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# Above-ground hydrogen storage: A state-of-the-art review

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ABSTRACT

Hydrogen is increasingly recognized as a clean energy alternative, offering effective storage solutions for widespread adoption. Advancements in storage, electrolysis, and fuel cell technologies position hydrogen as a pathway toward cleaner, more efficient, and resilient energy solutions across various sectors. However, challenges like infrastructure development, cost-effectiveness, and system integration must be addressed. This review comprehensively examines above-ground hydrogen storage technologies and their applications. It highlights the importance of established hydrogen fuel cell infrastructure, particularly in gaseous and $LH_2$ systems. The review favors material-based storage for medium- and long-term needs, addressing challenges like adverse thermodynamics and kinetics for metal hydrides. It explores hydrogen storage applications in mobile and stationary sectors, including fuel-cell electric vehicles, aviation, maritime, power generation systems, off-grid stations, power backups, and combined renewable energy systems. The paper underscores hydrogen's potential to revolutionize stationary applications and co-generation systems, highlighting its significant role in future energy landscapes.

## 1. Introduction

The escalating impact of fossil fuel emissions worsens global warming, prompting renewable energy adoption for electricity, like wind, solar, and hydro [1]. Hydrogen, abundant and high-density, replaces hydrocarbons for heat. Its compatibility with fuel cells is a primary appeal [2–4]. Hydrogen, boasting the highest energy content among fuels at 2.016 g/mol, emits only water during conversion, making it favorable for various applications. Despite its promise, challenges in infrastructure and storage impede widespread adoption. Projections foresee hydrogen powering 34% of global energy by 2050, highlighting the critical need for effective storage to realize its potential contribution to future energy demands [5–8].

Recent advancements have propelled hydrogen into the spotlight, driven by innovations in fuel cell technology and renewable energy integration [9]. As countries commit to reducing greenhouse gas emissions, hydrogen offers a dual advantage: it supports renewable energy systems and reduces reliance on fossil fuels. However, significant hurdles remain, particularly in storage and infrastructure [10]. Underground storage, utilizing porous geological formations like saline aquifers and depleted hydrocarbon reservoirs, offers promising long-term storage solutions for surplus renewable energy [11,12]. Underground storage using porous geological formations is promising for long-term surplus renewable energy storage [13]. However, underground hydrogen storage faces challenges related to geological suitability, hydrogen embrittlement, containment and leakage risks, and the need for continuous monitoring and safety measures [14].

Hydrogen's storage challenge lies in its considerable volume at ambient temperature and pressure: 1 kg occupies about 11 $m^3$. While solid hydrogen densifies at $-262\,^{\circ}C$ to 70.6 $kg/m^3$, gaseous hydrogen at $0\,^{\circ}C$ has a density of 0.089 $kg/m^3$, demanding substantial storage space. Solutions require volume reduction, with high costs currently impeding widespread adoption, which is expected to decrease as production scales. Despite challenges, technologies like liquid hydrogen ($LH_2$) composite cryo-tanks and fuel cells are mature, with functional prototypes [15–17].

Hydrogen's merits as an energy carrier offer compelling solutions to energy challenges and global warming threats. These include.

- Renewable hydrogen promotes sustainability.

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- Near-zero emissions improve urban air quality.
- Economic viability fosters global prosperity.

Various methods for hydrogen storage include 1) High-pressure gas cylinders, 2) Cryogenic tanks for $LH_2$, 3) Adsorption onto high-surface-area materials, 4) Absorption within host metals, 5) Chemical bonding in compounds, 6) Reactive metals (Li, Na, Mg, Al, Zn) storing hydrogen through oxidation reactions with water, and 7) Underground storage. The critical role of underground hydrogen storage in enhancing energy stability by addressing renewable intermittency and the effects of geological formations and hybrid systems is also of focus [18]. Above-ground hydrogen adsorption on carbon materials like activated carbon, graphite, carbon nanotubes, and nanofibers offers promising storage capacity [19]. For instance, liquid hydrogen storage ($LH_2$), methanol, ammonia, and dibenzyl-toluene offer advantages in storage density, cost, and safety [20]. The focus of this paper is mainly on the above-ground storage methods. Fig. 1 categorizes storage into underground and above-ground types.

Storage method selection hinges on end-user demand scale. $LH_2$, though rarely used for bulk storage, is vital for offshore shipment, akin to liquid natural gas practice [14]. Cryo-compressed hydrogen storage was developed to enhance storage density while minimizing space and weight, combining cryogenic and high-pressure methods to meet efficiency demands, particularly in transportation [4]. In addition to compressed and cryogenic tanks, interest in solid-state hydrogen storage is rising. Categories include chemically bound options like clathrate hydrates, LOHCs, metal hydrides (MHs), and chemical hydrides, as well as physically bound options such as carbon-based materials, MOFs, COFs, zeolites, and PIMs. MHs, notably, show promise for securely compactly storing large quantities of hydrogen with reversibility, driving research efforts. However, practical challenges remain, with existing MHs falling short of essential criteria for a viable hydrogen economy due to low capacity, slow kinetics, and unfavorable absorption/desorption temperatures [15,21–23]. A summary of these advancements to some of the more-researched-about solid-state storage materials such as MOFs, LOHCs, carbon-based materials, and metal hydrides as hydrogen storage can be seen in Figs. 2–5.

Looking back at the developments that occurred to the materials in Figs. 2–5, solid-state storage, irrespective of the relative youngness of this method, shows a great potential of paving the way to the feasibility of hydrogen economy. Long-term hydrogen storage faces losses and technical economic challenges requiring new measures for broad energy storage deployment [24]. Ma et al. predict declining costs with advancements and economies of scale, but storage, transport, efficiency, and adoption solutions are needed [25]. Effective storage aids renewable energy intermittency and decarbonization in transport and construction. Transport options include pipelines, cryogenic tankers, trailers, rail, and barges [26,27].

Hydrogen can be used in transportation and power generation systems, including fuel cells, internal combustion engines, or turbines [15]. Despite lower energy efficiency, hydrogen has advantages over batteries in specific mobility applications. Reliable storage is crucial for hydrogen's role in transportation, stationary, and portable applications [28,29]. Hydrogen from surplus renewable electricity must be used for power or fuel cells, with production projected at 19,200 tons/year by 2025 [30]. Despite the increased efficiency of aircraft, total pollutant emissions are on the rise. While efficient in terms of required fuel mass, component improvements prove ineffective in reducing overall environmental impacts. New energy concepts are crucial in aircraft design to meet targets. Hydrogen, as an energy carrier, holds significant potential and could represent the next revolutionary technological leap, akin to introducing the turbofan engine. Commercial and cargo ships, relying primarily on fossil fuels in diesel engines, contribute to significant economic and environmental impacts of high fuel consumption and substantial greenhouse gas emissions. According to the International Maritime Organization (IMO), shipping contributed to 1056 million tons of $CO_2$ emissions in 2018, representing approximately 2.89% of that year's global anthropogenic $CO_2$ emissions. A substantial increase in the production of green hydrogen holds the potential to significantly enhance various sectors, encompassing industrial, transportation, residential, and aerospace domains [31–33].

