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Hydrogen Storage: Review of Technologies and Future Prospects

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Hydrogen is emerging as a highly efficient energy carrier thanks to its high energy density and clean combustion, making it a promising option for sustainable technologies. However, storage remains the main challenge due to volumetric and gravimetric density limitations that affect its practical applicability. Among the most prominent routes are physical approaches, such as high-pressure compression and cryogenic storage in liquid form; in addition, underground alternatives and chemical strategies are being considered, including metal hydrides, organic liquid carriers, and advanced porous materials. Energy efficiency, costs, and safety vary depending on the technology, highlighting the need for integration with renewable sources. Similarly, hybrid approaches enable optimized thermal management and improved hydrogen recovery, while the development of stable materials with high cyclic stability is essential for optimizing adsorption and desorption processes, reducing losses, and improving overall efficiency. This review analyzes key indicators, assesses the current state of storage technologies, and discusses their advantages, limitations, and prospects for large-scale application.

1. Introduction

Energy has driven human development, but growing global demand and the impacts of fossil fuels make it urgent to transition to sustainable sources. Hydrogen stands out as a clean energy carrier, obtainable through water electrolysis and compatible with renewables, whose main by-product is water. The Paris Agreement (2015) requires limiting global temperature rise to <2°C, ideally 1.5°C (United Nations Framework Convention on Climate Change, 2015). In 2024, global energy supply was 648 EJ, dominated by fossil fuels (oil 29.8 %, coal 27.3 %, natural gas 23 %), while renewables and nuclear accounted for 15 % and 4.8 % (International Energy Agency, 2025a). Demand for hydrogen reached 97 million tons, but <1 % was green or blue (International Energy Agency, 2025b). H_2 has a high energy density per mass: 142 MJ/kg (HHV) (Nayebossadri et al., 2025). It also reaches 120 MJ/kg (LHV) (Mehrabianbardar et al., 2025). This is equivalent to 3 kg of gasoline for every kilogram of H_2. However, its low volumetric density of 12.8 MJ/m³ under normal conditions (Nayebossadri et al., 2025). This characteristic requires efficient storage strategies: gaseous (CAG) at 35–70 MPa, liquid (LH_2) at −253 °C, or solid by physisorption or chemisorption. In physisorption, H_2 is retained in porous materials such as activated carbons, MOFs, COFs and inorganic materials through weak interactions, with rapid reversibility but limited capacity at room temperature (Sutton et al., 2024). In chemisorption, chemical bonds form in metal hydrides, complexes, or chemicals (e.g., $LaNi_5H_6$, MgH_2, $NaAlH_4$, NH_3BH_3), with $LiBH_4$ standing out for its energy density (Pang et al., 2025). AB_5- and AB_2-type metal hydrides, as well as superlattices, enable efficient storage under moderate conditions (Sleiman et al., 2024). Complexes show gravimetric capacity but low reversibility, while nanoconfinement in porous materials, such as MgH_2 in boron-doped carbon nanotubes (BCNTs), improves kinetics, reversibility, and stability by shortening H_2 diffusion and preventing agglomeration (Feki et al., 2025).

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To prepare this review, the literature was compiled mainly through structured searches in Scopus, ScienceDirect, and Google Scholar, using keywords related to hydrogen storage, and supplemented with technical reports from international organizations (IEA and UNFCCC). The selection included peer-reviewed articles, reviews, and technical documents with scientific rigor, excluding sources without academic relevance or technical contribution. A total of 29 recent references were gathered, predominantly from 2024 and 2025. Unlike reviews focused on individual storage routes, this work offers an integrated analysis covering physical methods, chemical methods, and physisorption-based approaches, linked with performance comparisons and practical challenges. This unified perspective is the main distinctive contribution.

2. Hydrogen Storage

Hydrogen can be stored as compressed gas, cryogenic liquid, or solid (physisorption or chemisorption), each with limits in energy density, cost, and safety. Figure 1 summarizes these storage routes and their main types.

