu W, Clora F, Baudry G, et al. The decarbonisation of Europe powered by lifestyle changes. *Environmental Research Letters*. 2021; 16: 044057. Available from: https://doi.org/10.1088/1748-9326/abe890.

[3] Yang M, Hunger R, Berrettoni S, Sprecher B, Wang B. A review of hydrogen storage and transport technologies. *Clean Energy*. 2023; 7: 190-216. Available from: https://doi.org/10.1093/ce/zkad021.

[4] Maka AO, Mehmood M. Green hydrogen energy production: Current status and potential. *Clean Energy*. 2024; 8: 1-7. Available from: https://doi.org/10.1093/ce/zkae012.

[5] Maka AO, Ghalut T. An overview and perspective of solar photovoltaic-green hydrogen production system. *Fuel*. 2025; 400: 135760. Available from: https://doi.org/10.1016/j.fuel.2025.135760.

[6] Maka AO, Mehmood M, Chaudhary TN. Green hydrogen revolution and its pathway towards sustainable development. *Clean Energy*. 2025; 9(2): 124-131. Available from: https://doi.org/10.1093/ce/zkae106.

[7] Das L. Hydrogen-fueled internal combustion engines. *Compendium of Hydrogen Energy*. 2016; 3: 177-217. Available from: https://doi.org/10.1016/B978-1-78242-363-8.00007-4.

[8] Jain V, Kandasubramanian B. Functionalized graphene materials for hydrogen storage. *Journal of Materials Science*. 2020; 55: 1865-1903. Available from: https://doi.org/10.1007/s10853-019-04150-y.

[9] Balat M. Potential importance of hydrogen as a future solution to environmental and transportation problems. *International Journal of Hydrogen Energy*. 2008; 33: 4013-4029. Available from: https://doi.org/10.1016/j.ijhydene.2008.05.047.

[10] Lata D, Misra A. Theoretical and experimental investigations on the performance of dual fuel diesel engine with hydrogen and LPG as secondary fuels. *International Journal of Hydrogen Energy*. 2010; 35: 11918-11931. Available from: https://doi.org/10.1016/j.ijhydene.2010.08.039.

[11] Mazloomi K, Gomes C. Hydrogen as an energy carrier: Prospects and challenges. *Renewable Sustainable Energy Reviews*. 2012; 16: 3024-3033. Available from: https://doi.org/10.1016/j.rser.2012.02.028.

[12] Klopčič N, Grimmer I, Winkler F, Sartory M, Trattner A. A review on metal hydride materials for hydrogen storage. *Journal of Energy Storage*. 2023; 72: 108456. Available from: https://doi.org/10.1016/j.est.2023.108456.

[13] Broom DP. *Hydrogen Storage Materials: The Characterisation of Their Storage Properties*. London: Springer; 2011. Available from: https://doi.org/10.1007/978-0-85729-221-6.

[14] Usman MR. Hydrogen storage methods: Review and current status. *Renewable Sustainable Energy Reviews*. 2022; 167: 112743. Available from: https://doi.org/10.1016/j.rser.2022.112743.

[15] Von Colbe JB, Ares J-R, Barale J, Baricco M, Buckley C, Capurso G, et al. Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives. *International Journal of Hydrogen Energy*. 2019; 44: 7780-7808. Available from: https://doi.org/10.1016/j.ijhydene.2019.01.104.

[16] De Miguel N, Cebolla RO, Acosta B, Moretto P, Harskamp F, Bonato C. Compressed hydrogen tanks for on-board application: Thermal behaviour during cycling. *International Journal of Hydrogen Energy*. 2015; 40: 6449-6458. Available from: https://doi.org/10.1016/j.ijhydene.2015.03.035.

[17] Tarasov BP, Fursikov PV, Volodin AA, Bocharnikov MS, Shimkus YY, Kashin AM, et al. Metal hydride hydrogen storage and compression systems for energy storage technologies. *International Journal of Hydrogen Energy*. 2021; 46: 13647-13657. Available from: https://doi.org/10.1016/j.ijhydene.2020.07.085.

[18] Nguyen HQ, Shabani B. Review of metal hydride hydrogen storage thermal management for use in the fuel cell systems. *International Journal of Hydrogen Energy*. 2021; 46: 31699-31726. Available from: https://doi.org/10.1016/j.ijhydene.2021.07.057.