This paper explores prevalent methods for above-ground hydrogen

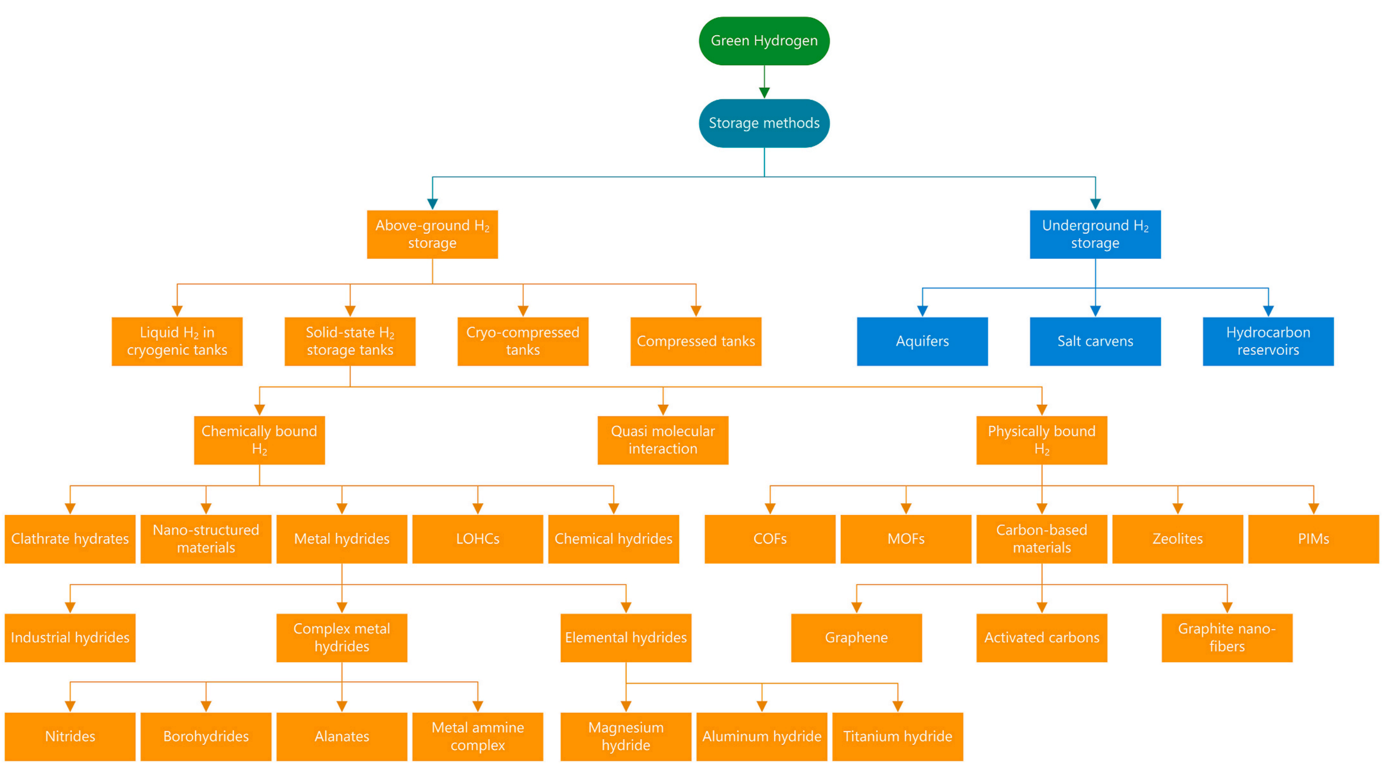


**Fig. 1.** Different hydrogen storage methods.

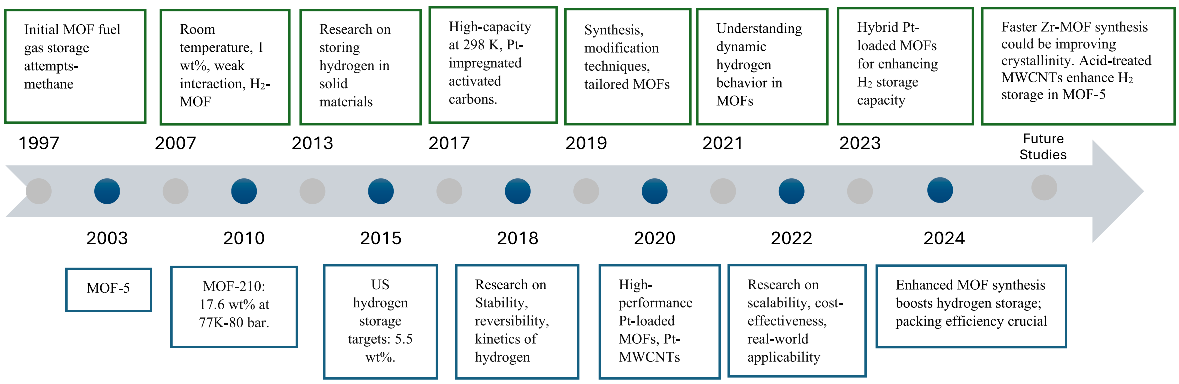


**Fig. 2.** Key timeline of MOFs for hydrogen storage breakthroughs.

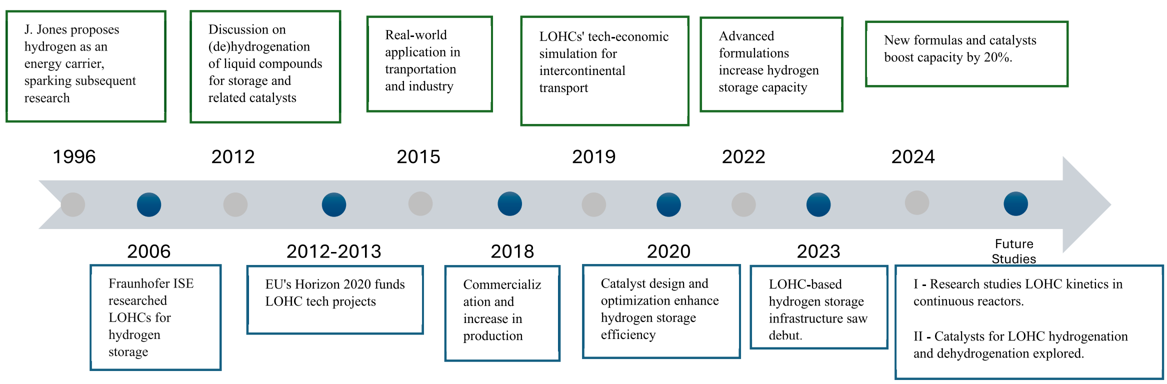


**Fig. 3.** Key timeline of LOHCs disvoceries for hydrogen storage breakthroughs.

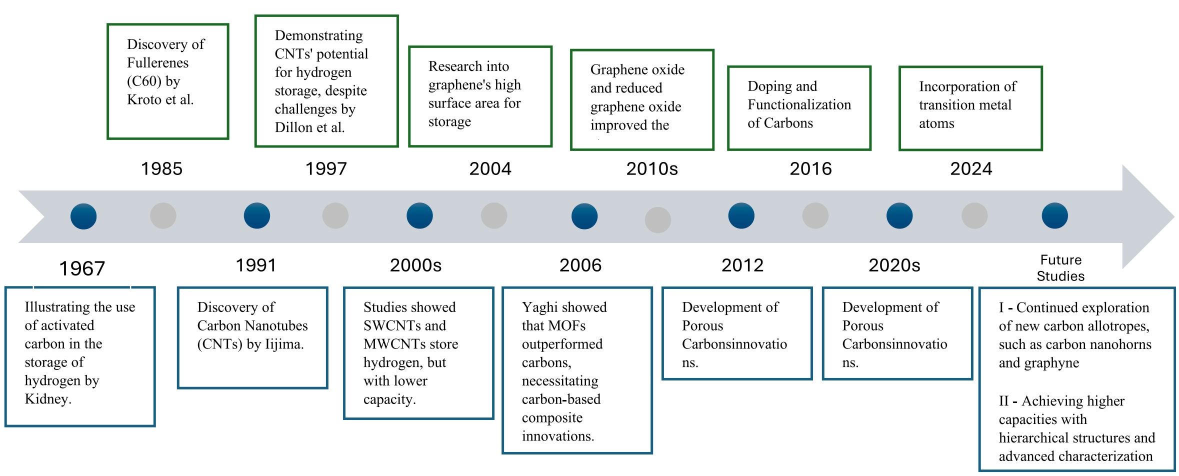


**Fig. 4.** Key Timeline of carbon-based materials Disvoceries for Hydrogen Storage Breakthroughs.

storage, categorizing them into chemically bound and physically bound methods. It also provides an overview of potential stationary and mobile applications, highlighting the widespread utilization of hydrogen across various sectors such as automotive, aviation, shipping, and power generation.