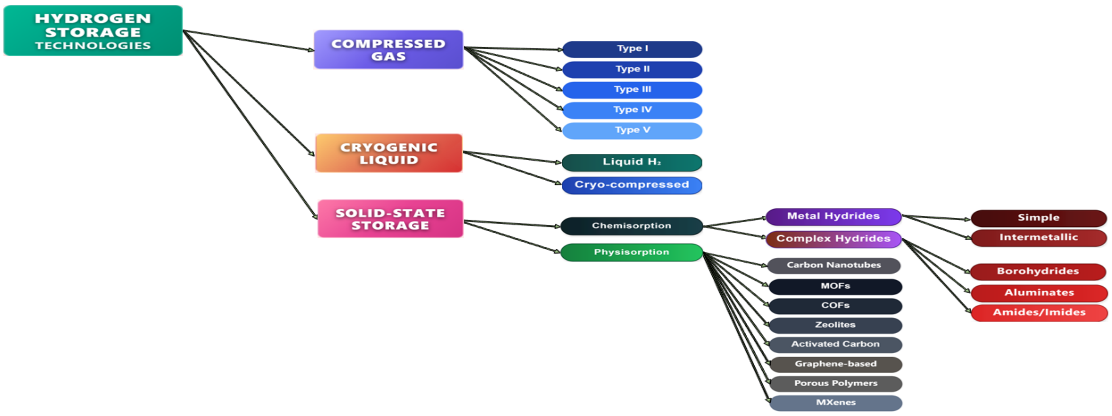

Figure 1: Hydrogen storage technologies: compressed gas, cryogenic liquid, and solid-state.

2.1 Solid Hydrogen storage

Solid H_2 storage operates at moderate temperatures and pressures close to ambient conditions, offering high energy density and ease of use. Its mechanisms are adsorption, which occurs at the solid-gas interface, and absorption, which involves penetration into the crystal lattice to form metal hydrides. Adsorption can be physisorption, based on weak Van der Waals interactions (–4 to –10 kJ/mol), reversible, favored at low temperatures and high pressures (5–10 MPa), or chemisorption, in which H_2 dissociates into atoms that form strong bonds with the surface (–50 to –100 kJ/mol) (Faye et al., 2022). While adsorption allows reversible surface storage, absorption offers higher density but slower kinetics, with chemisorption bridging the processes.

2.1.1 Hydrogen storage in porous materials

Physisorption is the main mechanism for storing H_2 in porous materials, with MOFs standing out with up to 10 % by weight, COFs with 6 %, and carbonaceous materials such as activated carbon, graphene, fullerenes, and CNTs with 3–5 %, in addition to zeolites and CNFs (Osman et al., 2024). However, under near-ambient conditions, the gravimetric density is low, falling to <1 % by weight even at 5–10 MPa, as many MOFs have weak bond enthalpies (–4 to –7 kJ/mol), limiting their capacity to ~1 % by weight at 298 K and 10 MPa. Improving performance under these conditions requires increasing the enthalpy to the range of –15 to –25 kJ/mol (Sutton et al., 2024). In this context, maximizing internal surface area and porosity, along with incorporating metals, applying irradiation, or adjusting temperature and pressure, are key strategies to enhance gas interaction.

2.1.2 Hydrogen storage in hydrides

Metal hydrides are effective for solid H_2 storage, as they allow controlled absorption and desorption, offering suitable densities by weight and volume for energy applications. Their synthesis and behavior depend on thermodynamic parameters (enthalpy and entropy) and kinetic factors (H_2 diffusion), which determine their performance under real conditions. They are classified as binary or simple, intermetallic, and complex.

- **Binary or simple hydrides:** Among binary hydrides (MH_x), MgH_2 is one of the most studied due to its high theoretical hydrogen storage capacity (7.6 wt% and ~109 g/L), as well as being abundant and inexpensive. However, its high thermodynamic stability ($\Delta Hf \approx -76$ kJ/mol) requires temperatures near 400 °C to release

H_2 (Kudiiarov et al., 2024), making it impractical for mobile applications. Added to this are kinetics limited by an activation energy of ~160 kJ/mol, which slows absorption and desorption (Miskan et al., 2025). To overcome these limitations, the nanodistribution of MgH_2 in carbon nanotubes (CNTs), especially boron-doped CNTs (BCNTs), allows operation at 250–300 °C with greater reversibility, since the nanometric particles shorten the H_2 path and the nanotubes prevent agglomeration, preserving the active surface and improving the kinetics toward practical storage conditions.

