Review

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Advancing hydrogen infrastructure: a review of storage and transportation solutions for a sustainable future

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Abstract: Hydrogen is a key energy carrier for decarbonizing high-emission sectors, supporting the transition to a sustainable energy future. This review evaluates critical hydrogen storage and transportation technologies essential for a hydrogen-powered economy. Storage methods, including compressed gas (350–700 bar), cryogenic liquid (−253 °C), cryo-compressed (−233 °C, 250–350 bar), material-based approaches (e.g., metal hydrides, LOHCs), and underground storage (salt caverns, aquifers), are analyzed for their technical feasibility, energy efficiency, and scalability. Transportation methods, including pipelines (up to 6,000 km), truck/rail (200–700 bar), and maritime shipping (e.g., liquefied hydrogen, ammonia, and LOHCs), are evaluated, with an emphasis on infrastructure requirements and cost optimization. The study emphasizes advancements in integrating green hydrogen with renewable energy, addressing safety concerns (e.g., hydrogen embrittlement, ammonia toxicity, and leakage risks), and technical challenges (e.g., boil-off losses and material durability), to support global decarbonization objectives.

Keywords: hydrogen storage; hydrogen transportation; compressed gas storage; cryogenic hydrogen storage; material-based hydrogen storage; underground hydrogen storage

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1 Introduction

Fossil fuels have long served as a conventional energy source, meeting the world's growing energy demands for decades. However, they have significant drawbacks. As nonrenewable resources, fossil fuels contribute to environmental issues such as acid rain and global warming, which adversely affect climate and ecosystems (Gyamfi et al. 2021; Kumar et al. 2019). With the global population projected to reach 10 billion by 2050 (Tarhan and Çil 2021), energy requirements are expected to increase substantially. To address the environmental challenges posed by fossil fuels and meet future energy needs, researchers are actively exploring renewable and sustainable energy sources as viable alternatives. Rapid changes in the global economy and shifts in energy consumption patterns are driving a transition toward a clean energy future, fostering healthier societies, more equitable outcomes, and a resilient planet. Researchers and scientists are investigating diverse energy sources that can be produced with minimal or no negative environmental impact. To achieve net-zero emissions by 2050, clean energy technologies must be deployed at large-scale with remarkable speed. Low-emission hydrogen, ammonia, and hydrogen-based fuels are critical for decarbonizing sectors that face significant challenges in reducing emissions (IEA 2023c).

The primary objective of this review paper is to navigate the intricate pathways of hydrogen storage and transportation. Unlike earlier publications, which often focus narrowly on isolated technologies, specific carrier classes, or regionally constrained infrastructure systems, the current study systematically evaluated both recent advancements and determined limitations across compressed gas, cryogenic, material-based, chemical carrier, and underground storage methods for hydrogen. The review not only collates comparative metrics such as energy consumption and technology readiness levels but also contextualizes these technical results within real-world infrastructure and safety considerations. Notably, it offers updated, critically compared data on emerging classes, such as ultra-high-pressure linerless composite tanks, cryo-compressed systems, and the integration of underground storage in nonsalt geological formations, drawing on operational experiences from pilot projects and national hydrogen strategies across multiple continents. Through this comprehensive and cross-cutting lens, the manuscript provides a different basis for advancing not only technical pathways but also actionable policies and investment decisions toward a resilient hydrogen infrastructure, thereby fulfilling a knowledge gap at the intersection of research, policy, and commercial deployment. By exploring these topics, an attempt has been made to provide a full understanding of the role hydrogen plays in shaping our energy landscape.

2 Hydrogen production, utilization, and global demand trends

Among various energy sources, hydrogen has captured significant attention from scientists, industries, and policymakers (Kumar et al. 2019). Its association with energy dates back to the 1800s, when the first demonstrations of water electrolysis and fuel cells captivated engineers. Over the past two centuries, hydrogen powered early combustion engines and, since the mid-20th century, has become integral to the energy industry, particularly in oil refining (IEA 2019). Hydrogen is considered as a clean fuel because it produces no greenhouse gas emissions, with water as its only byproduct, which can be recycled to regenerate hydrogen. Its applications extend beyond the energy sector, serving as a feedstock for producing various chemicals. Approximately half of the hydrogen produced is used in ammonia manufacturing, primarily for fertilizer production. Significant quantities of hydrogen are also employed in refining and upgrading heavy oil into lighter, and more valuable products (Kumar et al. 2019). With a gravimetric energy density approximately seven times higher than that of fossil fuels, hydrogen has the highest heating value (HHV) of 140 MJ/kg, nearly three times that of hydrocarbon fuels like coke and gasoline (Gorina and Lebedev 2022). The use of hydrogen as an alternative fuel in gas turbines and internal combustion engines offers high efficiency and minimal pollution (Gobbato et al. 2011; Verhelst and Wallner 2009).

Hydrogen production technologies encompass a wide array of processes that are generally classified into conventional fossil-based and renewable-based pathways, each with distinct technical, economic, and environmental attributes (AlNouss et al. 2020; Kumar et al. 2021; da Silva Veras et al. 2017; Zhang et al. 2017). Conventional methods such as steam methane reforming (SMR) (Boretti and Banik 2021; Chau et al. 2022; Van Beurden 2004), coal gasification (Al-Zareer et al. 2018; Ishaq et al. 2022), and catalytic methane decomposition (CDM) (Abánades et al. 2011; Dagle et al. 2017) dominate current global hydrogen output due to their mature infrastructure and low production costs, but they are also significant sources of CO_2 emissions. To reduce their environmental impact, transitional methods such as blue hydrogen and conventional production integrated with carbon capture, utilization, and storage (CCUS) have been developed (Yu et al. 2021). Researchers have been motivated to search for an environmentally friendly approach to sustainable hydrogen production, aiming to increase the share of hydrogen in total global consumption. Biomass and water are the most abundant renewable sources for producing green hydrogen. Different technologies for hydrogen production can be categorized into four groups: (1) electrochemical, (2) photobiological, (3) photoelectrochemical, and (4) thermochemical (da Silva Veras et al. 2017).

Renewable-based technologies, including water electrolysis powered by solar or wind energy, biomass gasification, and biological processes like photolysis and fermentation, offer low- to zero-carbon pathways for hydrogen generation (Atilhan et al. 2021; Islam et al. 2024; Ringsgwandl et al. 2022). Among these, electrolysis is particularly promising due to its high-purity output and compatibility with renewable electricity, although its cost and reliance on scarce materials remain barriers (Dermühl and Riedel 2023; IEA 2021, 2023b; Keçebaş et al. 2019; Pinsky et al. 2020).

Hydrogen production via water splitting has garnered significant attention as a sustainable and environmentally benign method for generating green fuel, with recent studies highlighting diverse pathways and materials to enhance its efficiency. One promising approach involves the use of polymorphic forms of aluminum oxide (α-, δ-, and γ-Al_2O_3), where γ-Al_2O_3 demonstrates superior radiation-catalytic activity due to its high surface area and electron-acceptor properties, facilitating more efficient hydrogen evolution under irradiation and thermal conditions (Ali et al. 2022a). Additionally, radiation-induced water splitting, particularly through ultraviolet and visible light, is crucial in activating semiconductor materials by generating electron–hole pairs that drive the redox reactions necessary for splitting water molecules into hydrogen and oxygen. This process requires semiconductors with a band gap equal to or greater than 1.23 eV to overcome the positive Gibbs free energy of the reaction, with visible light emerging as a practical and widely applicable radiation source due to its compatibility with solar energy (Ali et al. 2022c). Complementing these efforts, the development of green-synthesized nanoparticles has introduced an eco-friendly and cost-effective avenue for photocatalysis, wherein plant-derived or biologically fabricated nanomaterials offer desirable photo-activity and tunable band structures. These green nanoparticles not only minimize environmental toxicity associated with conventional chemical synthesis but also enable efficient photon absorption and charge carrier mobility, making them attractive candidates for water photolysis applications (Basheer and Ali 2019). These advancements underscore the multifaceted strategies being employed to optimize water splitting for large-scale hydrogen generation.

Other emerging hydrogen production methods, such as solar thermochemical cycles and plasma-assisted methane pyrolysis, are being explored for their ability to further reduce carbon emissions and improve efficiency (Dermühl and Riedel 2023; Dagle et al. 2017; Ringsgwandl et al. 2022). Each technology serves a strategic role depending on regional resources, policy frameworks, and end-use applications, underscoring the need for continued innovation and system-level integration to accelerate the transition to a sustainable hydrogen economy.

Advanced materials play a pivotal role in enhancing hydrogen production technologies, particularly through radiation-induced and thermally assisted water splitting processes. Studies have demonstrated that nanostructured catalysts, such as nano-Al_2O_3 and nano-ZrO_2, significantly improve hydrogen yields under gamma irradiation by providing high surface area and enhanced electron-trapping capabilities, which promote the efficient generation of reactive species and facilitate bond cleavage in water molecules. Moreover, temperature synergism with radiation has been shown to intensify hydrogen evolution, especially when using engineered materials like Zr and its niobium alloy (Zr1%Nb). These materials exhibit unique oxidation behaviors and form energetic surface sites that promote molecular hydrogen formation even from complex feedstocks such as seawater. The structural stability and crystalline properties of these catalysts, as confirmed by techniques such as XRD, underscore their durability and reusability, making them promising candidates for sustainable hydrogen production systems. These findings highlight the transformative potential of advanced catalyst materials in driving efficient, scalable, and clean hydrogen generation technologies (Ali et al. 2021, 2022b, 2023a, 2023b).

Approximately 96 % of hydrogen production currently relies on fossil fuels, with the following breakdown: 48 % from methane steam reforming, 30 % from oil/naphtha reforming, 18 % from coal gasification, and roughly 4 % from electricity generated using fossil fuels (Kothari et al. 2008; da Silva Veras et al. 2017). To address the finite nature of fossil fuel resources and their associated greenhouse gas emissions, future hydrogen production must shift toward renewable resources. The energy required for the conversion process is typically supplied through electricity or heat.

With the increasing adoption of hydrogen as a versatile energy carrier, supplying hydrogen to industrial users represents a substantial global business opportunity. As illustrated in Figure 1, the International Energy Agency's Stated Policies Scenario (STEPS) projects that global hydrogen demand (G7 and other regions) will grow gradually, reaching 110 million tons by 2030 and 120 million tons by 2035. Under this scenario, hydrogen utilization until 2035 will primarily remain concentrated in sectors already using hydrogen, with limited expansion into new applications (IEA 2023c).

In the International Energy Agency's Net Zero Emissions by 2050 (NZE) scenario, global hydrogen demand is projected to reach 470 million tons by 2050. According to this scenario, demand will nearly double from 94 million tons in 2021 to 177 million tons by 2030 and triple to 269 million tons by 2035, driven by new applications in electricity generation, heavy industry, long-distance transportation, and the production of hydrogen-based fuels. The use of hydrogen-based fuels is significantly higher in the NZE scenario than in others, nearly doubling from 2030 to 2035, while hydrogen demand for oil refining declines during the same period. In contrast, the IEA's Announced Pledges Scenario (APS) is less ambitious than the NZE scenario. The APS assumes that all announced

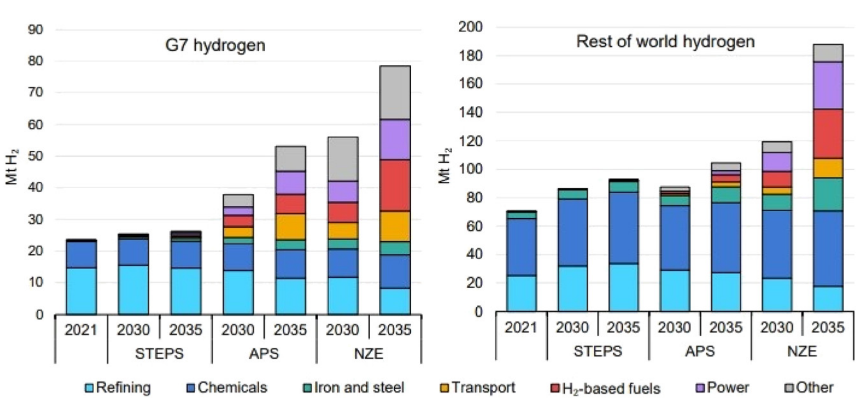

Figure 1: Hydrogen demand in the G7 and the rest of the world by sector and different scenarios. STEPS: Stated Policies Scenario, APS: Announced Pledges Scenario, NZE: Net Zero Emissions (IEA 2023c).

government climate targets are met on time and in full, with G7 countries playing a more prominent role than other regions (IEA 2023c).

In recent years, hydrogen has attracted significant attention from both industry and academia, with extensive discussions on its production methods, applications, and storage solutions (Agyekum et al. 2022; AlNouss et al. 2020; Balat 2008; Bossel et al. 2003; Brar et al. 2022; Corredor et al. 2019; Forsberg 2007; Kalamaras and Efstathiou 2013; Kothari et al. 2008; Kumar et al. 2019; Liu et al. 2020; Nikolaidis and Poullikkas 2017; Olabi et al. 2021; Palacios et al. 2022; Ramprakash et al. 2022; Rasul et al. 2022; Shanmughan et al. 2023; Sharma and Ghoshal 2015; Tarhan and Çil 2021; Verhelst and Wallner 2009; Voitic et al. 2018; Wang and Han 2022; Wang et al. 2014, 2019; Winter 2005; Xu et al. 2022; Yu et al. 2021; Zhang et al. 2016, 2017). Agyekum et al. (2022) reviewed methods for renewable hydrogen production and analyzed the parameters influencing their scalability. Xu et al. (2022) explored the future of hydrogen, focusing on bio-hydrogen as an energy source, discussing hydrogen production from fossil fuels, water, and biomass, and detailing bio-hydrogen production through biological and chemical methods. Liu et al. (2020) and Zhang et al. (2016) investigated trends, future challenges, and key technologies in hydrogen production and storage, with an emphasis on energy storage solutions. Olabi et al. (2021) examined large-scale hydrogen production and storage technologies.