[19] Greene DL, Ogden JM, Lin Z. Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *ETransportation*. 2020; 6: 100086. Available from: https://doi.org/10.1016/j.etran.2020.100086.
[20] Song L, Wang S, Jiao C, Si X, Li Z, Liu S, et al. Thermodynamics study of hydrogen storage materials. *The Journal of Chemical Thermodynamics*. 2012; 46: 86-93. Available from: https://doi.org/10.1016/j.jct.2011.06.022.
[21] Moradi R, Groth KM. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy*. 2019; 44: 12254-12269. Available from: https://doi.org/10.1016/j.ijhydene.2019.03.041.
[22] Godula-Jopek A. Hydrogen storage options including constraints and challenges. *Hydrogen Production: Electrolysis*. 2015; 273-310. Available from: https://doi.org/10.1002/9783527676507.ch7.
[23] Sorensen B, Spazzafumo G. *Hydrogen and Fuel Cells: Emerging Technologies and Applications*. London: Elesiver; 2018. Available from: https://doi.org/10.1016/C2015-0-01635-5.
[24] Rivkin C, Burgess R, Buttner W. *Hydrogen technologies safety guide*. National Renewable Energy Laboratory, United States. Technical Report: NREL/TP-5400-60948, 2015.
[25] Arsad AZ, Hannan M, Al-Shetwi AQ, Mansur M, Muttaqi K, Dong Z, et al. Hydrogen energy storage integrated hybrid renewable energy systems: A review analysis for future research directions. *International Journal of Hydrogen Energy*. 2022; 47: 17285-17312. Available from: https://doi.org/10.1016/j.ijhydene.2022.03.208.
[26] Kim SC, Lee SH, Yoon KB. Thermal characteristics during hydrogen fueling process of type IV cylinder. *International Journal of Hydrogen Energy*. 2010; 35: 6830-6835. https://doi.org/10.1016/j.ijhydene.2010.03.130.
[27] Danebergs J, Deledda S. Can hydrogen storage in metal hydrides be economically competitive with compressed and liquid hydrogen storage? A techno-economical perspective for the maritime sector. *International Journal of Hydrogen Energy*. 2024; 50: 1040-1054. Available from: https://doi.org/10.1016/j.ijhydene.2023.08.313.
[28] Lord AS, Kobos PH, Borns DJ. *A life cycle cost analysis framework for geologic storage of hydrogen*. Sandia National Lab. (SNL-NM), Albuquerque, NM (United States). Report No. SAND2009-6310; 275826, 2009.
[29] Caglayan DG, Weber N, Heinrichs HU, Linßen J, Robinius M, Kukla PA, et al. Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*. 2020; 45: 6793-6805. Available from: https://doi.org/10.1016/j.ijhydene.2019.12.161.
[30] AlZohbi G, Almoaikel A, AlShuhail L. An overview on the technologies used to store hydrogen. *Energy Reports*. 2023; 9: 28-34. Available from: https://doi.org/10.1016/j.egyr.2023.08.072.
[31] Berstad D, Gardarsdottir S, Roussanaly S, Voldsund M, Ishimoto Y, Nekså P. Liquid hydrogen as prospective energy carrier: A brief review and discussion of underlying assumptions applied in value chain analysis. *Renewable Sustainable Energy Reviews*. 2022; 154: 111772. Available from: https://doi.org/10.1016/j.rser.2021.111772.
[32] Morales-Ospino R, Celzard A, Fierro V. Strategies to recover and minimize boil-off losses during liquid hydrogen storage. *Renewable Sustainable Energy Reviews*. 2023; 182: 113360. Available from: https://doi.org/10.1016/j.rser.2023.113360.
[33] Ghorbani B, Zendehboudi S, Afrouzi ZA, Lohi A, Khan F. Efficient design of the hydrogen liquefaction system: Thermodynamic, economic, environmental, and uncertainty perspectives. *Industrial Engineering Chemistry Research*. 2024; 63: 14668-14699. Available from: https://pubs.acs.org/doi/10.1021/acs.iecr.3c04286.
[34] Liu H, Zhang J, Sun P, Zhou C, Liu Y, Fang ZZ. An overview of TiFe alloys for hydrogen storage: Structure, processes, properties, and applications. *Journal of Energy Storage*. 2023; 68: 107772. Available from: https://doi.org/10.1016/j.est.2023.107772.
[35] Liu J, Sun L, Yang J, Guo D, Chen D, Yang L, et al. Ti-Mn hydrogen storage alloys: From properties to applications. *RSC Advances*. 2022; 12: 35744-35755. Available from: https://doi.org/10.1039/D2RA07301C.
[36] Miller EL, Thompson ST, Randolph K, Hulvey Z, Rustagi N, Satyapal S. US department of energy hydrogen and fuel cell technologies perspectives. *MRS Bulletin*. 2020; 45: 57-64. Available from: https://doi.org/10.1557/mrs.2019.312.
[37] Klebanoff L. *Hydrogen Storage Technology: Materials and Applications*. London: CRC Press Tylor Franiccs; 2012.
[38] Crabtree GW, Dresselhaus MS, Buchanan MV. The hydrogen economy. *Physics Today*. 2004; 57: 39-44. Available from: https://doi.org/10.1063/1.1878333.
[39] Barthélémy H. Hydrogen storage-industrial prospectives. *International Journal of Hydrogen Energy*. 2012; 37: 17364-17372. Available from: https://doi.org/10.1016/j.ijhydene.2012.04.121.
[40] Bañares-Alcántara R, Dericks III G, Fiaschetti M, Grünewald P, Lopez JM, Tsang E, et al. *Analysis of Islanded Ammonia-Based Energy Storage Systems*. UK: University of Oxford; 2015.