- **Intermetallic hydrides:** These intermetallic hydrides ($A_mB_nH_x$) are formed with various elements. Among them, A (such as La, Ce, Ti, Mg) forms the hydrides, while B (such as Ni, Co, Fe) acts as a catalyst. According to the A/B ratio, they are grouped into families such as AB_5, AB_2, AB, A_2B, A_3B_2, AB_4, and multicomponent alloys, which allow for adjustment of capacity, cyclic stability, and desorption temperature. Their high volumetric density, operation under moderate conditions, and selective absorption make them attractive for mobile and stationary applications. $LaNi_5$ (AB_5) stands out for its reversibility and stability at room temperature, with a storage capacity of ~1.4 % by weight of H_2. Although it is inferior to MgH_2, it is easy to activate. Kinetic studies on $LaNi_5$ indicate an activation energy of 78 ± 4 kJ/mol, with effective absorption above 1 MPa and complete absorption within seconds under 5 MPa and 333 K (Sleiman et al., 2024). This explains its efficient commercial use without extreme conditions.
- **Complex Hydrides:** These complex hydrides are formed by the reaction of ionic hydrides (NaH, LiH) and covalent hydrides (AlH_3, BH_3), generating salts such as alanates $[AlH_4]^-$ ($LiAlH_4$, $NaAlH_4$), borohydrides $[BH_4]^-$ ($LiBH_4$, $NaBH_4$) and amides or imides $[NH_2]^-$ ($LiNH_2$, $NaNH_2$), where hydrogen is chemically bonded in these anions. Among them, $LiBH_4$ stands out for its high theoretical storage capacity, reaching up to 18.5 % by weight of H_2, although it has significant limitations: it requires temperatures of 350–400 °C, exhibits slow kinetics, low reversibility, is sensitive to air, and generates stable intermediates ($Li_2B_{12}H_{12}$) that hinder rehydrogenation under extreme conditions above 600 °C and 15 MPa. To counteract these limitations, it has been shown that adding 30 % by weight of the two-dimensional high-entropy oxide $(CoNiMnFeCr)_3O_4$ reduces the activation energy from 153.5 to 116.1 kJ· mol⁻¹ of H_2, significantly increases the dehydrogenation capacity (from 2.96 % in pure $LiBH_4$ to approximately 11.7 % at 400 °C) and allows H_2 recovery of 9.6 % in the first cycle and 6.4 % after ten cycles during rehydrogenation at 400 °C and 10 MPa (Pang et al., 2025). These 2D multicomponent catalysts not only improve reversibility, but also represent a key strategy for advancing the joint integration of binary, intermetallic, and complex hydrides within a hydrogen-based economy.

2.2 Storage of Compressed Hydrogen Gas

H_2 storage by compression is the most widely used method in industry and mobility, operating at 35–70 MPa through multi-stage compression (<200 °C, <10 MJ/kg). The density increases from 0.0813 kg/m³ at ambient conditions to ≈52 kg/m³ at 100 MPa and 0 °C, more than 600 times (Franco and Giovannini, 2024). It allows for rapid charging/discharging, has established technology, and moderate costs, although it requires specialized materials and high energy consumption. Its energy density is low: 0.003 kWh/L at atmospheric pressure and 1.2 kWh/L at 70 MPa, barely higher than lithium batteries (~0.5 kWh/L) (Zou et al., 2022). This requires large volumes and high-pressure tanks that are both resistant and lightweight. In addition, hydrogen is explosive, prone to leakage, and capable of penetrating pipes and tanks, causing embrittlement and affecting storage integrity (Koromila et al., 2025).