## 2. Above-ground hydrogen storage

The clear edge of above-the-ground hydrogen storage over under-the-ground is its independence from geological conditions. Lange et al. examined the market relevancy of these two storage types using the open-source energy system model and optimization framework of Europe. It clarified the less important role of capacity, comparatively lower cost to capacity, and higher annual hydrogen storage of the aboveground storage form. However, the low efficiency and high cost hinder the feasibility of extensive use of such storage methods [34]. On the other hand, these problems could be solved if the proper form of above-ground storage is employed for the purpose employed, which calls for a comprehensive look over the characteristics and pros and cons of each. Compression, liquefaction, metal frameworks, and chemical carriers, such as ammonia and liquid organic hydrogen carriers (LOHCs), represent some of the most viable options for hydrogen storage in fuel cell applications. These storage methods enable the release of high-purity hydrogen, making it suitable for use in both low- and

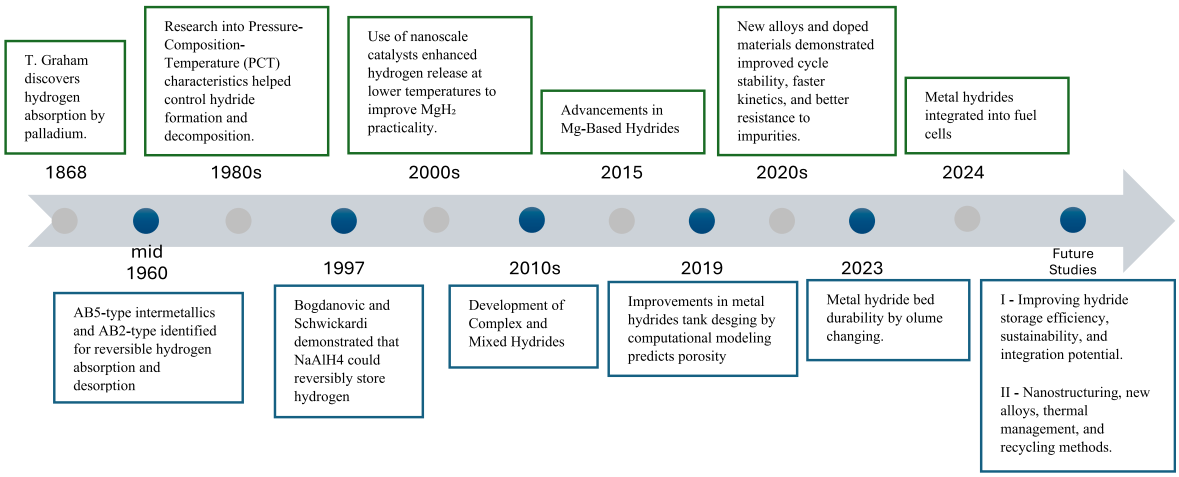


**Fig. 5.** Key Timeline of metal hydrides Disvoceries for Hydrogen Storage Breakthroughs.

high-temperature fuel cells [35].

### 2.1. Gas hydrogen

The main difference in compressing hydrogen and other natural gases is the energy required due to hydrogen's lower specific gravity. The common method is compressing hydrogen into gas and storing it in cylinders [15,36]. However, these typically handle only up to 20 MPa, which is insufficient for driving. Efforts aim to develop cylinders withstanding up to 70 MPa, but low density and high costs may limit commercial viability. Compressing hydrogen from 0.1 to 80 MPa requires about 2.21 kWh/kg $\mathbf{H_2}$ of energy, which is even higher in actual processes like liquefaction. A Linde report indicates that compressed hydrogen ($CGH_2$)'s cost exceeds that of $LH_2$, potentially limiting future use [37].

### 2.2. Liquid/Cryogenic Hydrogen Storage

Densifying hydrogen involves pressurization or liquefaction. $LH_2$ achieves higher density, about 71 g/L at its boiling point, 1.8 times denser than hydrogen at 70 MPa. However, $LH_2$ storage is limited to open systems due to their low critical temperature and energy-intensive nature, consuming over 30% of hydrogen's energy content [13,35,36,38]. Hydrogen evaporation rates vary based on vessel geometry and insulation [39]. $LH_2$ requires double-walled vessels to minimize heat leakage, with tank sizes from 1.5 to 75.0 $m^3$ [4,36].

Liquefaction technically needs 15.2 kWh/kg $\mathbf{H_2}$, with inevitable losses. Ortho-to-para hydrogen conversion aids gasification and $LH_2$'s low critical temperature limits storage in open systems. Boil-off restricts use to rapid consumption applications [37,40].

Numerous challenges accompany $LH_2$ storage, primarily an energy-intensive liquefaction process that consumes approximately 10 kWh/kg. Challenges include.

- Liquefaction consumes 30–33% of hydrogen's energy vs. 10% for compression.
- High storage tank material costs and security concerns.

Evaporation losses in storage tanks range from 0.1 to 1% per day, while capital investment for $LH_2$ liquefaction comprises 40–50% of $LH_2$ storage system expenses. Large-scale $LH_2$ vehicle use faces hurdles, but magnetic liquefaction shows promise [36,41]. Boil-off loss can be mitigated by recycling cold boil-off gas, employing it downstream, and using well-insulated containers [15,42].

### 2.3. Compressed hydrogen

Pure hydrogen storage primarily relies on high-pressure cylinders, ranging from 20 MPa to 70 MPa, akin to natural gas compression. Stored at ambient temperature, it eliminates costly insulation by being easily pumpable. Above-ground setups often use multiple cylindrical pressure vessels. Compression technologies include mechanical compressors and carbon fiber composite pressure vessels (COPV) for lightweight or high-capacity or metal pressure vessels, ranging from 20 MPa to 100 MPa [40,41,43]. Multi-stage compressors attain high output pressures, varying by application and transport mode. Tube trailers store hydrogen at 200 bars, while mobility uses 350 or 700-bar delivery [44].

Energy is reclaimed during cryogenic liquid vaporization and high-pressure gas withdrawal through expansion. Hydrogen's enthalpy changes from liquid to gas, yielding about 3700 J/g, accounting for 10% of liquefaction energy. The negative Joule-Thompson coefficient eliminates thermal input, but harnessing power from high-pressure hydrogen expansion faces challenges due to its low molecular weight [14]. Mechanical compressors, like diaphragm or reciprocating ones, face issues with hydrogen purity and noise, driving research into alternative methods like ionic liquid, MH, and electrochemical compressors [45].

Table 1 compares three hydrogen compressors: Ionic Liquid, ECHC, and MH Compressors. Ionic Liquid Compressors stand out for their ability to operate under high pressure and a wide range of temperatures. Their efficiency of 70% makes them a solid option for applications that demand robust performance. However, the complexity of their design, coupled with potential issues like liquid leakage and cavitation, suggests that these compressors are best suited for environments where these challenges can be managed effectively. ECHCs bring the advantages of high efficiency (up to 90%) and the capability to reach pressures as high as 1000 bars. Their noiseless operation and modular design make them ideal for use in settings where noise reduction and flexibility are priorities. Nonetheless, their dependency on precise humidity control and the need for structural reinforcement indicate that they might require more advanced maintenance and operational oversight compared to other technologies. MH Compressors are valued for their simplicity, reliability, and safety. They excel in scenarios where compactness and low maintenance are critical, particularly in utilizing waste heat to improve efficiency. However, their low efficiency and the lack of a well-established market limit their application primarily to niche areas where their specific advantages outweigh their inefficiencies.