[41] Grube T, Doré L, Hoffrichter A, Hombach LE, Raths S, Robinius M, et al. An option for stranded renewables: Electrolytic-hydrogen in future energy systems. *Sustainable Energy*. 2018; 2: 1500-1515. Available from: https://doi.org/10.1039/C8SE00008E.
[42] Makowski P, Thomas A, Kuhn P, Goettmann F. Organic materials for hydrogen storage applications: From physisorption on organic solids to chemisorption in organic molecules. *Energy Environmental Science*. 2009; 2: 480-490. Available from: https://doi.org/10.1039/B822279G.
[43] Jemblie L, Hagen AB, Hagen CHM, Nyhus B, Alvaro A, Wang D, et al. Safe pipelines for hydrogen transport. *International Journal of Hydrogen Energy*. 2024; 136: 672-685. Available from: https://doi.org/10.1016/j.ijhydene.2024.06.309.
[44] Mendibide C, Vucko F, Martinez M, Joshi G, Kittel J. Effect of degraded environmental conditions on the service behavior of a X65 pipeline steel not designed for hydrogen transport. *International Journal of Hydrogen Energy*. 2024; 52: 1019-1032. Available from: https://doi.org/10.1016/j.ijhydene.2023.05.309.
[45] Myhre A, Wan D, Sendrowicz A, Nyhus B, Matsunaga H, Olden V, et al. Assessing fracture toughness of vintage and modern X65 pipeline steels under in situ electrochemical hydrogen charging using advanced testing methodology. *Engineering Fracture Mechanics*. 2024; 301: 110026. Available from: https://doi.org/10.1016/j.engfracmech.2024.110026.
[46] Guo L, Su J, Wang Z, Shi J, Guan X, Cao W, et al. Hydrogen safety: An obstacle that must be overcome on the road towards future hydrogen economy. *International Journal of Hydrogen Energy*. 2024; 51: 1055-1078. Available from: https://doi.org/10.1016/j.ijhydene.2023.08.248.
[47] Dwivedi SK, Vishwakarma M. Hydrogen embrittlement in different materials: A review. *International Journal of Hydrogen Energy*. 2018; 43: 21603-21616. Available from: https://doi.org/10.1016/j.ijhydene.2018.09.201.
[48] Bulat HH, Kaymakçı ÖT, Ilhan H. Human factors in hydrogen storage: An analysis of safety implications. *International Journal of Hydrogen Energy*. 2024; 107: 548-558. Available from: https://doi.org/10.1016/j.ijhydene.2024.07.295.
[49] Jia H. *Deadly Accident Sounds Alarm for Safety in Chinese Labs*. UK: Royal Society of Chemistry; 2016. Available from: https://www.chemistryworld.com/news/deadly-accident-sounds-alarm-for-safety-in-chinese-labs/9350.article [Accessed 20th May 2025].
[50] Luong HM, Pham MT, Guin T, Madhogaria RP, Phan M-H, Larsen GK, et al. Sub-second and ppm-level optical sensing of hydrogen using templated control of nano-hydride geometry and composition. *Nature Communications*. 2021; 12: 2414. Available from: https://doi.org/10.1038/s41467-021-22697-w.