2.2.1 Types of containers for Hydrogen storage

Five main types of pressurized containers have been developed for hydrogen storage and transportation:

- **Type I tanks**: These are all-metal tanks (seamless steel or aluminum) used in industrial and subsea applications for large H_2 volumes. They are economical and can withstand pressures up to 30 MPa (Stops et al., 2024). However, in fuel cell vehicles they are impractical because of their high weight to volume ratio, with a gravimetric capacity below 0.01 kg H_2 per kg system. Thus, storing 5.6 kg of H_2 (about 500 km of range) would require more than 560 kg of system mass (Magliano et al., 2024). They are also susceptible to H_2 embrittlement, compromising structural integrity during prolonged exposure.
- **Type II tanks**: These tanks operate at 26–30 MPa (Li et al., 2021) and use a metal liner with composite reinforcement, achieving a 35 % weight reduction compared to all-metal tanks. Made of steel and CFRP, they withstand high internal stresses (Stops et al., 2024) and are widely used in stationary applications for their safety and reliability (Rampai et al., 2024). However, they remain heavy and costly, limiting their use in mobility applications that require low weight and high energy density (Feki et al., 2025).
- **Type III tanks**: These tanks have a metal liner (steel or aluminum alloy) covered by a complete composite shell made of carbon fiber or glass, allowing them to operate at up to 70 MPa (Feki et al., 2025). The liner

ensures watertightness and structural support, although it increases weight and vulnerability to mechanical fatigue (Feki et al., 2025). This configuration, optimized for high pressure, is suitable for advanced H_2 storage applications, ensuring integrity against leaks and internal stresses (Zhu et al., 2024).

- **Type IV tanks**: These are composite tanks, manufactured with carbon fibers arranged in a spiral and ring pattern on an inner liner, increasing their mechanical strength (Li et al., 2021). Its helical and circumferential architecture, together with intermediate layers, optimizes burst pressure with lower mass (Reda et al., 2024). It can operate at up to 70 MPa, improving the weight-to-strength ratio against impacts and cyclic loads, although fatigue due to filling and emptying remains a challenge (Feki et al., 2025). Type IV CPVs reduce weight by up to 75 % compared to Types I, II, and III and offer safer failure modes, making them ideal for domestic and aerospace applications. For this reason, electric vehicle manufacturers prefer them for storing hydrogen and maximizing range and energy efficiency (Azeem et al., 2024; Lv et al., 2025).
- **Type V tanks**: These are the most advanced hydrogen storage tanks, manufactured entirely from composite materials and without an internal liner, which eliminates the metal liner and improves structural efficiency (Magliano et al., 2024). Their design makes them approximately 20 % lighter than Type IV tanks, making them ideal when weight is critical, and they can withstand pressures of up to 100 MPa (Li et al., 2021). However, their commercial adoption remains limited by hydrogen permeation and high manufacturing costs (Feki et al., 2025), as summarized in Table 1, which compares the main types of hydrogen containers in terms of material, operating pressure, densities, and service life.

Table 1: Comparison of the main types of pressurized containers for hydrogen storage

Type	Main material	Pressure (MPa)	Compatibility with the environment	Gravimetric density (%)	Volumetric density (g·L^{-1})	Vehicle application	Ref
I	Fully metal tank	≤30	Susceptible to embrittlement and corrosion by H_2	≈1	14-17	No	(Stops et al., 2024)
II	Reinforced metal tank	26-30	Susceptible to embrittlement and corrosion by H_2	≈1.5	14-17	No	(Li et al., 2021
III	Coating metal composite	30-70	Susceptible to embrittlement and corrosion by H_2	≈2.4-4.1	35-40	Yes	(Feki et al., 2025)
IV	Coating composite plastic-fiber	<70	Susceptible to embrittlement and corrosion by H_2	2.5-5.7	38-40	Yes	(Feki et al., 2025)
V	Fiber structure	<100		-	-	-	(Li et al., 2021)