The large-scale deployment of hydrogen as an energy carrier necessitates the advancement of production, storage, and distribution technologies tailored to regional and resource-specific conditions. While renewable hydrogen production via wind or solar-powered water electrolysis offers a clean pathway, it remains constrained by the intermittent nature of renewable energy sources and by growing concerns over freshwater availability for electrolysis in arid and densely populated regions (IEA 2019; Kumar et al. 2024). In fact, alternative water sources such as seawater or wastewater are actively being explored, though they come with additional energy costs for pretreatment and purification (Kumar et al. 2024; Simoes et al. 2021). Meanwhile, fossil fuel-based hydrogen production, primarily from natural gas through steam methane reforming (SMR), remains the dominant method due to its commercial maturity (Boretti and Banik 2021; Chau et al. 2022; Van Beurden 2004). However, this approach generates substantial CO2 emissions, and integrating carbon capture, utilization, and storage (CCUS) technologies increases cost and complexity.

Hydrogen storage introduces a different range of complex technical and economic considerations. In its gaseous form, high-pressure storage requires robust infrastructure and incurs energy penalties during compression. Liquid hydrogen, while denser, demands cryogenic temperatures, making long-term storage and transport both energy-intensive and costly (Al Ghafri et al. 2022). Solid-state hydrogen storage, such as through metal hydrides or porous materials like MOFs, has shown promise in offering safer and more compact solutions but remains in early stages of commercialization due to slow kinetics, limited capacity, and material degradation (Sakintuna et al. 2007; Zhao et al. 2022).

Underground hydrogen storage (UHS) in depleted natural gas reservoirs, aquifers, and salt caverns has been identified as a potentially scalable and cost-effective solution, especially for seasonal energy storage. However, the geochemical reactivity of hydrogen with surrounding rock or microbial activity may lead to losses or contamination, and suitable geological formations are not uniformly distributed (Panfilov 2016; Tarkowski 2019). As such, a one-size-fits-all strategy is impractical, and regional optimization based on resource availability, climate conditions, and infrastructure readiness is required to ensure viable integration of hydrogen into future energy systems.

The transition to a hydrogen economy is in its early stages, requiring sustained research and government support to advance production and storage technologies. Incer-Valverde et al. (2023) describe the "hydrogen rainbow," a classification system for hydrogen production pathways distinguished by colors such as green, blue, and gray. Each color denotes a specific production method: green represents renewable sources, blue indicates fossil fuel-based production with carbon capture, and gray signifies fossil fuel-based production without carbon capture. This system outlines the feedstock, process, and emissions for each color, with a focus on carbon intensity. Key challenges include reducing costs, developing infrastructure, and improving transportation. Countries are prioritizing green or blue hydrogen, influenced by electricity costs and the production of electrolyzers. Although political support is robust, a standardized color code is critical for clear communication and effective decision-making in advancing the hydrogen economy.

By 2050, green hydrogen is expected to become the dominant production method and economically competitive with natural gas prices. Rasul et al. (2022) investigated hydrogen's potential as an energy carrier, covering its production, storage, and distribution. Amid growing concerns about global warming, hydrogen's role as a clean fuel is gaining momentum, with a focus on carbon-neutral production for "green hydrogen." Despite the availability of various production methods, a robust infrastructure for hydrogen transmission, storage, and delivery is essential to meet global demand. Advanced hydrogen technologies, bolstered by government support, are crucial for their widespread adoption in transportation and industry to meet emissions reduction targets. Progress in waste-to-biohydrogen processes has bridged laboratory and commercial applications, though challenges such as low productivity and high costs remain. Brar et al. (2022) explored current insights into hydrogen production, offering valuable guidance for researchers and policymakers promoting sustainable hydrogen utilization. Wang et al. (2019) reviewed hydrogen production from water and biomass, evaluating their economic, technical, and environmental aspects.

Although renewable methods are significantly greener than fossil-based alternatives, their widespread implementation faces challenges related to efficiency and scalability. Consequently, without substantial improvements in energy conversion efficiency, storage systems, and grid integration, renewable technologies may struggle to meet the rising global energy demand in a reliable and cost-effective manner. This underscores the urgent need for continued innovation in system design, material development, and supportive policy frameworks to bridge the gap between sustainability goals and practical deployment. Biomass electrolysis stands out with its direct use of raw biomass, reduced environmental impact, and potential for efficient, catalyst-free hydrogen production.

The hydrogen economy envisions a transformative shift in the production, distribution, and consumption of energy. Hydrogen is assumed to play a pivotal role as a versatile energy carrier, surpassing traditional boundaries to serve as a clean fuel for power generation and transportation while revolutionizing industrial processes, such as chemical manufacturing and synthetic fuel production. This transformative potential aligns closely with global sustainable development goals, including reducing carbon emissions and greenhouse gases, enhancing energy security, and improving air quality. To advance toward a hydrogen-powered future, a comprehensive exploration of various aspects of hydrogen evolution is essential.

3 Hydrogen storage and transportation

Storage and transportation challenges are significant in utilizing hydrogen's potential as a clean energy carrier. Developing safe and efficient methods for storing and transporting hydrogen is essential to unlocking its wide-ranging applications across various sectors. This section briefly examines the complexities of hydrogen storage and transportation, exploring the methods and technologies critical to this vital component of the hydrogen economy.

3.1 Hydrogen storage

Hydrogen storage systems are classified into physical-based and material-based categories. Physical-based storage involves altering hydrogen's physical state, such as increasing pressure (compressed gaseous hydrogen storage, CGH_2), lowering temperature below its boiling point (liquid hydrogen storage, LH_2), or combining both methods (cryo-compressed hydrogen storage, CcH_2). Material-based storage employs carriers that physically or chemically bond with hydrogen molecules or atoms. Among the most promising options for long-term hydrogen storage are ammonia and liquid organic hydrogen carriers (LOHCs), which offer improved storage density and safety compared to physical-based systems. However, many material-based storage technologies remain in experimental or demonstration phases.

3.1.1 Compressed gas storage of hydrogen

Due to its low density, hydrogen requires compression to serve effectively as an energy carrier (Felderhoff et al. 2007). Compressed gaseous hydrogen (CGH_2) storage is a well-established technology that has seen rapid adoption among hydrogen storage methods due to its simplicity. However, compressing hydrogen, which has a density of only 0.083 kg/m^3 at normal temperature and pressure (NTP), requires substantial energy input (Muthukumar et al. 2023). Storing hydrogen in pressure vessels, which increases its density to 39.2 kg/m^3 at 700 bar and ambient temperature, is the most common method among available storage techniques (Lemmon et al. 2008). Storing hydrogen in pressure vessels, similar to methods used for other gases, is relatively straightforward, particularly at low to moderate pressure ranges. However, hydrogen's tendency to diffuse into metals, causing material embrittlement, requires ongoing technological improvements for retrofitting. Compared to other storage methods, pressure vessels offer faster charge and discharge rates (Ni 2006). Historically, gasometers, large containers designed for gas storage under near-ambient conditions, served to balance short-term gaseous fuel demand but have become obsolete. Today, underground pipe networks and high-pressure requirements of modern fuel cells have rendered gasometers impractical (Elberry et al. 2021). Gasometers and spherical or cylindrical vessels remain suitable for small- to medium-scale hydrogen storage, supporting stationary or mobile applications. In contrast, large-scale storage relies on natural or artificial underground systems, which are more effective at low to moderate pressure ranges (Ghorbani et al. 2023).

In vehicle storage tanks, hydrogen is pressurized to 350–700 bar, enabling a driving range of up to 450 km with refueling times under 3 min (Burheim 2017). Tanks operating at lower pressures provide insufficient energy storage, while pressures above 700 bar significantly increase the mechanical energy required for hydrogen storage, as the gas deviates from ideal behavior (Felderhoff et al. 2007). As shown in Figure 2, mass density of hydrogen varies with pressure. Liquefying hydrogen consumes approximately 30 % of its chemical energy, based on the lower heating value (LHV) of 120 MJ/kg (Ghorbani et al. 2023).

A simple comparison with CGH_2 can be made by examining an ideal gas compressed under isothermal conditions. Using the ideal gas law, the mechanical energy required is approximately 8 MJ/kg of hydrogen (equivalent to 7 % of the LHV) to reach 700 bar. However, actual compression processes differ significantly from isothermal conditions, requiring consideration of technical efficiencies. Consequently, actual compression demands about 15 % of the LHV to achieve 700 bar and 12 % for 350 bar in practical settings. These energy requirements remain substantially lower than the 30 % of LHV needed for hydrogen liquefaction (Felderhoff et al. 2007; Ghorbani et al. 2023).

Hydrogen is typically stored in steel cylinders at pressures up to 200 bar, widely used in general industrial applications (Schlapbach and Züttel 2001). These cylinders, classified as Type-I tanks, have a relatively low gravimetric density of approximately 1 %. To achieve sufficient volumetric and gravimetric capacities, particularly for mobile applications, higher storage pressures are necessary (Muthukumar et al. 2023). Figure 3 provides a graphical comparison of various tank types, detailing their system weight, volume, and associated costs for vehicle applications.

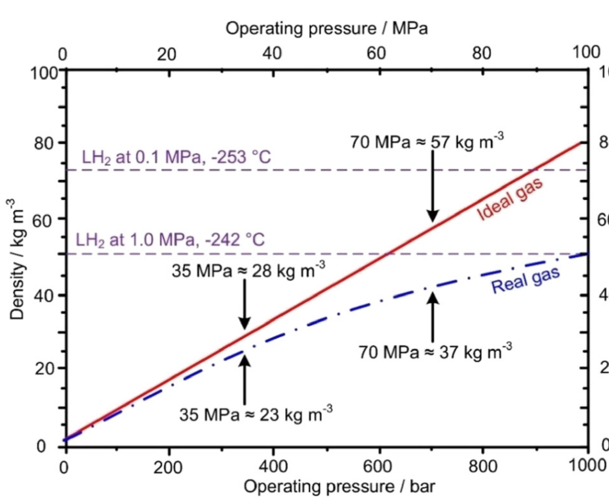

Figure 2: Relationship between hydrogen mass density and pressure (Ghorbani et al. 2023). Reproduced with permission from Elsevier.

The compressed hydrogen storage mainly comprises four tank types as below:

I) *Type-I tanks*: These tanks are ideal for industrial applications with access to warehouse facilities, as they avoid the costs of advanced tank materials and high-pressure hydrogen compression, which can exceed warehousing expenses. Constructed entirely from metal, these pressure vessels offer a traditional and cost-effective solution, despite their higher weight of approximately 1.36 kg/L. Typically made from aluminum or steel, they can withstand pressures up to 500 bar and achieve a gravimetric capacity of 1.7 wt% (Muthukumar et al. 2023; Moradi and Groth 2019; Rivard et al. 2019).

II) *Type-II tanks*: These tanks are utilized when the need for increased volumetric capacity outweighs cost considerations. Type-II tanks feature a thick aluminum or steel liner wrapped with a fiber-resin composite mesh, which enhances their structural strength and load-bearing capacity. This design enables them to withstand higher pressures while occupying less space. Although approximately 1.5 times more expensive than Type-I tanks, they achieve a 30–40 % weight reduction at storage pressures up to 300 bar and offer a gravimetric capacity of 2.1 wt% (Muthukumar et al. 2023, Moradi and Groth 2019, Rivard et al. 2019).

III) *Type-III tanks*: These tanks offer an advancement over Type-II tanks in construction and pressure capabilities. Unlike Type-II tanks, which have liners covering only the lateral surface where hoop stress occurs, Type-III tanks feature a liner enveloping the entire tank surface. Composed primarily of a composite body, typically carbon fiber, these tanks support a pressure range of 350–700 bar. The aluminum liner in Type-III tanks serves mainly as a sealant, bearing only 5 % of the mechanical load, while the composite outer shell supports the remainder. These tanks achieve a higher gravimetric capacity than Type-I and Type-II tanks, reaching 4.2 wt% (Hua et al. 2011; Muthukumar et al. 2023; Moradi and Groth 2019; Rivard et al. 2019).

IV) *Type-IV tanks*: These tanks employ synthetic materials, such as carbon fiber-reinforced resin, paired with polymer-based liners, typically high-density polyethylene (HDPE), and a carbon fiber composite overwrap. These tanks can withstand pressures up to 750 bar, making them highly suitable for mobile applications due to their lightweight composite construction. Notably, the hydrogen tank in the Toyota Mirai achieves a gravimetric capacity of 5.7 wt% at a pressure rating of 700 bar (Hua et al. 2011; Muthukumar et al. 2023; Moradi and Groth 2019; Rivard et al. 2019).