Given the discussion, Ionic Liquid compressers are well-suited for hydrogen refueling stations for fuel cell vehicles. ECHCs are ideal for environments where quiet, vibration-free operation is essential, such as in laboratories or research centers working on hydrogen fuel cell technologies [48] as well as settings where hydrogen needs to be purified

**Table 1**
Alternative types of hydrogen compressors.

| Type | Principle used | Feature | Pressure/ Temperature | Efficiency | Advantage | Disadvantage | References |
|---|---|---|---|---|---|---|---|
| Ionic liquid compressors<br>***Mechanical*** | • Operates like reciprocating compressors<br>• Uses ionic liquid in compression chamber<br>• Compresses hydrogen, recycles liquid | • Ionic liquid instead of piston<br>•Incompressible<br>•Good lubricating<br>•Performances in high-temperatures | **Pressure:** Max 1000 bars<br>**Temperature:** Wide range of temperatures | 70% | •Virtually no vapor pressures.<br>•Wide liquid phase temperature window.<br>•Low hydrogen solubility. | •Complex design<br>•Liquide leak<br>•Cavitation and corrosion phenomena | [45,46] |
| ECHC (Electrochemical Hydrogen compressor)<br>***Non-mechanical*** | •Hydrogen fed to the anode is collected from the cathode. | Internal:<br>• Anode<br>• Cathode<br>• PEM<br>External:<br>• Pump<br>• Back-pressure controller<br>o No moving part<br>oHydrogen Purifier<br>oThe proton-exchange membrane (PEM) technology for water electrolyzers.<br>oIsothermal compression process | **Pressure:**<br>• 50 and 6.5 bar inlet pressure<br>• 54 bar cathode-anode pressure difference at 25 $\pm 2 ^\circ C$<br>• Max 875 bar in a single-stage compression.<br>• The highest pressure is 1000 bar.<br>**Temperature:** Operating in low temperatures: (30 $^\circ C$-80 $^\circ C$) | 60%–90% | • Noiseless, vibration-free operation<br>• Modularity<br>• No moving parts<br>• Higher efficiency than mechanical compressors | • Reliability issues; precise humidity control essential.<br>• Voltage losses, gas crossover concerns.<br>• Challenges in sealing assembly.<br>• Structural reinforcement needed | [47–51] |
| MH Compressors<br>***Non-mechanical*** | • Hydrogen transfer is vital during absorption/ desorption. | • Pure, high-pressure hydrogen storage via reversible MHs.<br>• Utilizes thermally powered systems.<br>• Coupled with electrolyzer outlets.<br>• Common Alloys like AB5 and AB2-type. | **Pressure:** 800–900 bar<br>**Temperature:** 120–150 °C | Below 10% when working with waste heat | • Simplicity in design and operation<br>• The absence of moving parts<br>• Compactness<br>• Safety, reliability.<br>• Using industrial excess heat waste boosts efficiency.<br>• Low maintenance operation costs. | • Low efficiency<br>• Not established market/no mass production | [52] |

and compressed simultaneously, such as in the production of high-purity hydrogen for electronics manufacturing or pharmaceuticals [53].

The use of pressure vessels for hydrogen dates back to 1880, when hydrogen was stored in wrought iron vessels at 12 MPa. Typically, hydrogen cylinders can be pressurized to 25 MPa, 35 MPa, or 70 MPa [36]. Compressed gaseous hydrogen ($CGH_2$) storage relies on vessels with thick walls, which are crucial for safety at pressures up to 700 bars. Advancements in composites enable lighter carbon fiber tanks, prioritizing safety, reliability, and cost [2,4]. Table 2 provides a comprehensive overview of the various types of pressure vessels.

The table compares various hydrogen storage vessels by highlighting their materials, performance, and applications. Type I vessels, made from steel, are robust and cost-effective, suitable for stationary uses such as hydrogen storage facilities and backup power systems. However, their heaviness and internal corrosion issues limit their use in mobile applications. Type II vessels, featuring a steel shell wrapped with CFRP (carbon fiber reinforced polymer), balance cost and weight while supporting pressures up to 1000 bars. They are commonly used in hydrogen refueling stations but also face internal corrosion problems. Type III-vessels, constructed with CFRP or glass fiber and aluminum or steel liners, are lighter and support pressures up to 450 bars. These are ideal for experimental hydrogen vehicles and prototypes due to their weight reduction benefits, although they are more expensive and prone to galvanic corrosion. Type IV vessels, the lightest and strongest, use CFRP wrapped around a polymer liner, making them optimal for hydrogen fuel cell vehicles, including commercial cars and trucks. They are used in high-performance applications like Cryomotive's truck tanks but require careful temperature management. Type V vessels, made from advanced carbon fiber composites, offer the highest performance and lowest weight, suitable for aerospace and maritime industries, though they are currently expensive with limited pressure capabilities. Overall, Type III and IV vessels are preferred for vehicle applications due to their lightweight construction and superior mechanical strength [38,54].

### 2.4. Cryo-compressed hydrogen storage

Cryo-compressed storage combines compressed and liquid methods, maintaining hydrogen in a supercritical state at around −233 °C [35]. Aceves et al. introduced this method, compressing supercritical cryogenic gas instead of liquefying it [4]. This storage method combines the benefits of compressed gaseous and liquefied hydrogen systems, aiming to minimize hydrogen boil-off while maintaining high energy density. Hydrogen is stored in an insulated tank capable of withstanding cryogenic temperatures and high pressure (at least 30 MPa) at ambient temperature, optimizing weight and volume. The tank's high-pressure tolerance allows for significant pressure increases before venting hydrogen, extending storage duration and reducing evaporative losses. Filling the tank with compressed gas instead of liquefied hydrogen is expected to be more cost-effective. Cryo-compressed tanks offer refueling versatility, accommodating both gaseous and liquid forms and enhancing infrastructure adaptability [29,38,57]. At 80 K, hydrogen density increases by 3.73 times compared to 298 K, extending vehicle range and requiring less energy for production (20Mpa-80K), approximately 10 MJ/kg [58]. With a boiling point below ambient pressure at 20 K for $LH_2$, cryo-compressed hydrogen gas emerges as a viable alternative for fuel storage [59].