2.3 Liquid hydrogen storage

Liquid hydrogen (LH_2) is stored at −252.87 °C and ≈0.1 MPa, reaching densities >70 kg/m³, almost double that of H_2 compressed at 50 MPa, allowing 5 kg to be stored in 71 L and reducing the volume and weight of tanks, which facilitates its use in vehicles (Simanullang, 2025). Its low pressure reduces structural requirements compared to high-pressure tanks, although liquefaction consumes 30–40 % of the lower heating value (LHV) (Fang et al., 2025). Cryogenic tanks, made of stainless steel or aluminum alloys, are used in stationary and mobile applications and in fuel cell or direct combustion vehicles (Simanullang, 2025). Spherical tanks, which are more expensive, have a lower surface-to-volume ratio and uniform stresses, reducing evaporation; cylindrical tanks, which are more common, have higher heat losses (Mwakipunda et al., 2025). For operational stability, vacuum insulation with multilayer materials (MLI), expanded perlite, glass microspheres, aerogel, or foams is used (Claussner et al., 2024). With a latent heat of vaporization of ~450 kJ/kg, LH_2 offers high volumetric density and allows for reduced tank volume and weight, making it attractive for heavy transport, aerospace, and centralized distribution. However, its application is limited by high costs, complex infrastructure, and evaporation losses.

2.4 Underground hydrogen storage (UHS)

Underground hydrogen storage (UHS) allows H_2 to be stored in deep geological formations, such as aquifers, salt caverns, or depleted reservoirs, enabling large volumes and taking advantage of existing infrastructure (Mwakipunda et al., 2025). It also protects against natural disasters and offers economic advantages. Its large-scale adoption depends on technical and economic feasibility, and knowledge gaps remain regarding H_2–rock interaction, geochemical processes, gas migration, microbial activity, and geomechanical stability (Opoku Duartey et al., 2025). Table 2 summarizes the main technical and safety parameters of the different types of formations, highlighting the factors that must be considered to ensure safe, efficient, and socially acceptable storage, thereby contributing to the energy transition and decarbonization (Mwakipunda et al., 2025).

Table 2: Comparison of technical & safety parameters for underground hydrogen storage (UHS).

Parameter	Reservoirs depleted	Aquifers	Salt caves
Rock type	Massive non-foliated metamorphic, large sedimentary, intrusive igneous	Sandstones and, in some cases, conglomerates	Salt formations
Airtightness	High	Low	High
Key factors	Microbial activity, rock composition, formation fluids	Microbial activity, rock composition, and fluids; evaluation of tightness	Saline domes preferred
Seismic risk	Medium	High	Low
Risk of leakage	High	High	Low
Pressure	1.5–28.5 MPa	3–31.5 MPa	3.5–27 MPa
Depth	300–2,700 m	300–1,800 m	400–2,300 m
Safety	Low	Low	High
Application (H_2)	It was used with city gas, currently under investigation.	Studied for H_2 and mixtures with CH_4 (<10 %)	Proven technology
Capacity (H_2)	Medium to large	Large to very large	Small to medium
Development	Laboratory scale	Laboratory scale	Commercial use

3. Conclusions

Hydrogen is a promising energy carrier due to its high energy density and zero emissions, although its storage remains a key challenge. Physical solutions like compressed gas and liquid hydrogen ensure high volumetric density and rapid response, while solid systems based on metal hydrides, complexes, and porous materials provide stability, reversibility, and improved cycling efficiency. The different types of tanks and containers offer a balance between safety, cost, and capacity, and deep geological storage expands the possible scale using suitable underground formations. The choice of the right technology depends on the end use, the available infrastructure, and the system's energy requirements. Optimizing advanced materials, absorption/desorption kinetics, and overall process efficiency is essential to consolidate hydrogen as a viable large-scale energy carrier, facilitating the transition to a sustainable and decarbonized energy system.

Recent literature reports notable advances such as nanostructured hydrides with greater reversibility, high-entropy catalysts that enhance dehydrogenation rates, and improved composite designs for Type IV and Type V tanks. However, important gaps persist, including the limited capacity of porous materials near ambient conditions, the high temperatures required by complex hydrides, permeation and fatigue issues in lightweight tanks, and the limited understanding of hydrogen–rock interactions in geological storage. Overcoming these challenges through more stable materials, stronger tank structures, and more accurate geological models will be essential for enabling safer, more efficient, and scalable hydrogen storage systems.

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