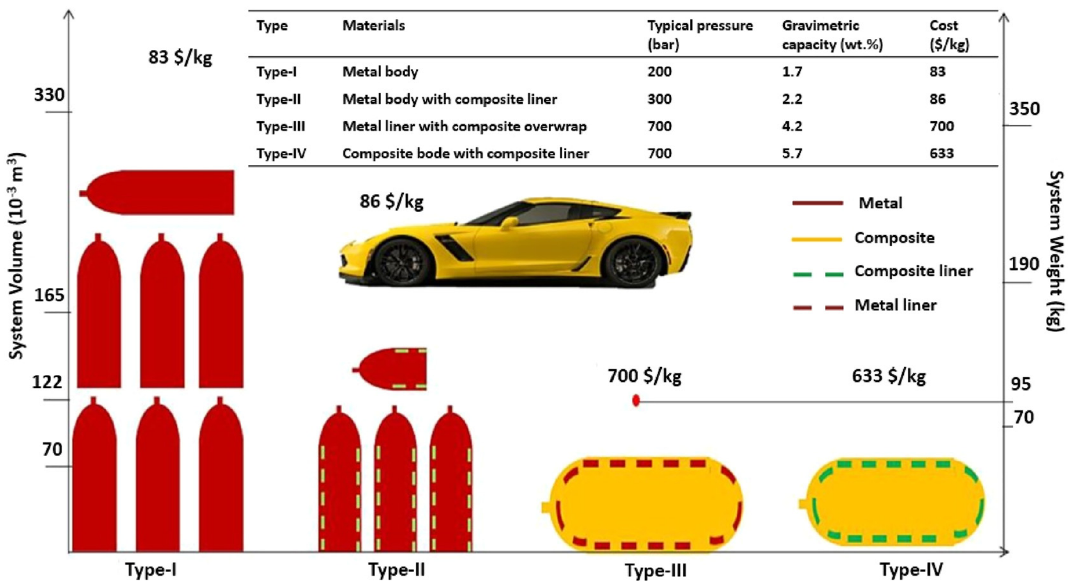

Figure 3: An overview of the various types of tanks utilized for hydrogen storage. Modified from (Muthukumar et al. 2023). Reproduced with permission from Elsevier.

V) *Type-V tanks*: Type-V tanks, fully composite vessels reinforced primarily with carbon fiber and designed without a liner, represent an advancement over Type-I to Type-IV tanks (Cheng et al. 2024; CompositesWorld 2023; Gardiner 2024). These linerless pressure vessels are the lightest among the five types. However, the absence of a liner, which typically prevents gas and cryogenic liquid permeation into the composite laminate, poses challenges, particularly at high pressures up to 993 bar. Developing linerless tanks capable of reliably withstanding thousands of pressurization cycles remains technically demanding. By eliminating the need for a metal or plastic liner, Type-V tanks reduce weight, manufacturing costs and time, and associated logistical and production complexities.

The linerless design of Type-V tanks mitigates challenges such as entrapped air between the liner and composite overwrap and other quality issues historically linked to tank failures (CompositesWorld 2023). Their enhanced pressure capabilities also make them suitable for space applications, creating new opportunities for high-pressure, lightweight infrastructure solutions. Compared to traditional all-metal tanks used for storing and transporting industrial gases, Type-V tanks achieve up to 90 % less mass, and up to 40 % less mass compared to conventional composite-overwrapped metal pressure vessels (COPVs) commonly used in space vehicles. Additionally, they offer at least a 70 % reduction in lead time and up to a 50 % cost reduction compared to traditional COPVs. However, Type-V tanks may exhibit higher gas permeation than pressure vessels with metal liners. These advancements could foster collaborations between local industries and academic institutions, potentially supporting internships and knowledge exchange initiatives (CompositesWorld 2023; Gardiner 2024).

3.1.2 Liquid/cryogenic hydrogen storage

Cryogenic hydrogen storage requires liquefying hydrogen at −253 °C, its boiling point at ambient pressure, posing significant challenges in maintaining these extreme storage conditions. The substantial density difference between gaseous and liquid hydrogen (LH_2) necessitates large, high-pressure-resistant containers for transporting compressed hydrogen gas, which may not always be cost-effective (Trevisani et al. 2007). Alternatively, specialized containers designed for LH_2 storage and transportation provide a viable solution, particularly for long-distance transport (Yang and Ogden 2007).

Liquefying hydrogen can facilitate peak shaving by storing excess power as liquid fuel for utilization during high-demand periods (Al-Hallaj et al. 2017). However, liquid hydrogen production faces significant challenges, including high economic costs, low efficiency, and substantial energy losses (Aasadnia and Mehrpooya 2018). The liquefaction process is both time- and energy-intensive, with up to 40 % of the energy content lost, compared to approximately 10 % for compressed hydrogen storage (Barthelemy et al. 2017). Although LH_2 offers the highest density among physical hydrogen storage methods, its volumetric energy density remains lower than that of conventional liquid fuels, such as gasoline or diesel, as shown in Figure 4(a) (Morales-Ospino et al. 2023). For example, 0.25 L of gasoline or 0.22 L of diesel provide the same energy as 1 L of LH_2. Nevertheless, hydrogen's superior gravimetric capacity remains a key advantage.

Figure 5 illustrates the hydrogen liquefaction process (Al Ghafri et al. 2022). The process begins with precompression, as the hydrogen feed enters at relatively low pressure. This is followed by an optional precooling stage to 80 K and an adsorption stage to remove impurities that could freeze during cryogenic liquefaction. Subsequently, hydrogen is cooled to below temperature below 30 K using a closed-loop cryogenic refrigeration cycle. This cycle includes continuous or batch catalytic conversion of ortho- to para-hydrogen. The process typically concludes with adiabatic expansion, achieved through either Joule–Thomson or turbine expansion. Liquid hydrogen is stored at 20–23 K (0.1–0.2 MPa), with a para-hydrogen fraction exceeding 98 % (Al Ghafri et al. 2022; Gupta et al. 2016).

The hydrogen molecule consists of two protons and two electrons, exhibiting two distinct molecular configurations based on nuclear spin: para-hydrogen and ortho-hydrogen. Para-hydrogen occurs when nuclear spins are antiparallel, whereas ortho-hydrogen occurs when spins are parallel. When electron spins are antiparallel, hydrogen transitions to a lower energy state, as shown in Figure 4(b) (Ghorbani et al. 2023). At ambient conditions, hydrogen exists predominantly as ortho-hydrogen, with approximately 75 % ortho-hydrogen and 25 % para-hydrogen (Lee et al. 2021). Although ortho-hydrogen and para-hydrogen share similar chemical properties, their mechanical properties differ. Pure ortho-hydrogen is difficult to isolate, as para-hydrogen predominates at lower temperatures due to its lower energy state. The melting and boiling points of para-hydrogen are approximately 0.1 K lower than those of normal hydrogen. Cooling hydrogen to its boiling point of 21.2 K results in approximately 99.9 % para-hydrogen. However, the slow conversion from ortho- to para-hydrogen can lead to evaporation and loss of LH_2 in storage tanks. Catalysts, such as iron(III) hydroxide, nickel, chromium, or manganese, accelerate this conversion process. This conversion, which releases heat and contributes to boil-off, is critical for long-term LH_2 storage to minimize hydrogen losses. When storing normal hydrogen as a liquid, the conversion enthalpy released within the tank causes LH_2 evaporation (Ghorbani et al. 2023).

Cryogenic storage is primarily used for medium- to large-scale hydrogen storage and distribution, such as truck delivery and intercontinental shipping, as illustrated in

Figure 4: (a) Graphical comparison of energy content per unit volume based on the lower heating values (LHV) of the fuels (Morales-Ospino et al. 2023); (b) the direction of parallel and antiparallel nuclear spins of hydrogen molecules (Ghorbani et al. 2023). Reproduced with permission from Elsevier; Hydrogen transportation examples: (c) Iwatani Corporation LH_2 transport container (Kawasaki 2025), and (d) Ship Carrying Liquefied Gases in Bulk (total carrying capacity: 2,500 m^3) (Kawasaki 2014).

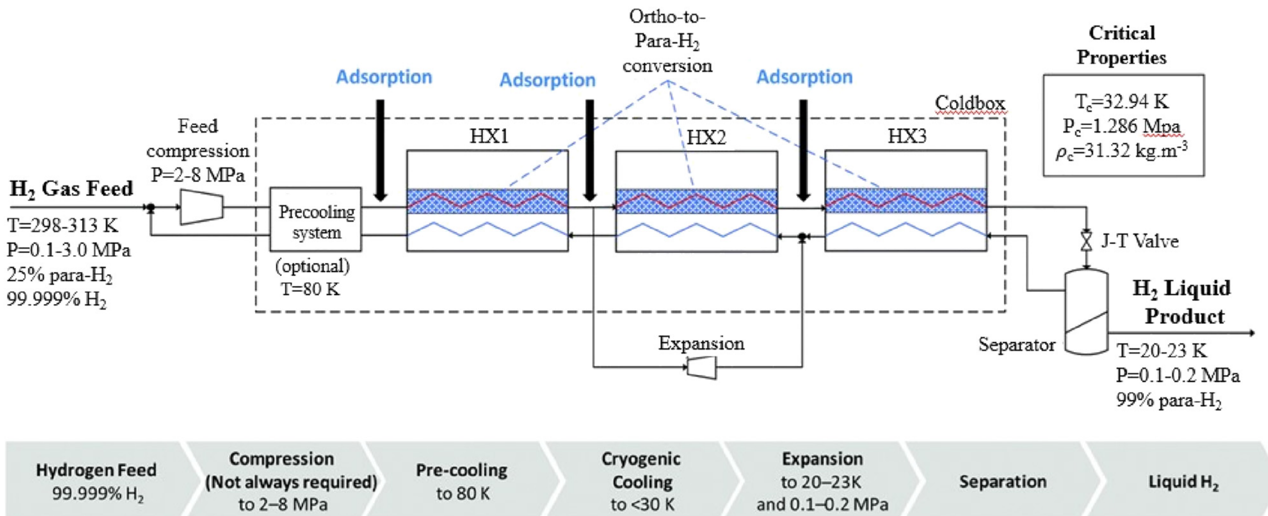

Figure 5: Simplified schematic diagram of the hydrogen liquefaction process based on the simple Claude cycle (Al Ghafri et al. 2022).

Figure 4(c and d). A typical cryogenic tanker can transport up to 5,000 kg of hydrogen, approximately five times the capacity of compressed hydrogen gas tube trailers (Moradi and Groth 2019). This storage method supports applications like truck delivery and intercontinental hydrogen shipping. Large-scale storage and transportation of hydrogen can be efficiently conducted in liquid form using specialized vessels. However, the cryogenic storage requirements of LH_2 demand advanced tank designs to minimize evaporation caused by heat transfer from the surroundings. As LH_2 is noncorrosive, well-insulated tanks made of stainless steel or aluminum alloys are used for cryogenic storage. For safety, these cryogenic vessels are equipped with an additional protective layer, such as a vacuum jacket, to safeguard against accidents. Moreover, hydrogen exhibits low adiabatic expansion energy at extremely low cryogenic temperatures, meaning that in the event of a leak or tanker rupture, a severe explosion is unlikely unless an ignition source is present. To further reduce thermal conductivity between the inner vessel and the outer jacket, super-insulation techniques, such as wrapping with layers of aluminum films or using perlite powder, are employed (Barthelemy et al. 2017).

3.1.3 Cryo-compressed hydrogen storage

Cryo-compressed hydrogen (CcH_2) storage combines the benefits of both compressed gas and liquid hydrogen storage by containing hydrogen at extremely low temperatures (around −233 °C) in a high-pressure vessel, typically operating between 250 and 350 bar. Unlike conventional cryogenic storage, which keeps liquid hydrogen at pressures near atmospheric levels, CcH_2 is designed to accommodate hydrogen in several forms, such as liquid hydrogen, cold-compressed hydrogen, or a two-phase mixture of saturated liquid and vapor, within the same system (Ahluwalia et al. 2010). This approach improves versatility and storage efficiency compared to traditional methods.

Figure 6 compares three hydrogen storage methods: GCH_2, LH_2, and CcH_2. Among them, cryo-compressed storage shows significant promise in both storage capacity and safety. It provides a high storage density of approximately 80 g/L, which is about 10 g/L higher than that of LH_2 storage (Elazab et al. 2025). CcH_2 also features a lower hydrogen loss rate, ranging from 0.2 to 1.6 g/h/kg, compared to 8 g/h/kg for LH_2 tanks (Yan et al. 2023). Additionally, the thermal insulation required for CcH_2 is only one-tenth of that needed for LH_2 tanks. Refueling rates are also superior with CcH_2, reaching up to 80 kg/min, whereas LH_2 tanks offer about 1.14 kg/min (Stolten et al. 2016; Yan et al. 2023). Therefore, CcH_2 represents a particularly suitable storage solution for high-power, heavy-duty vehicles.

As previously discussed, conventional Type III and IV vessels are prone to failure, as illustrated in Figure 7(a) (Berro Ramirez et al. 2015; Rivard et al. 2019). In the safe mode (without ejection of the metallic bosses), failure predominantly occurs in the cylindrical section, where the metallic bosses move inward into the tank. This burst is mainly caused by fiber breakdown in the outer, circumferential plies. While this mode is primarily triggered by fiber breakage, other forms of composite damage, such as matrix cracking and delamination, can slightly influence this burst mode. The axial displacement recorded on the tank shows a sharp decline upon reaching the maximum displacement

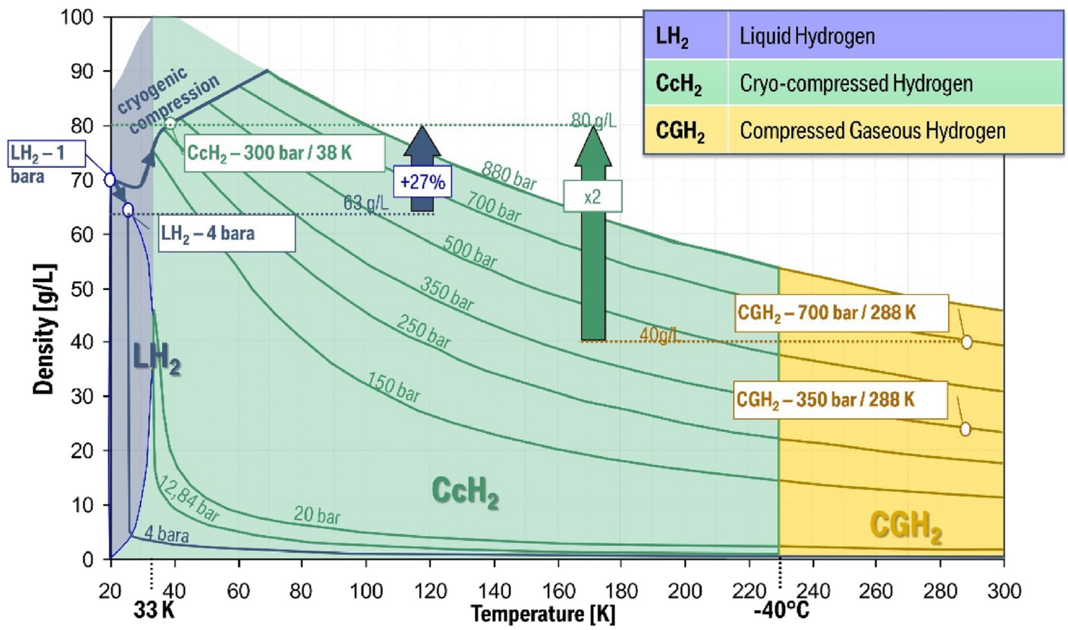

Figure 6: Variation of hydrogen density and temperature in different physical-based hydrogen storage (Elazab et al. 2025). Reproduced with permission from Elsevier.

point, indicating this failure (Figure 7(b)). Under cryogenic conditions, weak interlayer adhesion may arise due to the different thermal expansion behaviors of the aluminum cylinder and the composite layer, leading to delamination between the two materials (Islam et al. 2015). In the unsafe mode (characterized by ejection of metallic bosses), failure initiates at the dome, causing a metallic boss to be expelled differently (Figure 7(c)). The primary cause of this structural failure is fiber breakage in the helical plies; however, additional damage modes, especially matrix cracking, can significantly alter the burst mode from safe to unsafe by contributing to fiber overload (Berro Ramirez et al. 2015).