**Table 2**
Different types of vessels used for compressed hydrogen storage.

| Vessel | Utilized Material | Typical Pressure (bars) | Specifications | Weight and Cost | Advantages | Disadvantages | Application | References |
|---|---|---|---|---|---|---|---|---|
| Type I | **Utilized Material:** All Metals (mainly steel) **Feature:** Constructed based on BPVC standard; Metallic liner; Neck with optional end plug. | 200 (Max 300) | Gravimetric Energy Density WT%: 1.7 | **Weight:** The heaviest **Cost:** Relatively cheap | • Cheap • Maximum strength • Ultra-high-pressure applications | • Unsuitable for vehicle applications • Internal corrosion | • Stationary industry, mobile trailers, and gas bottles. • Hydrogen Tank | [29,45,54] |
| Type II | **Utilized Material:** Steel Shell wrapped with filament winding of CFRP **Feature**: Synthetic material for outer strengthening. | Max 1000 | Gravimetric Energy Density WT%: 2.1 | **Weight:** Weighing less than Type I **Cost:** Relatively more expensive than I. | • Material Selection Flexibility • Moderate Weight • Moderate Strength • Relatively Low Cost • Medium-Pressure Applications | • Unsuitable for vehicle applications • Internal corrosion causes it to fail quickly. | • Refueling stations | [54] |
| Type III | **Utilized Material:** CFRP or glass fiber with aluminum or steel seal, using Tory T700S or T800S. **Feature:** High mechanical strength; Better mechanical resistance. | Max 450 (Tested for cycling 700) | • Gravimetric Energy Density WT%: 4.2 • Specific Heat Capacity (J/kg K): 900 • Thermal Conductivity (W/mK): 167 | **Weight:** Lighter than previous types (25%–75% heavier than Type I.) **Cost:** Favored over Type IV for mature manufacturing | • Better mechanical resistance. • Moderate Strength • Moderate Weight • High-Pressure applications | • Costly • Galvanic corrosion between liner and fiber. | • Vehicle applications: **Instances:** • Experimental use: Toyota Prius hybrid. • Cryomotive's full-scale truck tank. • Meets European vehicle weight efficiency standards. | [29,54,55] |
| Type IV | **Utilized Material:** Wrapped such as Type III. CFRP wall and polymer liner seal **Feature:** Composite materials ensure safe hydrogen storage. | 350 (Max 700) | • Gravimetric Energy Density WT%: 5.7 • Specific Heat Capacity (J/kg K): 1400 • Thermal Conductivity (W/mK): 1.5 | **Weight:** The lightest by far. **Cost:** High | • Lightweight • High Strength • Corrosion Resistance • Safety • Increased Storage Capacity • Gas Containment • Design Flexibility | • Too costly • Needs precooling to stop the tank from 85 °*C*. | • Optimal for vehicle applications (No creep-fatigue) • Meeting European weight efficiency standards | [24,29,54,55] |
| Type V | **Utilized Material:** - COPVs - Carbon fiber laminate - Fully composite **Feature:** High-pressure tolerance | High pressures like type IV (pending investigation) | High potential for increasing the gravimetric and volumetric density | **Weight:** significantly lighter than Type IV **Cost:** Unspecified due to the high cost of composite materials | • Internal Polymer Gas Barrier Elimination • High-Pressure Hydrogen Containment • High-Performance COPV | Insufficient pressures for practical hydrogen storage. | • Industries with high-pressure • Automotive Industry • Aerospace • Maritime Industry | [55,56] |

### 2.5. *Solid-state hydrogen storage*

Solid-state storage uses nanostructured materials and hydrides to bond with hydrogen, overcoming volume constraints [60,61]. Efficient but low-density, these materials use physisorption and chemisorption, releasing hydrogen via heat. Challenges include slow kinetics, limited capacity, and cost-effectiveness for fuel cell operations [4,62–64]. Key solid-state hydrogen storage processes.

**Hydrogen Absorption:** The absorption process involves hydrogen gas interacting with a metal surface, which initially forms a weak physisorbed state through van der Waals forces, overcoming an activation barrier to form a stronger chemisorbed state and diffusing through the metal lattice [16,65–67]. Surpassing traditional methods, MHs need high capacity, low dissociation temperature/pressure, affordability, and stability. Solid absorbers like metallic hydrides offer safety and higher volumetric capacity [6,45].

**Hydrogen Adsorption:** Gas molecules diffuse into adsorbent micropores, requiring low temperatures for substantial hydrogen adsorption [36]. Despite the potential, hydrogen sorption remains lab-scale due to low density [68]. Adsorption capacity depends on surface area and weak van der Waals forces ($4^{-10}$ kJ mol$^{-1}$). Cooling to 77 K enhances storage. MOFs, novel porous materials, have high surface areas, up to 5000 m$^2$/g [45].

**Electrochemical Hydrogen Storage:** In electrochemical storage, atomic hydrogen adsorbs during electrochemical decomposition, bypassing molecular dissociation and improving storage [69].

**Carbon Adsorption:** This research method pressures hydrogen into a cooled tank with porous activated carbon for efficient absorption [40].

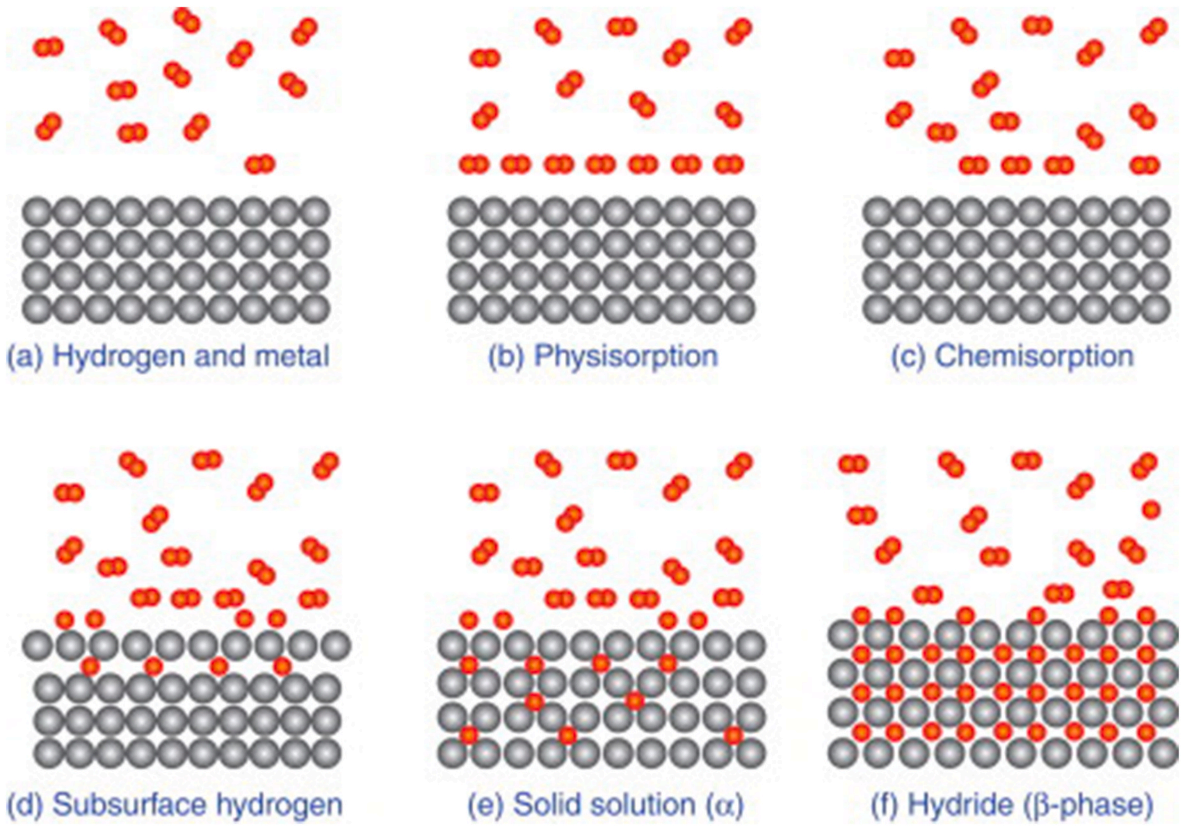


**Fig. 6.** (A) The metal lattice is subjected to hydrogen gas in a non-equilibrium state; (b) hydrogen molecules adsorb onto the metal surface at low temperatures; (c) hydrogen molecules dissociate, and hydrogen atoms are chemisorbed; (d) hydrogen then moves into the subsurface region; (e) hydrogen atoms mix uniformly within a metal hydride's crystal lattice [72].

**Hydrogen Chemisorption:** Hydrogen dissociates on solid surfaces, forming chemical bonds in chemisorption [23]. Hydrogen dissociates on solid surfaces, forming chemical bonds in chemisorption [64,70].

**Hydrogen Physisorption:** Porous materials like MOFs and zeolites physisorb hydrogen with 4–7 kJ/mol adsorption enthalpy [71]. Physisorption offers rapid kinetics, reversibility, and stability [66,70]. Cryogenic temperatures maximize sorption but reduce efficiency. Chemisorption requires higher release temps and is irreversible [64,70].

Fig. 6 illustrates the six steps into hydrogen absorption.