Additionally, high-pressure hydrogen can easily permeate the lattice structure of the aluminum cylinder upon contact, leading to embrittlement. As a result, this embrittlement can cause fractures and cracks in the cylindrical material, especially under high-pressure conditions (Laadel et al. 2022; Qiu et al. 2021; Yan et al. 2024). These findings highlight the significant challenges posed by liners in CcH_2 storage tanks. Therefore, eliminating the liner structure by using composite materials with sufficient hydrogen-barrier properties could make linerless Type V vessels a promising option for CcH_2 storage (Yan et al. 2024).

Heavy-duty vehicles can benefit significantly from cryo-compressed hydrogen storage, thanks to extended dormancy periods, improved safety, and rapid refueling capabilities. However, achieving the necessary pressure-bearing capacity and hydrogen-barrier performance in modern linerless Type V CcH_2 storage containers, especially under extreme cryogenic temperatures and high pressures, remains a major challenge. The primary factor limiting cryogenic performance is resin failure. Comparative studies indicate that interlayer films can effectively reduce hydrogen permeability, and that thermoplastics are generally more suitable than other materials for toughening resins. Additionally, incorporating nanoparticles into resins not only helps prevent the propagation of microcracks but also creates complex pathways within the composite, further impeding hydrogen permeation (Yan et al. 2024). Nevertheless, further research is needed regarding temperature-induced strain and the modulation of nanomaterial states.

3.1.4 Material-based hydrogen storage

Solid-state hydrogen storage emerges as a promising alternative, offering notable advantages in energy efficiency, safety, and both gravimetric and volumetric storage capacities. According to the technical benchmarks established by the US Department of Energy (DOE) for onboard hydrogen storage systems in light-duty vehicles, some materials can achieve the required gravimetric and volumetric storage capacities at the material level. However, these materials have yet to meet the DOE's system-level targets, 0.055 kg H_2/kg system and 0.040 kg H_2/L system as of 2017, as illustrated in Figure 8 (Godula-Jopek 2015; Züttel 2004).

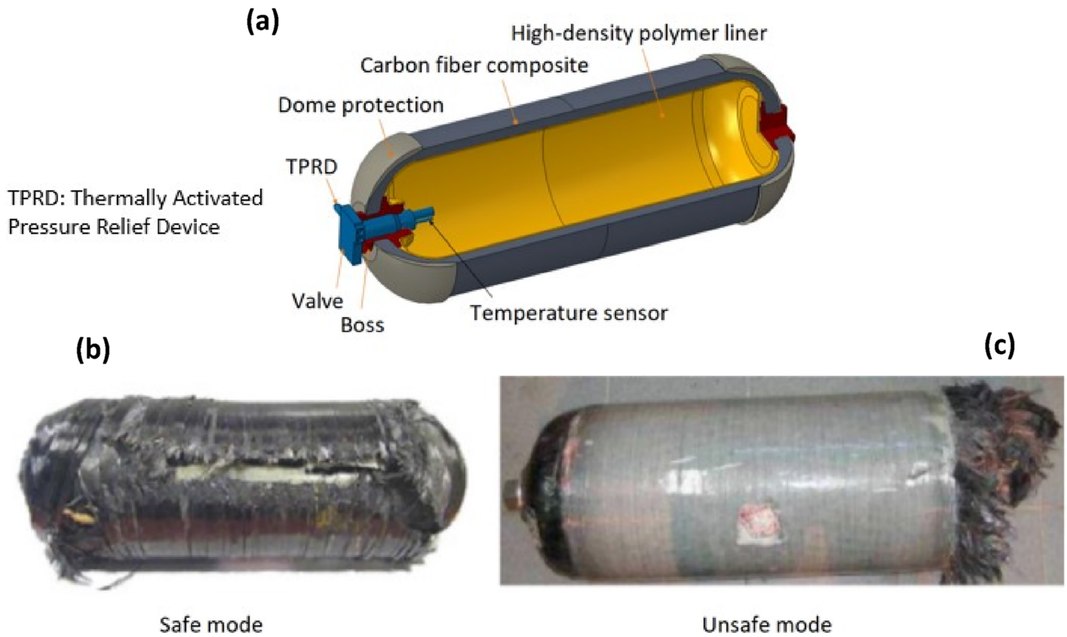

Figure 7: Hydrogen pressure vessel. (a) Type-IV composite overwrapped hydrogen pressure tank (Rivard et al. 2019); composite failure in Type IV vessels in (b) safe and (c) unsafe mode (Berro Ramirez et al. 2015). Reproduced with permission from Elsevier.

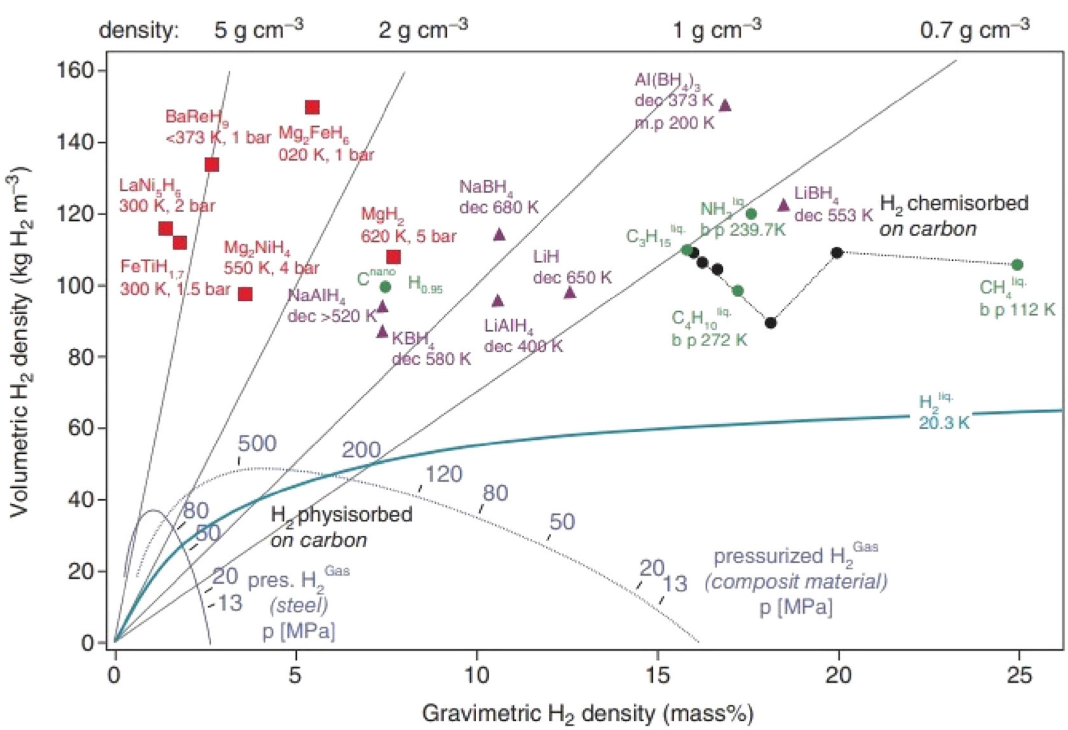

Figure 8: Volumetric and gravimetric hydrogen density of some selected hydrides (Züttel 2004). Reproduced with permission from Springer Nature.

In both physical and chemical sorption storage methods, many base materials are used in powder form, while some, such as liquid organic hydrogen carriers, are in a liquid state. During hydrogen charging and discharging, heat is either generated or absorbed; however, powder-based materials are often inefficient at transferring heat. To address this limitation, various preprocessing techniques, such as casting, foaming, coating, uniaxial pressing, and templating, are employed to enhance thermal conductivity and handling. After processing, the material is incorporated into a containment system. These containment systems typically include an integrated heat exchanger for effective thermal management, as well as connections for controlling hydrogen flow and filtering the input and output hydrogen gas (Moradi and Groth 2019).

3.1.4.1 Chemical storage

In chemical hydrogen storage, chemical bonds form between the atoms of a solid compound and hydrogen. As a result, chemisorption takes place prior to hydrogen absorption on the bulk surface, followed by the formation and breaking of chemical bonds during hydrogen uptake and release (loading and unloading) (Godula-Jopek 2015). Metal hydrides are among the most important materials used for this purpose. However, chemical sorption materials still face several challenges, including reducing operating temperatures, weights, and costs; improving charge–discharge kinetics; and controlling the production of undesirable gases during desorption (Ren et al. 2017; Motyka 2015). One of the most remarkable features of metallic hydrides is their exceptionally high volumetric density of hydrogen atoms within the host lattice (see Figure 8). Complex hydrides such as Mg_2FeH_6 and $Al(BH_4)_3$ exhibit volumetric hydrogen densities of approximately 150 $kg{\cdot}m^{-3}$, which is more than double that of liquid hydrogen. Metallic hydrides like $LaNi_5$ achieve a volumetric hydrogen density of around 115 $kg{\cdot}m^{-3}$. While most metallic hydrides can absorb hydrogen up to a hydrogen-to-metal (H/M) ratio of 2, some compounds, such as $BaReH_9$, display significantly higher ratios, up to H/M = 4.5, meaning that for every metal atom, there are 4.5 hydrogen atoms in the lattice (Yvon 1998).

It is noteworthy that all hydrides with a hydrogen-to-metal (H/M) ratio greater than 2 are ionic or covalent compounds, classified as complex hydrides. Among these, $LiBH_4$ exhibits the highest gravimetric hydrogen density, reaching up to 18 mass%. Metal hydrides provide a practical solution for the safe and efficient storage of large amounts of hydrogen in a compact form. However, it is important to note that at atmospheric pressure and ambient temperature, all reversible hydrides are transition metal-based, which limits their gravimetric hydrogen density to less than 3 wt%. Therefore, further research is needed to explore the properties of lightweight metal hydrides to fully unlock their potential (Züttel 2004).

Liquid Organic Hydrogen Carriers (LOHCs) represent a promising option for hydrogen storage. In LOHC systems, hydrogen is stored by chemically bonding with hydrogen-lean carrier molecules and released through a catalytic dehydrogenation process (Modisha et al. 2019; Preuster et al. 2017; Samoilov et al. 2023). These storage systems offer several advantages, including easy handling under ambient conditions, carbon-free hydrogen storage and release, reusability of the carrier liquid without consumption, nontoxic and noncorrosive properties, and low-pressure storage requirements. However, a major challenge for LOHCs is their relatively low hydrogen storage capacity, with a maximum reported value of 7.2 wt%. This limitation may constrain their applicability in certain contexts (Modisha et al. 2019; Niermann et al. 2019).

LOHCs store hydrogen by forming chemical bonds through hydrogenation and release it via catalytic dehydrogenation. The manuscript mentions LOHCs like N-ethylcarbazole and methylcyclohexane (MCH) as examples (Modisha et al. 2019; Preuster et al. 2017; Samoilov et al. 2023). For a generic hydrocarbon LOHC, the process can be represented as: $R\text{-}H_n \rightarrow R + (n/2)H_2$, where $R\text{-}H_n$ is the hydrogenated (hydrogen-rich) form of the LOHC, R is the dehydrogenated (hydrogen-lean) form, and n is the number of hydrogen atoms stored per molecule. As another example, methylcyclohexane (C_7H_{14}) is hydrogenated to store hydrogen and dehydrogenated to release it, converting back to toluene (C_7H_8) (Cui et al. 2019). The reversible reaction is:

$$C_7H_{14} \rightarrow C_7H_8 + 3H_2 \quad (1)$$

This reaction typically requires a catalyst (e.g., platinum or palladium) and heat (200–300 °C) due to the endothermic nature of dehydrogenation, consuming approximately 20–40 % of the hydrogen's lower heating value (LHV).

Methanol is a promising option for hydrogen storage and has been a well-established method commercially available since the early 1900s. Hydrogen can be produced from methanol through processes such as partial oxidation, steam reforming, and thermolysis (Eqs. (2)–(4)). However, using methanol as a hydrogen storage solution causes environmental issues at the utilization site due to the production of carbon dioxide during the direct utilization or decomposition of methanol (Yang et al. 2023). Consequently, this approach is not CO_2-free and results in a positive carbon footprint across the entire energy system.

$$2CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \quad (2)$$

$$CH_3OH \rightarrow CO + 2H_2 \quad (3)$$

$$CH_3OH + 0.5O_2 \rightarrow CO_2 + 2H_2 \quad (4)$$

Methanol steam reforming is the most advantageous method for releasing hydrogen from methanol compared to other catalytic processes, due to its higher hydrogen yield per methanol molecule and relatively lower energy consumption. However, the energy-intensive CO_2 separation step, commonly performed by absorption using amine solutions, further intensifies the environmental impact (Aziz et al. 2020; Yang et al. 2023). Ammonia presents a highly promising option for hydrogen storage, offering a high hydrogen density of 17.8 % and versatile applications in both mobile and stationary sectors. Its chemical stability makes ammonia suitable for addressing energy storage challenges across both spatial (energy export/import) and temporal (long-term stationary storage) dimensions (Yang et al. 2023). Unlike hydrogen, ammonia can be easily liquefied at −33 °C under atmospheric pressure or at 20 °C when pressurized to 7.5 bar. This ease of liquefaction makes ammonia the preferred choice for large-scale liquid storage, with vessels capable of holding up to 50,000 tons (Ono and Erhard 2000).

Ammonia can be utilized by directly employing it as a fuel or extracting its stored hydrogen. Ammonia is a promising hydrogen carrier due to its high hydrogen content (17.8 wt%) and ability to be stored and transported efficiently. The decomposition of ammonia, an endothermic reaction, to release hydrogen occurs via a catalytic process, typically at elevated temperatures (300–600 °C), with catalysts such as nickel or ruthenium. The primary reaction for ammonia decomposition is:

$$2NH_3 \rightarrow N_2 + 3H_2 \tag{5}$$

The process yields nitrogen and hydrogen gases, with no CO_2 emissions, making it a carbon-neutral option when powered by renewable energy.

Ammonia is widely used today in the production of explosives, pesticides, and other chemicals, as well as a key fertilizer in agriculture and a refrigerant gas (Fecke et al. 2016; Ikäheimo et al. 2018). Additionally, handling protocols and regulations for ammonia are well-established internationally. Numerous studies have explored ammonia's potential as an alternative energy source (Balci et al. 2024; Frattini et al. 2016; Joseph Sekhar et al. 2024). Storage facilities are essential in manufacturing and processing plants to manage fluctuations in shipments and usage. When production and consumption are geographically separated, suitable transportation infrastructure is required, which may include pipelines, tank cars, river barges, rail, or oceangoing ships. Although ammonia is usually handled in liquid form, supplying ammonia vapor directly to downstream users on-site can sometimes be advantageous, as it reduces the refrigeration energy demand of the ammonia factory. As a liquefied gas, ammonia shares many characteristics with other liquefied gases regarding storage and distribution technologies (Ono and Erhard 2000).

Ammonia still faces several challenges before it can be widely adopted in the energy sector. These include its inherent properties, conversion technologies, and potential environmental impacts after use. Factors influencing the successful adoption of ammonia as an alternative fuel include availability, pricing, safety standards, propulsion technology, port infrastructure, stakeholder support, implementation of carbon pricing, public awareness about emissions, research and development efforts, and the presence of early adopter companies using the fuel. Among these, the most critical success factors are public awareness, the number of early adopters, stakeholder engagement, and carbon taxation. Addressing these key criteria will pave the way for the establishment of ammonia safety regulations and further advancements in research and development, ultimately improving ammonia-powered propulsion systems and enabling a large-scale supply of green ammonia (Balci et al. 2024).

3.1.4.2 Physical storage

One promising approach to developing reliable, high-capacity hydrogen storage units involves the use of porous material-based systems. Among these, metal–organic frameworks (MOFs) and porous carbon materials are widely recognized as the most promising candidates (Sengupta et al. 2023; Yousaf et al. 2023; Xia et al. 2013; Zhu and Xu 2014). This approach offers advantages such as high surface area, low hydrogen binding energy, faster charge and discharge kinetics, and relatively low material costs. Additionally, physical adsorption can reduce heat management challenges during hydrogen uptake and release. However, this method also presents challenges, including the weight of carrier materials, the requirement for high pressure and low temperature, and still limited volumetric and gravimetric hydrogen densities (Moradi and Groth 2019). Furthermore, physical sorption technologies remain far from large-scale deployment, as most testing has been conducted at small scales and key performance targets, including operating temperature, pressure, and storage capacities, have yet to be achieved.

MOFs are composed of small organic molecules, typically aromatic rings (C6), linked by metal clusters to form a three-dimensional structure. These frameworks can adsorb hydrogen in very large and dense amounts. This occurs because, while hydrogen forms bonds within the metal framework itself, the extensive cavities created by the MOF structure serve as the primary sites where hydrogen is adsorbed and densely packed (Burheim 2017). According to Rosi et al. (2003), MOF-5 exhibited hydrogen storage capacities of 4.5 wt% at −195 °C and 1.0 wt% at room temperature under 20 bar pressure. A ball-and-stick illustration of the MOF-5 structure is shown in Figure 9 (Wikipedia). Since adsorption and absorption processes are often accompanied by temperature changes, an effective thermal management system is necessary to maintain performance (Chakraborty and Kumar 2013). It is important to note that MOFs have very low thermal conductivity, approximately 0.3 W/(m·K), compared to materials like copper, which has a thermal conductivity of about 400 W/(m·K) (Li et al. 2021). This poor thermal conductivity complicates temperature management in MOF-based hydrogen storage systems (Hardy et al. 2018). Because designing heat transfer devices for such systems is resource-intensive, Hardy et al. (2018) proposed a method to evaluate the overall performance of an ideal system. Their analysis concluded that, to meet the 2025 Department of Energy (DOE) targets, a material used in a MOF-based hydrogen storage system would need to store roughly 4.5 times more hydrogen than MOF-5.

The utilization of MOFs with their desirable properties makes them a promising option for hydrogen storage. These materials exhibit high crystallinity, large surface area, and substantial pore volume. Furthermore, their tunable nature allows for the modification and design of their structures and properties to meet specific application requirements. MOFs are also enriched with open metal sites, which enhance charge density and increase hydrogen-binding enthalpies (Chen et al. 2022). However, MOFs face challenges such as low hydrogen uptake at ambient temperatures and limited processability. Therefore, achieving an optimal balance among hydrogen adsorption performance, processability, and mechanical stability is essential when selecting suitable adsorbents for hydrogen storage.

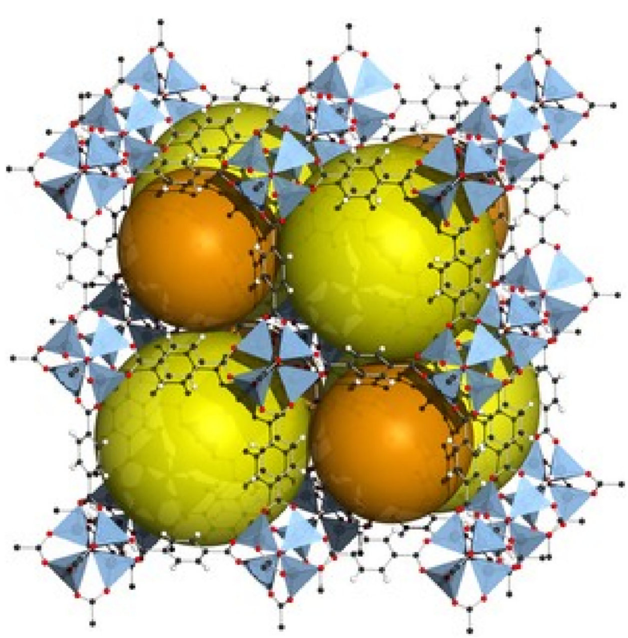

Figure 9: The unit cell structure of MOF-5. The spheres in yellow and orange indicate the pore's volume. Red is oxygen, black is carbon, white is hydrogen, and blue polyhedron is zink. Tetrahedrons show how the zinc core and 1,4-benzenedicarboxylate (BDC) are coordinated (Reproduced from Boehle 2013). Source: https://commons.wikimedia.org/wiki/File:MOF-5.png). Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license; author: Tony Boehle.

In addition to MOFs, other materials such as covalent organic frameworks (COFs), porous organic polymers (POPs), carbon-based materials, and zeolites have also attracted attention for their utilization as hydrogen sorbents (Chen et al. 2022). COFs and zeolites are porous solids with crystalline and well-organized structures similar to those of MOFs. COFs consist of organic building blocks linked by covalent bonds, forming two- or three-dimensional frameworks characterized by high chemical and thermal stability. Zeolites are microporous aluminosilicate minerals with well-defined pore structures and readily accessible channels. These materials often contain counter-ions, which can influence the interactions and binding energies of guest molecules. However, hydrogen binding energies in silica-based zeolites are generally comparable to those found in carbon-based materials.

POPs and carbon-based materials typically have amorphous structures but maintain permanent porosity. Due to their excellent mechanical stability and ease of processing, amorphous POPs have been investigated as promising alternatives for hydrogen storage. Carbon-based materials, such as carbon fibers, carbon nanotubes, porous carbons, and fullerenes, are also considered suitable sorbents for gas storage because of their structural diversity. Their composition and porosity can be tailored to improve hydrogen storage capacity. Moreover, carbon-based materials have attracted significant interest as hydrogen sorbents due to their abundance, lightweight nature, ease of processing, and exceptional chemical and thermal stability (Cousins and Zhang 2019; Chen et al. 2022; Ding and Wang 2013; Han et al. 2008; Lopes et al. 2009; Mandal and Gregory 2009; Titirici et al. 2015).

3.1.4.3 Comparative analysis of material-based hydrogen storage

A comparison of hydrogen carriers, particularly chemical storage methods such as methanol, ammonia, and liquid organic hydrogen carriers (LOHCs), with common technologies like compressed gas storage has been performed (Table 1). This study highlights that hydrogen storage systems can be broadly categorized into physical-based (e.g., compressed gas, cryogenic liquid, and cryo-compressed) and material-based (e.g., chemical and physical sorption) methods. Compressed gas storage, a mature technology with a Technology Readiness Level (TRL) of 8–9, is widely used due to its simplicity and established infrastructure. It involves storing hydrogen at high pressures (350–700 bar) in Type I–IV tanks, with Type V linerless tanks emerging as a lighter, high-pressure option (up to 993 bar). However, compressing hydrogen to these pressures requires significant energy, approximately 15 % of the lower heating value (LHV) for 700 bar and 12 % for 350 bar, compared to the ideal gas law estimate of 7 % LHV for 700 bar (Felderhoff et al. 2007; Ghorbani et al. 2023). The gravimetric capacity of compressed gas storage ranges from 1.7 wt% for Type I tanks to 5.7 wt% for Type IV tanks, with Type V tanks potentially offering higher capacities but facing challenges with permeation and pressure-cycle fatigue (CompositesWorld 2023; Muthukumar et al. 2023). Volumetric density remains a limitation, with hydrogen at 700 bar achieving approximately 39.2 kg/m^3, significantly lower than liquid hydrogen or chemical carriers (Ghorbani et al. 2023).

In contrast, chemical storage methods, such as those using methanol, ammonia, and LOHCs, rely on forming chemical bonds with hydrogen, offering advantages in terms of safety, ambient storage conditions, and potentially higher energy densities. Methanol, a well-established hydrogen carrier since the early 1900s, stores hydrogen through chemical bonding and releases it via processes like steam reforming, partial oxidation, or thermolysis (Yang et al. 2023). The manuscript notes that methanol steam reforming is particularly efficient, yielding a higher hydrogen output per molecule with lower energy consumption compared to other methods (Aziz et al. 2020; Yang et al. 2023). However, methanol-based storage has a gravimetric hydrogen capacity of approximately 12.5 wt% and a volumetric density of around 100 kg/m^3, but its environmental drawback is the production of CO_2 during hydrogen release, resulting in a positive carbon footprint (Yang et al. 2023). The energy required for methanol synthesis and hydrogen release, including CO_2 separation via amine absorption, adds to the process's energy intensity, consuming approximately 20–30 % of the hydrogen's energy content (Aziz et al. 2020; Yang et al. 2023).

Ammonia stands out as a promising chemical carrier due to its high hydrogen content (17.8 wt%) and volumetric density (121 kg/m^3 when liquefied at −33 °C or 7.5 bar), making it suitable for both stationary and mobile applications (Yang et al. 2023). Ammonia's ability to be liquefied at relatively moderate conditions simplifies storage and transportation compared to liquid hydrogen, which requires cryogenic temperatures of −253 °C. The manuscript highlights ammonia's established infrastructure for large-scale storage (up to 50,000 tons per vessel) and its use in industries like fertilizer production (Fecke et al. 2016; Ikäheimo et al. 2018).

However, extracting hydrogen from ammonia via catalytic decomposition is energy-intensive, requiring approximately 10–15 % of the hydrogen's energy content, and ammonia's toxicity poses safety and environmental challenges (IEA 2021). Despite these hurdles, ammonia's high TRL of 7–8 reflects its commercial maturity, supported by well-established handling protocols (Aziz et al. 2020; Fecke et al. 2016; Ikäheimo et al. 2018; Yang et al. 2023).

LOHCs, such as N-ethylcarbazole or methylcyclohexane (MCH), offer a carbon-neutral alternative for hydrogen storage, with a gravimetric capacity of up to 7.2 wt% and volumetric densities ranging from 50 to 60 kg/m^3 (Modisha et al. 2019; Niermann et al. 2019). LOHCs store hydrogen

Table 1: Comparison of material-based hydrogen storage technologies.