*2.5.1. Chemically bound hydrogen*

Chemical sorption involves splitting hydrogen molecules into atoms and integrating them into the material's structure. MHs are common, but challenges include cost, weight, operating temperatures, kinetics, and managing unwanted gas formation during desorption [4]. Another issue with chemical hydrogen storage is the need for regeneration. The primary challenge lies in selecting the appropriate material for a given application [73]. These materials, such as porous carbon, metal-organic frameworks, polymers, and zeolites, are notable for hydrogen storage. However, their low energy densities and heat generation during absorption limit applications, particularly for stationary storage [42]. Common chemical hydrogen storage methods are discussed below.

*2.5.1.1. Chemical hydrides.* Chemical hydrides, which are composed of lighter elements than metal hydrides, are a class of materials that store hydrogen through chemical bonds which offer high hydrogen storage rates and easy decomposition when hydrogen is covalently bonded to carbon, nitrogen, or boron atoms [7,68]. Hydrides are classified into two main categories: metal-containing and non-metal-containing [61,74].

Chemical hydrides offer higher energy densities and milder hydrogen release conditions than metal hydrides but require off-board regeneration due to irreversible dehydrogenation reactions [74].

The main challenges with chemical hydrides include difficulties in recycling and regenerating the spent material after hydrogen release, the need for specific reaction conditions, and the potential release of by-products during hydrogen generation. Much of current research on hydrogen release from chemical hydrides is directed toward single-use applications where the spent fuel is disposed of. However, there is growing interest in creating systems capable of multiple cycles, which is essential for commercializing hydrogen vehicles [75]. However, storing chemical hydrides inside metal organic frameworks (MOFs) nanopores speeds up hydrogen release and lowers the temperature needed for dehydrogenation. This also reduces the formation of unwanted byproducts [76].

*2.5.1.2. Metal hydrides.* Materials absorb hydrogen under pressure, forming reversible hydrides. Heat is released during absorption, and hydrogen is released with reduced pressure and heat [40]. Metal hydrides (MHs) contain metals and hydrogen [28,77]. Hydrogen splits surfaces and diffuses into metal lattices, forming hydrides. Mg-based hydrides face unfavorable kinetics [60,71]. Hydrogen splits surfaces, enters metal lattices, diffuses, and forms hydrides. Desorption needs 120–200 °C, offering safe, compact storage. Energy recovery at 50%, needing 14.7 MJ/kg to compress hydrogen [36,38,64].

In the 2010s, MH systems for hydrogen storage were developed for stationary uses like emergency power units [78]. They are too heavy for transport, so they appeal to battery-reliant mobile applications due to their safety and high energy density [79]. Lightweight MHs store hydrogen efficiently at low temperatures [73]. MH storage uses plateau pressure, favoring low-temp MHs [80]. The shift from Ni/Cd to Ni/MH batteries highlights MH's benefits. Research focuses on MHs and MH/air batteries for charge storage [81].

MHs store hydrogen exothermically; releasing it requires heat. MHHCs offer simplicity and modular design [43]. Lower pressure during unloading needs less heat. Room-temp MHs achieve high gravimetric energy density [41,68].

In the following sections, some of these hydrides will be discussed.

*2.5.1.2.1. Complex metal hydrides.* Complex MHs, like $NaAlH_4$, $LiAlH_4$, and $LiBH_4$, have non-stoichiometrically bound hydrogen within their ionic lattice, offering high gravimetric densities of up to 20 wt% hydrogen [2,82]. Complex MHs, with partially covalently bound hydrogen atoms, offer high gravimetric capacities. They include nitrogen-containing (amides or imides) and boron-containing (borohydrides) groups, often with lithium or magnesium and sometimes sodium, calcium, or transition metals [61]. Complex hydrides present challenges with non-reversible reactions, favoring nitrides for hydrogen storage [7,23,70]. Like $Mg(BH_4)_2$, metal borohydrides exhibit diverse applications, including hydrogen storage and ion conductivity. Their stability and multifunctionality make them promising materials for various technological advancements [83,84].

*2.5.1.2.1.1. Borohydrides*

Borohydrides, part of a class of materials with the highest gravimetric hydrogen densities, are pivotal in hydrogen storage research, particularly the $M(BH_4)^n$ compounds. These tetrahydridoborates are studied for their potential due to their high hydrogen content and complex structures. Li $BH_4$, for example, decomposes at 320–380 °C, releasing up to 80% of its hydrogen, and its decomposition temperature can be reduced when mixed with silica [85]. Mg $(BH_4)^2$ and Ca $(BH_4)^2$, with densities of 1.12 g/ $cm^3$ and decomposition temperatures of 360 °C–500 °C, release hydrogen in multiple stages [86]. The thermodynamic stability of $M(BH_4)^n$ can be systematically predicted by considering the electronegativity of the metal, which is essential for developing materials with appropriate stability and high hydrogen density. For instance, Hydrazine borane ($N_2H_4BH_3$), with its high hydrogen content of 15.4 wt%, is a promising hydrogen storage material with efficient hydrogen production using advanced catalysts [87,88]. Addressing challenges like high dehydrogenation temperatures and slow kinetics is essential for improving $M(BH_4)^n$ hydrogen storage, with a focus on destabilization strategies, additives, and new heating methods to enhance reaction kinetics and reversibility [89,90]. Another study on doped g-C3N4 catalysts highlights that borohydrides like ammonia borane undergo enhanced dehydrogenation with improved photocatalytic and catalytic activity due to modifications with metals and non-metals [91].

*2.5.1.2.2. Elemental hydrides.* Elemental hydrides, which involve hydrogen bonding with a single metal element such as magnesium, aluminum, or titanium, are among the simplest forms of metal hydrides. Magnesium hydride has a theoretical hydrogen storage capacity of 7.6 wt% and is inexpensive and widely available. However, it requires around 75 kJ/mol $H_2$ of energy for hydrogen desorption and operates at high temperatures of approximately 300 °C, making it less ideal for applications like transportation [92,93]. Recent research has focused on improving its charging and discharging characteristics through additives like titanium compounds. In contrast, aluminum hydride, with a higher theoretical storage capacity of 10.1 wt%, has relatively weak hydrogen bonds with a desorption energy of around 7 kJ/mol $H_2$ and operates at a lower temperature of about 100 °C [94]. However, it requires very high pressures for hydrogen absorption, which limits the reversibility of the reaction and necessitates electrochemical methods for regeneration. On the other hand, Titanium hydride operates at high temperatures between 650 and 750 °C and low pressures but offers a lower storage capacity (about 1 wt%). Despite its lower capacity, titanium hydride's high-temperature operation and low-pressure requirements make it suitable for specific applications [95].

*2.5.1.2.2.1. Mg-based hydrides*

Magnesium forms $MgH_2$ with 7.6% hydrogen but needs 300 °C for a 1-bar plateau pressure. Ball milling and composites enhance diffusion rates, offering improved capacities [71,77].

Magnesium-based MHs, like magnesium hydride, store hydrogen, and thermal energy, finding applications in concentrating solar power for high-temperature thermal energy storage [73]. Magnesium hydride's abundance and cost-effectiveness make it appealing for hydrogen storage, offering energy densities of 7.6 wt% and 13.22 MJ/L with a density of 1.45 g/$cm^3$ [28]. With up to 7.6 wt%-$H_2$ gravimetric hydrogen storage density in pure $MgH_2$, these materials demonstrate cycle stability and commercial potential, benefiting from magnesium's abundance and low cost as a lightweight base material [96].

*2.5.1.2.3. Interstitial hydrides.* Metallic hydrides, also known as interstitial hydrides, are a subtype within the broader group of metal hydrides. They can store more hydrogen per unit volume than liquid hydrogen and offer greater hydrogen content by weight [97]. Unlike chemical hydrides with fixed stoichiometric ratios between hydrogen and metal atoms, metallic hydrides are nonstoichiometric, where hydrogen atoms occupy interstitial sites in the metal's crystal lattice without a fixed ratio, allowing the hydrogen-to-metal ratio to vary [98]. In contrast, chemical hydrides like magnesium hydride ($MgH_2$) involve a well-defined and fixed hydrogen-to-metal ratio and typically exhibit more ionic or covalent bonding characteristics [99]. In summary, Interstitial hydrides typically store 1–2 wt% hydrogen and have fast absorption/desorption kinetics, making them suitable for portable applications, while chemical hydrides, such as magnesium hydrides, can store up to 7.6 wt% hydrogen but require higher temperatures (200–300 °C) for hydrogen release and involve complex reaction byproducts [95,100].