Technology	Gravimetric density (wt.%)	Volumetric density (kg/m^3)	Energy consumption (% of LHV)	TRL	Environmental considerations	Key advantages	Key challenges
Compressed gas (Type I–IV)	1.7–5.7	39.2 (at 700 bar)	12–15 % (compression)	8–9	Minimal emissions during use; material production impacts	Mature technology, fast refueling, widespread use	Low volumetric density, high-pressure safety risks, embrittlement
Compressed gas (Type V)	~6–7 (estimated)	~40–50 (at 993 bar)	15–20 % (compression)	6–7	Minimal emissions; composite production impacts	Ultralight, high-pressure capacity	Permeation, pressure-cycle fatigue, cost
Methanol	12.5	~100	20–30 % (synthesis and reforming)	7–8	CO_2 emissions during reforming	Established infrastructure, high density	Positive carbon footprint, energy-intensive CO_2 separation
Ammonia	17.8	121 (liquefied at −33 °C)	10–15 % (decomposition)	7–8	Toxicity risks, minimal CO_2 if used directly	High density, stable for long-term storage	Toxicity, energy-intensive hydrogen extraction
LOHCs	Up to 7.2	50–60	20–40 % (hydrogenation / dehydrogenation)	5–6	Carbon-neutral if green hydrogen used	Ambient storage, safe handling	Low capacity, high energy for dehydrogenation, catalyst durability

through hydrogenation of a hydrogen-lean molecule, which is later released via catalytic dehydrogenation. This process allows storage and transport under ambient conditions, enhancing safety and compatibility with existing liquid fuel infrastructure (Preuster et al. 2017; Modisha et al. 2019; Samoilov et al. 2023). However, the energy required for dehydrogenation is significant, consuming 20–40 % of the hydrogen's energy content, depending on the carrier and process efficiency. The manuscript notes that LOHCs are still at a TRL of 5–6, indicating they are in the demonstration phase, with challenges related to catalyst durability, system integration, and cost reduction (Modisha et al. 2019; Niermann et al. 2019).

Comparing these chemical carriers to compressed gas storage reveals distinct trade-offs. Compressed gas storage benefits from high TRL, fast charge/discharge rates, and widespread adoption, particularly for vehicular applications where Type III and IV tanks provide sufficient range (up to 450 km) with refueling times under 3 min (Burheim 2017). However, its energy consumption for compression and lower volumetric density (39.2 kg/m^3 at 700 bar) make it less efficient for large-scale or long-distance applications compared to chemical carriers (Ghorbani et al. 2023). Ammonia and LOHCs offer higher volumetric densities and safer handling under ambient conditions, but their energy-intensive hydrogen release processes and, in the case of methanol, CO_2 emissions, reduce their overall efficiency and environmental benefits (Yang et al. 2023). Metal hydrides, another chemical storage option mentioned in the manuscript, achieve exceptional volumetric densities (up to 150 kg/m^3 for complex hydrides like Mg_2FeH_6), but their gravimetric capacity (up to 18 wt% for $LiBH_4$) is limited by heavy transition metals, and their slow kinetics and high operating temperatures pose practical challenges (Motyka 2015; Ren et al. 2017; Züttel 2004).

The choice of storage method depends on the application, scale, and regional infrastructure. For short-range mobility, compressed gas storage remains dominant due to its maturity and fast refueling capabilities. For long-distance transport or large-scale storage, ammonia and LOHCs are more promising due to their higher energy density and compatibility with existing logistics systems, though they require advancements in energy-efficient release processes and safety measures. Future research should focus on improving catalyst efficiency for LOHC dehydrogenation, reducing ammonia's toxicity risks, and developing CO_2-free methanol reforming pathways to enhance the competitiveness of chemical storage against compressed gas systems.

3.1.5 Underground hydrogen storage

Utilizing suitable existing salt caverns, aquifers, and depleted gas reservoirs presents another promising option for storing compressed gaseous hydrogen, complementing the methods discussed earlier. Similar to natural gas, hydrogen can be compressed and injected underground for storage in various geological formations, such as salt caverns, depleted oil and gas fields, and deep aquifers, as illustrated in Figure 10 (Bai et al. 2014; Ebrahimiyekta 2017). Underground hydrogen storage (UHS) has been specifically developed to accommodate large volumes of excess hydrogen generated seasonally from renewable energy sources or imported for medium- to long-term storage. When evaluating a potential UHS site, geological characteristics are the main consideration for researchers and engineers. Typically, salt caverns are the preferred choice for storing pure hydrogen due to their viscoelastic evaporitic rocks, which serve as highly effective gas seals (Tarkowski

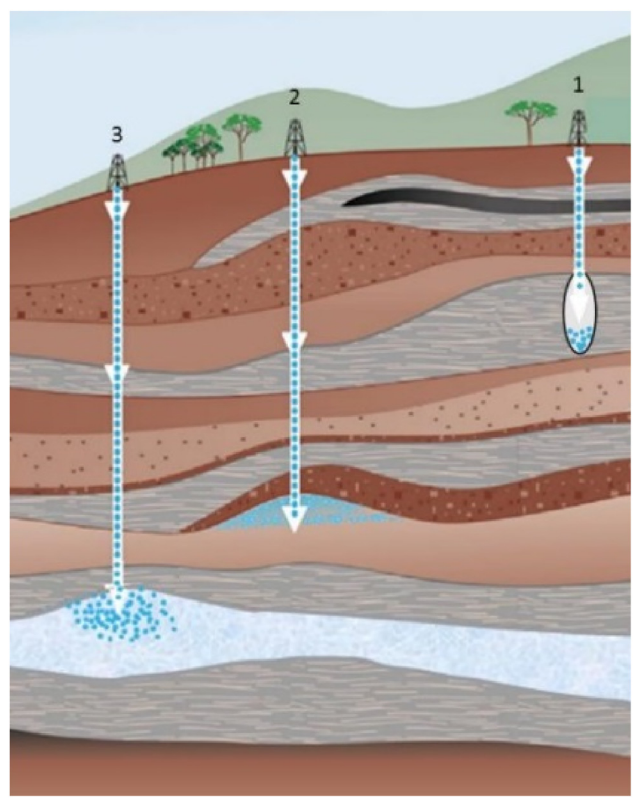

Figure 10: Geological profile of several underground hydrogen storage methods: (1) salt caves, (2) depleted oil and gas, and (3) saline aquifer (Bai et al. 2014; Ebrahimiyekta 2017). Reproduced with permission from Elsevier.

2019). Moreover, salt caverns offer tight deposits with favorable mechanical properties and strong resistance to chemical reactions (Tarkowski 2019).

Salt caverns, widely used for natural gas storage, are also employed for hydrogen storage in various countries. These caverns feature stable walls that resist gas permeation throughout their operational lifespan. The plastic behavior of salt prevents fracturing, thereby ensuring the caverns remain impermeable. Unlike porous geological media, where bacteria can actively consume hydrogen, the high salinity of the brine environment within salt caverns inhibits bacterial activity, preventing hydrogen from being converted into other gases. Salt caverns typically range in physical volume from 100,000 to 1,000,000 cubic meters, and depending on their depth, they can store several million to 100 million standard cubic meters (st-m^3) of working gas. This storage solution offers flexibility in both volume and modularity, enabling multiple caverns at a single site to be used to adjust storage capacity according to demand fluctuations. However, the use of salt structures is limited by their relatively small volume compared to aquifers and the limited availability of suitable salt deposits for cavern construction. In contrast, siliciclastic porous deposits, such as saline aquifers and depleted gas reservoirs, are attracting increased attention due to their capacity to store much larger gas volumes, with some aquifers capable of holding up to 18 billion st-m^3 of gas. Despite their potential, underground hydrogen storage in these geological formations introduces new scientific and technical challenges, due to their unique physicochemical behavior relative to conventional gas storage environments (Panfilov 2016).

Several options are available for the commercial use of underground hydrogen storage in transportation and industry. In regions with favorable geological conditions, where large amounts of electrical energy (tens of terawatt-hours (TWh)) can be generated from intermittent renewable sources, electricity prices fluctuate seasonally, and supportive government policies are in place, such solutions may be economically viable. Experience from existing gas storage operations, including hydrogen storage in salt caverns in the United States and the United Kingdom, demonstrates that subterranean hydrogen storage is a practical and scalable method for mass energy storage. Similar to underground carbon dioxide storage, the widespread deployment of full-scale underground hydrogen storage depends on successfully addressing geological, engineering, economic, legal, and societal challenges (Hu et al. 2023; Jafari Raad et al. 2022; Uliasz-Misiak and Przybycin 2016).

A variety of underground storage facilities have been utilized worldwide for hydrogen storage. Natural gas storage has taken over a salt cavern storage facility (at 150 bar and a depth of 820 m) in Bad Lauchstädt, Germany. Since 1971, a salt cavern in Kiel, Germany, currently used for natural gas, has also been employed to store produced gas containing 62 % hydrogen. In Teesside, England, Imperial Chemical Industries (ICI) stores one million Nm^3 of nearly pure hydrogen (95 %) at a pressure of 50 bar in salt caverns for industrial applications, including ammonia and methanol production. In Texas, Air Liquide is completing a salt cavern leaching project to meet rising customer demand, while ConocoPhillips has been storing hydrogen in a salt dome (at 195 bar and 850 m depth) attached to the Old Ocean refinery since the 1980s. Praxair also operates underground hydrogen storage in Texas to enable peak-shaving of hydrogen production. Additionally, from 1956 to 1972, Gaz de France (GDF) stored gas containing 50 % hydrogen in a saline aquifer at a depth of 430 m in France (Panfilov 2016).

An aquifer located at a depth of 200–250 m in sandstone near Ketzin, Germany, was originally used to store produced gas and has since been repurposed for CO_2 storage. This geological formation could potentially serve as a pilot site for future hydrogen storage projects. Additionally, an aquifer in Lobodice, Czech Republic, currently stores town gas comprising 50 % hydrogen and 25 % methane, operating at 90 bar pressure, 34 °C temperature, and a depth of 430 m. In Argentina, Hychico C.A. in Diadema has initiated a pilot program injecting hydrogen into a natural gas storage system within a sandstone geological structure. Diadema comprises two reservoirs located at 600 and 800 m depth, operating at approximately 10 bar and 50 °C. One reservoir is dedicated to methane storage, while the other stores hydrogen (10 % by volume) produced by electrolyzers powered by a nearby wind plant. Furthermore, for aerospace industry applications, pure hydrogen has been stored underground in large iron tanks in Russia (Panfilov 2016).

3.2 Hydrogen transportation

The infrastructure for transporting and storing hydrogen and its derivatives remains limited but is crucial for supporting emerging distributed applications. Hydrogen storage and transportation technologies can be broadly classified into two main categories: physical-based and materials-based approaches. Each method offers unique advantages and faces specific limitations, with varying degrees of maturity in terms of practical implementation. Continued research and development are essential to improve the energy efficiency and overall viability of hydrogen storage and transportation solutions.

The geographic distribution of renewable energy resources, along with the readiness of supporting infrastructure and key governmental policies, plays a crucial role in shaping the global landscape of green hydrogen production. Countries such as Australia, the USA, Morocco, and Norway are well-positioned to become leaders in the emerging hydrogen economy due to their abundant renewable energy potential and well-developed infrastructure. In contrast, regions including Japan, India, China, France, Spain, and several European Union member states may rely heavily on hydrogen imports because of limitations in domestic resources or infrastructure capacity. Currently, hydrogen demand is largely concentrated in North America, Europe, and East Asia, which together account for approximately 65 % of global consumption (Hydrogen Council 2022). The levelized cost of green hydrogen production varies significantly across countries, reflecting differences in policy frameworks and the dynamics of hydrogen trade, including import and export of green, blue, and gray hydrogen (Muthukumar et al. 2023).

Presently, hydrogen production and consumption often occur at the same location, which reduces the need for extensive transportation infrastructure. Hydrogen can be distributed and transported using two main methods: the first includes railroad tank cars, truck trailers, bulk storage vessels, and containers, while the second method involves pipelines (Nikolaidis and Poullikkas 2017). The first transportation method tends to be costly due to the low hydrogen-carrying capacity of these modes and their limited efficiency in handling hydrogen effectively (Zheng et al. 2012).

Hydrogen rail delivery can be cost-effective for transporting cryogenic liquid hydrogen. However, relatively few shipments use this method due to challenges such as tight scheduling requirements and limited transport capacity, which hinder the avoidance of significant hydrogen boil-off. Additionally, there is a shortage of suitable rail carriages designed specifically for hydrogen transport. Typically, small amounts of hydrogen are transported over short distances (up to about 200 km) by compressing the hydrogen to 200 bar and carrying it in long cylinders on truck trailers (Ahmed et al. 2022). For longer distances and relatively small quantities, liquid hydrogen trailers tend to be more cost-effective, although the energy-intensive liquefaction process and the need for cryogenic insulation lead to substantial operational costs (Ahmed et al. 2022; Muthukumar et al. 2023). With rising demand and the development of new applications, there is an increasing urgency to establish efficient infrastructure that effectively links hydrogen production centers with demand hubs. The technical feasibility of repurposing existing natural gas pipelines for hydrogen distribution faces significant challenges, primarily due to hydrogen's tendency to cause material embrittlement and increased leakage risks. Consequently, constructing new pipelines specifically designed for hydrogen transport requires substantial capital investment. Addressing these technical obstacles is essential to enable efficient, large-volume hydrogen transport over long distances, such as those exceeding 4,000 km (Muthukumar et al. 2023).

Gaseous hydrogen can be transported by pipeline similarly to natural gas. Pipeline systems are currently the most efficient and cost-effective means of transporting hydrogen, particularly over distances of 2,500 to 3,000 km and at capacities of up to approximately 200 kilotons per year (IEA 2022). In the United States, private companies own and operate around 2,600 km of hydrogen pipelines, while Europe has a network of about 2,000 km, primarily serving industrial users. Various regions are actively developing new hydrogen infrastructure, with Europe playing a leading role in these initiatives.