In industry, metal hydrides are used for hydrogen storage and typically include complex metal hydrides and advanced metal hydrides designed for practical large-scale applications [84]. These hydrides are valued for their enhanced hydrogen storage capacities and operational efficiencies in various industrial contexts. The hydrides include intermetallic hydrides, such as those formed from combinations of metals like titanium and nickel. They are used for both high-density storage and practical applications [101].

They are used in various applications, including energy storage systems, fuel cells, and portable hydrogen storage solutions. They are particularly valuable in applications requiring high-density hydrogen storage and efficient release. However, challenges such as high operating temperatures, energy-intensive regeneration processes, and material costs remain significant [102,103].

*2.5.1.3. Liquid organic hydrogen carriers.* Liquid Organic Hydrogen Carriers (LOHCs) are organic substances capable of storing hydrogen in a chemically bonded form, achieving 5–6 wt% hydrogen and up to 56 $kgH_2/m^3$. Loading and unloading reactions occur in a chemical reactor with various catalysts and temperatures typically above 100 °C, often between 200 °C and 400 °C. Hydrogen release from the LOHC system happens under low pressures, typically below 5 bar, allowing ambient handling during storage and transport and utilizing existing fuel infrastructure. LOHCs represent a promising technology for safely handling hydrogen, particularly in underground applications, significantly reducing the risk of hydrogen-induced explosions. Toluene and dibenzyl toluene LOHC systems show potential for large-scale production, but further development is needed, especially regarding thermodynamics. Lower dehydrogenation enthalpies are advantageous, reducing heat requirements and improving molecular stability and recyclability across cycles [28,42,45,68,104–106]. Table 3 comprehensively reviews studies done on LOHCs in the literature.

Table 3 reviews recent research on Liquid Organic Hydrogen Carriers (LOHCs) and their properties and applications. They have been identified as effective for decentralized energy storage, offering the ability to meet increasing storage demands and utilize waste heat to enhance efficiency. The materials are suitable for both stationary applications, such as hydrogen storage facilities, and community systems, with potential

**Table 3**
Literature review on LOHCs.

| Author (Year) | Properties of the studied material | Research objective | Methodology | Key Findings | Conclusion |
|---|---|---|---|---|---|
| Daniel Teichmann et al. (2015) [107] | • Hydrogenation: 150 °*C* and 70 bar<br>• Dehydrogenration: 230 °*C* and 1 bar | Proposal: LOHC-based decentralized energy storage, assess economic feasibility and explore revenue from thermal loss utilization. | • Assess investment using the Equivalent Annuity Method.<br>• Discount cash flows to Net Present Value (NPV).<br>• Use the annuity factor for annual cash flow.<br>• Revenue from reserve provisions and price arbitrage.<br>• Calculate heating revenue equipment depreciation. | • LOHCs meet rising storage demands.<br>• Waste heat improves hydrogen storage efficiency.<br>• Thermal losses aid house heating economics. | • LOHCs promise decentralized energy storage.<br>• Adoption addresses growing storage needs.<br>• Benefits individual buildings to community systems.<br>• Extends to sustainable hydrogen mobility, linking storage and transportation. |
| Daniel Teichmann et al. (2011) [108] | **Material:**<br>Heterocyclic aromatic hydrocarbons such as N-ethyl carbazole<br>• Hydrogenation: 130–160 °*C* and 70 bars.<br>• Dehydrogenation: 200–230 °*C* and slightly above ambient.<br>• Catalyst: Pt/Pd for dehydrogenration. | Proposal: Competitive energy distribution via LOHC, storing excess renewables and integrating them into hydrogen mobility. | • Evaluate physico-chemical properties of LOHCs.<br>• Assess the compatibility of LOHCs with current energy infrastructure. | • Fossil fuels energy match storage, ideal for distribution and mobility.<br>• Integration may need dehydrogenation or blending.<br>• Toxicity test: vital for LOHC systems.<br>• Challenges in efficient dehydrogenation for vehicles<br>• Collaboration is needed for LOHC tech advancement. | • LOHCs store renewables for mobile use efficiently.<br>• Collaboration is vital for LOHC tech advancement. |
| Patrick Preuster et al. (2016) [109] | • Dibenzyltoluene (H0-DBT)/ Perhydrodibenzyltoluene (H18-DBT) LOHC<br>• Organic compounds undergo catalytic hydrogenation/ dehydrogenation cycles. | LOHC tech for energy, logistics, mobility; assessing hydrogen economy role. | • Literature Review: Analyze existing LOHC research, identifying gaps.<br>• Case Studies: Evaluate LOHC applications in various sectors.<br>• Technical and Economic Evaluation: Assess feasibility, viability, and environmental impact.<br>• Research Needs: Identify areas needing development. | **Stationary Energy Storage:**<br>• LOHCs offer efficient grid-connected and off-grid storage, complementing renewable sources cost-effectively.<br>**Hydrogen Logistics:**<br>• LOHC-based transport proves economically feasible, enhancing energy delivery flexibility and cutting transportation costs.<br>**Hydrogen Mobility:**<br>• Although LOHCs enable on-demand hydrogen supply (vehicles), efficiency and integration challenges persist.<br>**Direct-LOHC-fuel cell (D-LOHC-FC):**<br>• Promising for on-board hydrogen generation, but efficiency and reliability hurdles persist. | • LOHC tech is promising for a hydrogen-based energy economy, aiding storage, transport, and mobility. Ongoing R&D is needed.<br>• LOHCs have the potential for sustainable energy. |
| Matthias Niermann et al. (2019) [110] | **Storage Capacity:**<br>• N-ethyl carbazole holds 5.8 wt.-% capacity, reduced to 5.2 wt.-% for a liquid state; dibenzyl toluene boasts 6.2 wt.-%, reduced to 6.0 wt.-%. 1,2-dihydro-1,2-azaborine shows the highest at 7.1 wt.-%, subject to variations.<br>**Energy Density:**<br>• N-ethylcarbazole reaches 2.5 kWh/L, reduced to 2.25 kWh/L; dibenzyltoluene achieves 1.9 kWh/L; 1,2-dihydro-1,2-azaborine slightly higher at 2.4 kWh/L, potentially varying.<br>**Availability:** | Evaluating LOHC's viability in mobility, energy transport, and storage applications. | • LOHCs are categorized by criteria: capacity, availability, toxicity, dehydrogenation temp, and technical readiness for varied applications. | • Dibenzyltoluene: Promising for transport and storage with added heat.<br>• N-ethylcarbazole: Suitable but costly for transport and storage.<br>• 1,2-dihydro-1,2-azaborine: Research needed; potential for mobility.<br>• Formic acid, low-temperature reformed methanol: Catalyst improvements needed.<br>• Naphthalene: Limited due to toxicity.<br>• Toluene: Versatile for transport and storage.<br>• Phenazine: Potential for storage; solvent issues to address. | • LOHCs resemble crude oil, fitting existing infrastructure and making them public-friendly substitutes.<br>• Requires more evaluation. |