In 2020, the European Hydrogen Backbone initiative (Slowinski et al. 2023) was launched, uniting 33 gas infrastructure operators with the goal of establishing a comprehensive hydrogen network across Europe. In June 2022, the Dutch government announced a EUR 750 million investment plan to develop a national hydrogen transmission network (Reuters 2022). To achieve the targets set forth in the Net Zero Emission (NZE) Scenario, approximately 15,000 km of hydrogen pipelines, comprising both new constructions and repurposed existing pipelines, will be required by 2030. For long-distance hydrogen transport, alternative methods such as shipping hydrogen and using hydrogen carriers are considered cost-competitive and viable alternatives to pipeline infrastructure.

The Hydrogen Energy Supply Chain (HESC 2022) project achieved a major milestone in February 2022 by successfully demonstrating the shipment of liquefied hydrogen from Australia to Japan for the first time. However, the logistical complexities and technical challenges associated with transporting liquefied hydrogen have led to an increasing focus on exploring alternative methods. Some projects are exploring the feasibility of shipping hydrogen in the form of ammonia as a hydrogen carrier. According to projections in the NZE Scenario, global shipments of low-emission hydrogen, including both hydrogen and hydrogen-based fuels, are expected to surpass 15 million tons by 2030 (IEA 2023b).

Infrastructure development for hydrogen storage will be crucial as hydrogen utilization expands. Currently, salt caverns in the United States and the United Kingdom are used for large-scale industrial hydrogen storage. To meet the globally growing demand, additional storage capacity with flexible operation is necessary. Ongoing research projects such as HyCAVmobil (EWE 2021) in Germany and HyPSTER (Hypster 2021) in France aim to demonstrate fast-cycling capabilities in large-scale hydrogen storage, with tests planned for this year. Moreover, initiatives in the Netherlands (Hystock 2021), Germany (H2CAST-Etzel 2022), and France (Teréga 2020) are investigating the repurposing of natural gas salt caverns for hydrogen storage. Research efforts also focus on developing other underground storage options, including depleted gas fields, aquifers, and lined hard rock caverns (IEA 2022). For example, Sweden launched a demonstration facility for hydrogen storage in lined hard rock caverns in 2022 (SSAB 2022). According to the NZE Scenario, global bulk hydrogen storage capacity is projected to increase from 0.5 TWh currently to 70 TWh by 2030 (IEA 2023a).

Recent advancements in hydrogen logistics were highlighted by the successful demonstration of liquefied hydrogen transportation via ship under the Hydrogen Energy Supply-chain Technology Research Association (HySTRA) project. This achievement highlights the potential for international hydrogen trade. The hydrogen storage tanks, with a substantial liquefied hydrogen capacity of 225 kilotons, were transported from Australia to Japan, demonstrating the feasibility of long-distance hydrogen shipment (HySTRA, IEA 2021). However, the energy-intensive processes involved in hydrogen compression and liquefaction have driven growing interest in alternative hydrogen carriers, such as ammonia, LOHCs, and methanol, which may offer more efficient storage and transport options.

Among the alternatives discussed, ammonia stands out due to its high hydrogen density and well-established industrial applications. It offers advantages, such as a higher boiling point and greater volumetric hydrogen density, compared to liquid hydrogen. However, challenges remain, including ammonia's toxicity and the significant energy required for hydrogen extraction. In contrast, transporting methanol and methylcyclohexane (MCH) is economically attractive due to factors highlighted by projects performed by the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD). AHEAD is a Japanese organization focused on developing a global hydrogen supply chain using the organic chemical hydride method (AHEAD). Nevertheless, because of its superior volumetric efficiency, ammonia continues to be a compelling option for long-distance hydrogen (Ahead 2024; IEA 2021).

The development of hydrogen infrastructure is vital for the widespread adoption of hydrogen energy across various sectors, especially transportation. This infrastructure includes production, storage, transportation, and distribution facilities, all of which are essential to support a growing hydrogen economy. Governments, regulators, and financial stakeholders play pivotal roles in establishing a stable legal framework, providing subsidies, and investing in infrastructure to address the rising demand for hydrogen-powered vehicles. However, significant challenges remain, including high costs, varied levels of technological readiness, and safety concerns. The requirement for specialized facilities, high-pressure storage, and advanced transportation systems, combined with substantial initial investments, poses barriers to building a resilient and efficient hydrogen supply chain. Nevertheless, investing in hydrogen infrastructure is crucial for meeting global decarbonization targets and facilitating the transition to a low-carbon economy.

3.2.1 Costs of transporting hydrogen

The economic viability of hydrogen as a clean energy carrier is fundamentally dependent on the cost-effectiveness of its transportation infrastructure. Hydrogen transportation presents unique challenges due to its low volumetric energy density, requiring specialized conversion and handling methods that significantly impact overall delivery costs. The analysis in this section examines the various transportation pathways for hydrogen, their associated costs, and the factors that determine their economic competitiveness across different applications and distances (Table 2).

Pipeline transportation represents the most economically efficient method for large-scale, continuous hydrogen delivery over terrestrial distances. The techno-economic analysis demonstrates that pipeline systems offer substantial cost advantages, particularly for high-volume applications. For dedicated hydrogen pipelines, the levelized cost ranges from \$1.50 to 2.50 per kilogram over 1,000 km, with European estimates suggesting costs as low as €0.10–0.15 per kilogram of hydrogen depending on the distance traveled. The economic attractiveness of pipeline transport stems from its low operational expenditure once infrastructure is established, though initial capital investment requirements are substantial (EAI 2024; Khan et al. 2021).

The retrofitting of existing natural gas pipelines presents an opportunity to reduce infrastructure costs by more than 50 % compared to new construction (EU 2021). However, this approach faces technical limitations due to hydrogen embrittlement concerns and material compatibility issues. The small molecular size of hydrogen increases leakage risks and can cause cracking in steel pipelines, particularly those with higher carbon content. Despite these challenges, pipeline transport can transmit ten times the energy at one-eighth the cost of electricity transmission lines, making it highly competitive for long-distance transport (Hydrogen Council 2021; EAI 2024). The cost structure of hydrogen pipelines involves significant capital expenditure for construction, compression stations, and right-of-way acquisition, but relatively low operational costs over the 40- to 80-year lifespan of the infrastructure (ANZ 2024).

Table 2: Hydrogen transportation cost via different methods.

Method	Cost ($/kg, unless noted)	Typical distance range	Remarks
New hydrogen pipeline	$1.50–2.50/kg$H_2$ (over 1,000 km)	Up to 2,000–3,000 km	Most cost-effective for high-volume, continuous transport; high initial capital expenditure; low operational cost; challenges include hydrogen embrittlement and leakage risk. Retrofitting existing gas pipelines can reduce costs by over 50 %.
Retrofitted pipeline	<$0.50/kg$H_2$ (up to 6,000 km, large repurposed lines)	Up to 2,500–6,000 km	Uses existing natural gas pipelines with technical limits (embrittlement, leakage); significantly cheaper than new pipelines for suitable segments.
Compressed gas road trailer	$3.50–5.00/kg$H_2$ (over 1,000 km)	First/last mile; up to ~322 km	Suited for small- to mid-scale, flexible delivery; high compression, specialized vehicles; limited to short/medium distances due to low payload.
Liquid hydrogen road trailer	Higher than $3.50–5.00/kg$H_2$ (energy-intensive)	First/last mile; up to ~322 km	Larger capacity than compressed gas trailers; much higher cost due to liquefaction and cryogenic handling; primarily for flexible, shorter hauls.
Rail (tank cars)	$4.00–6.00/kg$H_2$ (over 1,000 km)	Intermediate (500–2,000 km)	Larger shipments than road; requires specialized tank cars and terminal infrastructure; costlier than pipeline, but enables bulk transport without pipeline access.
Maritime (ammonia carrier)	$1.90–2.20/kg$H_2$ (over 8,000 km); as low as $1.00/kg$H_2$ without reconversion	>3,000 km (esp. 8,000–16,000 km); intercontinental	Ammonia conversion allows existing ship/tanker use; cost-effective for ultra-long distances or where chemical carriers are acceptable; reconversion to H2 adds cost/complexity, direct use is cheaper.
Maritime (LOHC carrier)	$2.00–2.50/kg$H_2$ (over 8,000 km)	>8,000 km; intercontinental	Uses chemical carriers for ease of handling/storage; costly reconversion; best suited for long distances with chemical process tolerance.
Maritime (liquefied H_2 carrier)	$2.00–3.70/kg$H_2$ (over 8,000 km)	>3,000 km (up to 16,000 km)	Highest cost due to liquefaction (−253 °C) and cryogenic storage; direct H2 delivery for high-purity needs; capital-intense ships.

Road transportation of hydrogen utilizes specialized trailer systems designed for either compressed gas or liquid hydrogen delivery. Compressed hydrogen tube trailers typically carry 300–500 kg per shipment, with transport costs ranging from $3.50 to 5.00 per kilogram over 1,000 km (EAI 2024). The higher costs reflect the energy-intensive compression requirements, specialized vehicle needs, and safety protocols associated with transporting high-pressure gas. Liquid hydrogen trailers offer higher capacity but incur substantially greater costs due to the energy-intensive liquefaction process and cryogenic handling requirements. The economic viability of road transport is generally limited to distances under 200 miles (~322 km) and applications requiring flexibility in delivery scheduling that pipeline systems cannot provide (Burke et al. 2024).

Road transport infrastructure costs include specialized trailers ($0.96 million for compressed gas systems, $1.39 million for liquid hydrogen systems) and associated safety equipment (ANZ 2024). The higher capital requirements, combined with lower payload capacities compared to other transport modes, contribute to the premium pricing of road-based hydrogen delivery. However, road transport provides essential first-mile and last-mile connectivity, particularly for distributed hydrogen refueling networks and industrial applications in areas without access to pipelines.

Rail transportation of hydrogen occupies a niche position between road and pipeline transport in terms of cost and capacity. Rail systems can accommodate larger shipments than road transport while providing greater flexibility than fixed pipeline infrastructure. Transport costs via rail range from $4.00 to 6.00 per kilogram over 1,000 km (EAI 2024). The cost structure includes specialized tank car leasing or purchase, terminal infrastructure development, and rail access fees. The higher costs compared to pipeline transport reflect the need for specialized rolling stock capable of handling high-pressure or cryogenic hydrogen, as well as the operational complexities of intermodal transfer points. Rail transport requires significant investment in loading and unloading facilities at both origin and destination points, adding to the overall system cost. Safety regulations for hazardous materials transport further increase operational costs and complexity.

Rail transport becomes economically viable for intermediate distances where pipeline infrastructure is not available, and road transport becomes prohibitively expensive due to volume requirements. The system is particularly suited for bulk movements between major industrial hubs where consistent demand patterns can justify the infrastructure investment.

Maritime transportation enables long-distance, intercontinental hydrogen trade through several carrier technologies. Ammonia serves as an alternative hydrogen carrier, offering significant advantages in terms of utilizing existing infrastructure. Projected expenses for importing ammonia from North and South America are approximately 10–15 % higher compared to those from the Arabian Gulf. The modeled cost difference ranges between \$0.20 and \$0.40 per kilogram of delivered hydrogen, or equivalently \$6 to \$12 per megawatt-hour of hydrogen, depending on the total import volume. This analysis suggests that the United States could become a competitive supplier of low-carbon hydrogen to international markets, especially if the price disparity between United States and European natural gas markets continues to grow, and if recent U.S. policy measures aimed at accelerating clean hydrogen development prove effective (Tatsutani et al. 2023).

By 2030, shipping hydrogen as ammonia or liquid organic hydrogen carrier (LOHC) is expected to be more cost-effective than transporting it as liquefied hydrogen (LH_2) for long distances, such as 8,000 km, according to the International Energy Agency's Energy Technology Perspectives 2023 report. Ammonia shipping costs range from \$1.9 to 2.2/kgH_2, potentially dropping to \$1/kgH_2 if used directly without reconversion to gaseous H_2, while LOHC costs \$2.0–2.5/kgH_2, and LH_2 is the priciest at \$2.0–3.7/kgH_2 (for an 8,000-km trip) due to expensive storage tanks requiring temperatures below −253 °C. These costs cover conversion, storage, shipping, and reconversion but exclude hydrogen production, with conversion and energy losses driving the majority of expenses (Collins 2023).

In contrast, long-distance pipelines offer a cheaper alternative, with repurposed 48-inch (122 cm) pipelines delivering hydrogen up to 6,000 km for less than \$0.50/kgH_2 and new pipelines costing about double that, making them preferable for distances up to 2,000–2,500 km. However, hydrogen shipping (\$16–31/GJ) remains significantly more expensive than natural gas shipping (\$3–7/GJ), although low-cost hydrogen production could make it competitive with high gas prices. Transporting electricity via offshore cables for local hydrogen production is likely the most expensive option (Collins 2023).

Maritime shipping infrastructure requires substantial capital investment, with specialized vessels costing \$310–533 million, depending on the carrier's technology. Liquid hydrogen carriers demand the highest capital investment due to their cryogenic handling requirements, while ammonia and LOHC systems can leverage existing chemical tanker designs with modifications (ANZ 2024).

The economic optimization of hydrogen transport depends critically on distance, volume, and end-use requirements. Analysis shows that different transport modes achieve cost advantages within specific distance ranges. For distances up to 3,000 km, compressed hydrogen pipelines offer the lowest costs, particularly for high-volume applications. Between 3,000 and 16,000 km, liquid hydrogen shipping demonstrates competitive performance, while chemical carriers (ammonia and LOHC) become optimal for distances exceeding 16,000 km (EU 2021).

The cost competitiveness also depends on the required hydrogen purity and end-use application. Direct hydrogen applications requiring high purity favor liquid hydrogen or pipeline transport, while applications tolerating chemical conversion processes can utilize ammonia or LOHC systems more economically. The energy penalties associated with conversion and reconversion processes significantly impact the overall system efficiency and cost. Volume scaling effects provide substantial cost reductions across all transport modes. Large-scale operations enable economies of scale in infrastructure development, operational efficiency improvements, and reduced unit costs. The analysis indicates that giga-scale hydrogen projects are essential for achieving cost-competitive transport economics, particularly for long-distance applications.

3.3 Comparative analysis of hydrogen storage and transportation technologies

Hydrogen storage technologies have evolved considerably in response to the growing demands of a hydrogen-based energy economy. The current study presents an expanded and technically enriched evaluation of both conventional and emerging hydrogen storage technologies across five main categories: compressed gas, cryogenic liquid, cryo-compressed, material-based (chemical and physical), and underground storage. By integrating current progress in the design, implementation, and scaling of hydrogen logistics, the article highlights both established and emerging methods, consistently contextualizing their discussion within the broader scientific literature.

3.3.1 Compressed gas storage of hydrogen

This study presents a detailed classification of pressure vessel technology, ranging from Type I (metal, low-pressure) to advanced Type V (linerless carbon composites) vessels, addressing their operational capacities, safety factors, permeation challenges, and scalability. The manuscript notably emphasizes the significance of Type V linerless tanks, crafted primarily with carbon fiber composites and designed for pressures up to 993 bar, citing their potential for mass reduction of up to 90 % and cost decreases of 50 % compared to conventional tanks.

Earlier studies, such as Moradi and Groth (2019) and Olabi et al. (2021), typically focus on the evolution through Type I–IV and discuss limits relating to hydrogen embrittlement, leakage, and economic cost, but rarely delve into linerless composite tank manufacturing or the inherent technical barriers to their wider deployment. The current study not only presents up-to-date data on gravimetric and volumetric densities but also crucially links these technical evolutions to the needs of aerospace and next-generation mobility. The assignment of a TRL of 8–9 for Type I–IV and 6–7 for Type V tanks highlights the significant progress yet to be fully realized for linerless composite vessels, positioning the current review as a crucial bridge between research and industrialization.

3.3.2 Liquid/cryogenic hydrogen storage

The current review supplies a comprehensive discussion of the thermophysics of liquefaction, energy losses (up to 40 % for LH_2), boil-off phenomena, and tank design for the safe handling and transportation of liquid hydrogen (Barthelemy et al. 2017). Previous studies primarily noted the energy penalties associated with LH_2 (up to 40 % energy loss during liquefaction) compared to about 10 % energy loss in compressed hydrogen storage (Barthelemy et al. 2017). A cryogenic tanker has the capacity to transport 5,000 kg of hydrogen, which is approximately five times the capacity of compressed hydrogen gas tube trailers (Moradi and Groth 2019). The current study addresses recent developments in container insulation systems and the ortho–para hydrogen conversion process, detailing the effects on evaporation losses. These findings provide enhanced clarity on the challenges of managing LH_2 boil-off and address system safety innovations, such as vacuum jackets and perlite insulation, which are currently minimally covered in prior work. The TRL of 7–8 for cryogenic liquid storage reflects a technology that is industrially mature, with the caveat of continued optimization for losses and insulation.

3.3.3 Cryo-compressed hydrogen storage

Cryo-compressed hydrogen storage (CcH_2) as a hybrid method remains underrepresented in earlier literature. An attempt has been made to bridge this gap by discussing CcH_2 in terms of its dual-phase operation, thermodynamic advantages (80 g/L storage density), and suitability for high-power mobility applications. The technical insights into pressure vessel failures, resin degradation, nanoparticle reinforcement strategies, and fiber delamination, particularly at cryogenic temperatures, have been studied. This marks a distinct departure from past models that offered only high-level theoretical considerations (Ahluwalia et al. 2010; Yan et al. 2024). As such, the current review supplies crucial operational information and assigns a TRL of 5–6, marking cryo-compressed storage as a technology at the demonstration/prototype stage and poised for wider implementation with continued material advancements.

3.3.4 Material-based hydrogen storage

3.3.4.1 Chemical storage

Metal hydrides (e.g., $LaNi_5$, Mg_2FeH_6), complex hydrides, and chemical carriers (LOHCs, e.g., N-ethylcarbazole, ammonia, methanol) form the crux of this domain. This study offers a perspective by integrating lifecycle environmental impacts (notably CO_2 emissions from methanol) and the synthesis, processing, and practical deployment of new hydride and carrier families. This update goes beyond the mostly physical metrics of Züttel (2004), Godula-Jopek (2015), and Modisha et al. (2019), providing insight into advances such as green nanomaterial hydrides and their role in gravimetric and volumetric efficiency. The TRL for commercialized hydrides is assessed at 6–7, with emerging green hydrides and LOHC systems at 4–6, reflecting the variable maturity across this domain.

3.3.4.2 Physical storage

The review accounts for the evolving landscape of porous adsorbent materials, especially MOFs, COFs, zeolites, and amorphous polymers, emphasizing their advantages (e.g., high surface area, tunability) and noting persistent challenges (low ambient uptake, thermal management). While past reviews, such as Chen et al. (2022) and Hardy et al. (2018), focus on structural properties and synthetic chemistries, the current study situates these materials within the context of actual system deployment, integrating data on modularity, balance-of-plant, and economic feasibility. These details enhance understanding of the real-world challenges of physical storage under ambient or near-ambient conditions. The TRL of 4–5 is appropriate, as most systems remain at laboratory or limited prototype scale.

3.3.4.3 Underground hydrogen storage

The current review offers an in-depth and up-to-date analysis of underground hydrogen storage (UHS) across various geological formations, including salt caverns, depleted reservoirs, and aquifers. Critically, while earlier works like Tarkowski (2019) and Panfilov (2016) dissected the geochemical and theoretical potentials of these formations, the present review incorporates global case studies and operational pilot data, such as from Germany, UK, Czech Republic, and Argentina, that now support the practical viability and scalability of UHS. The appraisal of microbial effects, gas migration, and regulatory frameworks is a distinctive contribution, reflecting an up-to-date and applied understanding. The TRL is rated at 7–8 for salt cavern storage, 4–6 for aquifers and depleted reservoirs, corresponding to pilot to early commercial status.

3.3.4.4 Hydrogen transportation

Section 3.2 of this study provides a comprehensive overview of hydrogen transportation, examining pipelines, roads, rail, ships, and novel carrier molecules. Transportation aspects, briefly noted in previous studies such as the studies by Rasul et al. (2022) and Brar et al. (2022), who classify the technologies into rail/truck, pipeline, and maritime transport, and compare their respective energy and economic costs, are investigated in the current study. The review further integrates recent initiatives like the European Hydrogen Backbone (EHB) (2023), HESC (2022), HySTRA (HySTRA, IEA 2021), and HyCAVmobil (EWE 2021), all of which are missing or superficially referenced in earlier analyses. The authors enrich this section with techno-economic perspectives on liquefied hydrogen shipping and highlight policy-linked infrastructure expansion, such as the Dutch €750 million national hydrogen grid.

This review demonstrates technical and policy aspects by evaluating embrittlement, retrofitting costs, policy initiatives (e.g., the European Hydrogen Backbone), and emerging carrier-based international trade (e.g., LH_2, ammonia, methanol). This expands upon the more sectoral or techno-economic focuses of earlier studies, such as Yang and Ogden (2007) and the Global Hydrogen Flows report (Hydrogen Council 2022), incorporating logistical, engineering, and market-readiness dimensions. The maturity of pipeline and local transport is rightly at TRL 8–9; shipborne LH_2 and advanced carrier tankers are at TRL 6–7. A comparative analysis of hydrogen storage technologies is presented in Table 3.

4 Conclusion and future outlook

This review has thoroughly assessed hydrogen storage and transportation technologies, highlighting their critical role in building a low-carbon energy future. The analysis covers a range of storage methods, including compressed gas (Type I–V tanks), cryogenic liquid, cryo-compressed, material-based (chemical and physical), and underground storage in salt caverns, aquifers, and depleted reservoirs, evaluated for their technical feasibility, energy efficiency, and scalability. Transportation methods, such as pipelines, truck/rail, and maritime shipping utilizing liquid hydrogen, ammonia, and liquid organic hydrogen carriers (LOHCs), were also examined, focusing on infrastructure needs, energy costs, and economic optimization.

Each storage and transportation method offers distinct benefits and challenges. Compressed gas storage, particularly advanced Type V linerless tanks, achieves significant weight reduction (up to 90 %) and cost savings (up to 50 %) compared to traditional tanks, but managing hydrogen permeation at high pressures (up to 993 bar) remains a challenge. Cryogenic liquid storage, despite incurring high energy losses (up to 40 % during liquefaction), enables large-scale transport with capacities of up to 5,000 kg per tanker, far surpassing those of compressed gas trailers. Cryo-compressed storage, with a high density of 80 g/L and low boil-off rates (0.2–1.6 g/h/kg), is well-suited for heavy-duty vehicles; however, progress in linerless vessel designs is required to address resin degradation and embrittlement at −233 °C. Material-based storage, including metal hydrides and LOHCs, offers high volumetric density and enhanced safety, but is limited by slow reaction kinetics, a restricted gravimetric capacity (e.g., 7.2 wt% for LOHCs), and environmental concerns, such as CO_2 emissions from methanol reforming. Underground storage in salt caverns is a mature and scalable option, whereas aquifers and depleted reservoirs face challenges related to microbial activity and gas purity.

Transportation analysis indicates that pipelines are cost-effective for distances of up to 3,000 km, with repurposed pipelines delivering hydrogen at a cost of less than $0.50/kg. For longer distances exceeding 16,000 km, maritime shipping of ammonia and LOHCs is more economical than liquid hydrogen ($1.9–2.5/kg vs. $2.0–3.7/kg), though high capital costs for specialized liquid hydrogen vessels ($310–533 million) and energy losses in chemical carrier conversion (20–40 % of lower heating value for LOHC dehydrogenation) pose challenges.

The versatility of hydrogen as an energy carrier supports the integration of renewable energy, stabilizes grids, and decarbonizes sectors such as heavy industry and long-distance transport. However, technical barriers, such as improving material durability, reducing energy losses, and ensuring safety to prevent risks like hydrogen leakage and ammonia toxicity, must be addressed. Adapting existing infrastructure, particularly natural gas pipelines, requires careful management of material compatibility and regulatory standards. The shift to a hydrogen economy depends on collaborative efforts among researchers, industry, and policymakers. Sustained investment in material science, including nanocomposite-reinforced tanks and green

Table 3: Comparative table of hydrogen storage and transportation technologies.

Technology	Key features/scope	TRL	Comparative insight (earlier studies)	Distinctive contributions of the current study
Compressed gas (Type I–IV)	350–700 bar; steel/composite tanks; 1–5.7 wt%	8–9	Widely studied; high TRL; industry standard	Detailed classification; system performance analysis; new cost/weight ratios
Compressed gas (Type V)	Linerless; ultralight carbon fiber tanks; up to 993 bar	6–7	Largely absent from prior reviews	Introduces pressure-cycle fatigue, resin nanotech, aerospace/space use cases
Cryogenic storage (LH_2)	−253 °C, high liquefaction loss (~40 %), boil-off	7–8	Energy loss acknowledged; general overview	Adds boil-off metrics, conversion kinetics, safety design specifics
Cryo-compressed (CcH_2)	−233 °C, 250–350 bar, hybrid liquid/gas system	5–6	Rarely covered; mostly theoretical	Structural failures, nanocomposite reinforcements, aerospace fuel tank analysis
Metal hydrides	High volumetric density; reversible (e.g., $LaNi_5$, Mg_2FeH_6)	6–7	Common focus on storage density	Discusses new alloy classes; better gravimetric/volumetric trade-offs
Complex/green hydrides	H/M up to 4.5 (e.g., $BaReH_9$); lifecycle insights	4–5	Rarely discussed; theoretical	Addresses synthesis scalability, ionic/covalent hydride properties
MOFs/COFs/porous carbons	High surface area; weak ambient density	4–5	Limited to materials science	Integration challenges, thermal limitations, structural tuning for vehicular systems
LOHCs	7.2 wt% H_2; ambient storage; catalytic release	5–6	Cited as low-TRL emerging tech	Lifecycle focus, dehydrogenation process evaluation, energy use balance
Methanol/ammonia carriers	Liquids with reforming (methanol), direct use (ammonia)	7–8	Ammonia noted; methanol minimally explored	CO_2 emissions trade-offs; real-world process pathways and environmental impacts
Underground storage – salt caverns	High-purity; cyclic reuse; 100 k–1M m^3 storage	7–8	Case examples are missing or limited	Real project data (US, UK, CZ); safety, scale, microbial resistance
Underground storage – aquifers/fields	Large volume; low purity; microbial risks	4–6	Conceptual focus	Microbial interaction, geological risk, pilot examples (e.g., Diadema, Ketzin)
Pipeline transport	Efficient for 2,500–3,000 km	8–9	Deployment reported	Adds EHB 2040, national projects (NL), H2Hubs strategy
Truck/rail transport	Up to 200 bar; LH_2 tankers; short range	8–9	Common; energy cost not deeply quantified	Interface economics, mobile refueling logistics
LH_2 maritime shipping	2,500 m^3 tanks; 225 kiloton demo (HySTRA)	6–7	Mentioned briefly	Includes liquefaction costs, Suiso Frontier project, and HESC insights

hydrides, alongside supportive policies for large-scale projects, will be essential for scaling infrastructure and lowering costs. By addressing technical, economic, and regulatory challenges through global cooperation, hydrogen can become a cornerstone of a decarbonized energy system, reducing emissions, enhancing energy security, and promoting environmental sustainability.

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