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**Table 3** (*continued*)

| Author (Year) | Properties of the studied material | Research objective | Methodology | Key Findings | Conclusion |
|---|---|---|---|---|---|
| | • N-ethyl carbazole costs around 40 V/kg, dibenzyl toluene about 4 V/kg, and 1,2-dihydro-1,2-azaborine data scarcity, possibly due to boron availability issues.<br>**Toxicity:**<br>• Moderate health hazards for N-ethyl carbazole and dibenzyl toluene. Limited toxicity data for 1,2-dihydro-1,2-azaborine; expected low toxicity.<br>**Dehydrogenation Temperature:**<br>• N-ethylcarbazole needs 270 °C; dibenzyltoluene, >310 °C; 1,2-dihydro-1,2-azaborine, 80 °C.<br>**Process Design:**<br>• N-ethyl carbazole remains liquid without solvent; dibenzyl toluene likewise. 1,2-dihydro-1,2-azaborine requires solvent addition + post-de-hydrogenation purification.<br>**Gas Flow:**<br>• Varied gas flow rates: N-ethylcarbazole, 68.0 to 163.1 gH2/(L h); dibenzyltoluene, 11.3 to 27.5 gH2/(L h); limited data for 1,2-dihydro-1,2-azaborine.<br>**Technical Readiness:**<br>• N-ethylcarbazole at TRL 3; dibenzyltoluene at TRL 9, widely implemented; 1,2-dihydro-1,2-azaborine at TRL 3, requiring further research. | | | • Overcoming challenges crucial for LOHC's energy potential. | |
| Yeonsu Kwak et al. (2021) [111] | • Comparing dehydrogenation of MCH, $H_{12}$-BPDM, H12-MBT, and $H_{18}$-DBT, reaction and diffusion affect capacity. | • Benchmark homocyclic LOHCs.<br>• Identify efficient hydrogen storage.<br>• Assess reaction kinetics, diffusion, and energy. | • Utilize high-throughput LOHC screening.<br>• Conduct dehydrogenation experiments with Pt/$Al_2O_3$ catalysts.<br>• Analyze LOHC properties and catalysts.<br>• Assess energy-economic feasibility → maritime transport. | • MCH excels in most testing.<br>• H18-DBT faces diffusion issues.<br>• $H_{18}$-DBT and $H_{12}$-BPDM offer benefits.<br>• $H_{12}$-MBT shows efficiency potential. | • Superior performance across varied conditions.<br>• H18-DBT: lower dehydrogenation due to molecular complexity.<br>• H18-DBT and H12-BPDM: capacity advantages over MCH.<br>• H12-MBT efficient dehydrogenation at lower temperatures.<br>• Economic assessment: LOHC-assisted hydrogen's cost reduction potential. |
| Purna Chandra Rao and Minyoung Yoon. (2020) [105] | • Toluene and dibenzyl toluene offer scalability and compatibility with the current infrastructure. | • Assess LOHCs for hydrogen storage and transport.<br>• Review recent advancements and catalytic methods. | • Review key aspects of high-performance LOHC development.<br>• Evaluate molecules based on various criteria. | • Toluene and dibenzyl toluene LOHCs have potential but need refinement.<br>• Lower dehydrogenation enthalpies enhance stability and recyclability.<br>• Essential: hazard, economic assessments for practicality. | • Advanced LOHC technology is needed for broader use, focusing on efficiency, catalysts, understanding, hazards, and economics. |
| M. Niermann et al. (2019) [112] | • Toluene<br>• Dibenzyltoluene N<br>• Ethylcarbazole 1,2<br>• Dihydro-1,2-azaborine<br>• Formic acid<br>• Methanol<br>• Naphthalene | Simulation evaluates LOHCs → intercontinental ship transport, comparing their viability to established methods. | • Assessing various LOHC storage systems → technical-economic viability, evaluating their applicability in transport and storage.<br>• The potential of LOHC technology → energy transport. | **Simulation results:**<br>• The simulation compares energy flows and mass distribution in LOHC and compressed hydrogen systems.<br>**Technical analysis:**<br>• Efficiency parameters, including storage and transport efficiency, varied | • Promising LOHCs: methanol, dibenzyl toluene, toluene.<br>• Waste heat boosts efficiency and cuts costs.<br>• LOHCs ensure sustainable energy transport.<br>• Reactor system development is pivotal for progress. |

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**Table 3** (*continued*)

| Author (Year) | Properties of the studied material | Research objective | Methodology | Key Findings | Conclusion |
|---|---|---|---|---|---|
| | | | | across different LOHCs, with significant enhancements observed in storage efficiency through waste heat utilization.<br>**Economic analysis:**<br>• Methanol and dibenzyl toluene: economically favorable system costs affected by production, conversion, storage, transport, and release.<br>**Literature comparison:**<br>• Highlighting the need for consistent methodologies in efficiency/cost analysis.<br>**Environmental assessment:**<br>• Life cycle assessments: lower greenhouse gas emissions for LOHC systems, particularly methanol and dibenzyltoluene.<br>**Techno-economic optimization:**<br>• Optimization analyses: cost-effective solutions, emphasized impact of critical parameters on overall system costs.<br>**Safety and regulatory considerations:**<br>• Safety assessments: compliance with regulations, while regulatory considerations focused on transportation, storage, and handling standards.<br>**Scalability and commercialization:**<br>• Some LOHCs are promising for large-scale commercialization for favorable performance and technical feasibility. | • Scaling up LOHC systems reduces costs and advances green hydrogen. |
| M. Markiewicz et al. (2015) [113] | Various LOHC compounds proposed:<br>- perhydro-benzyltoluene<br>- perhydro-dibenzyltoluene<br>- N-ethylcarbazole (NEC)/perhydro-N-ethylcarbazole | • Assessing risks of LOHC compounds for safe energy system integration. | • Early examination of LOHC system hazards ensures environmental and human safety, which is crucial for development and implementation. | • LOHCs facilitate renewable to CO2-free energy transition.<br>• Safe, effective organic compounds are crucial.<br>• Known ingredients simplify management and enhance safety.<br>• LOHCs are advantageous over conventional fuels. | • Risk communication is critical for public acceptance.<br>• Eco-friendly LOHCs are crucial for broad adoption.<br>• LOHCs are beneficial over fossil fuels.<br>• Need more research for optimization and integration. |

extensions into sustainable hydrogen mobility. Studies have demonstrated that LOHCs like N-ethyl carbazole and dibenzyl toluene are capable of efficiently storing and distributing excess renewable energy. However, challenges related to dehydrogenation efficiency and system integration remain. LOHCs are also evaluated for their potential in energy storage and transport. Dibenzyltoluene and N-ethylcarbazole are highlighted as promising options for transport and storage, though additional research is needed for other compounds like 1,2-dihydro-1,2-azaborine. Comparisons of LOHCs reveal that while MCH performs well, improvements are needed for compounds such as H18-DBT. The technology's economic feasibility, efficiency, and integration are key focus areas, with ongoing research necessary to address these issues. LOHCs offer a promising alternative for energy storage and transport, with potential environmental benefits, but require further development to overcome current challenges.

### 2.5.2. *Physically bound hydrogen*

Physical hydrogen storage methods, like those utilizing MOFs and porous carbon materials, offer promising pathways for high-capacity storage [4,114,115]. However, limited storage capacity and safety

**Table 4**
Literature review on MOFs.

| Author(s) (Year) | MOFs Type(s) | Structural Properties | Research Objective | Methodology | Key Findings | Conclusion |
|---|---|---|---|---|---|---|
| Kuthuru Suresh et al. (2021) [118] | MOF-5 | Zn4O cluster with the organic linker of 1,4 4-benzo dicarboxylic acid | • Enhance volumetric hydrogen storage density by improving powder packing efficiency.<br>• Linking between improved packing density and reduced damage upon compaction.<br>• Yield sorbents with high surface area and density. | **Ditopic Carboxylic Acid ($H_2L$) Linkers:**<br>• Alkane dicarboxylic acids tested as additives at 5–10 mol % showed no change in MOF-5 cubic crystal morphology.<br>**Tritopic Carboxylic Acid ($H_3L$) Linkers:**<br>• Studied four carboxylic acids, observing crystal shape variations with H3BTB and NH2–H3BTB. Achieved uniform octahedral and cuboctahedral shapes at different concentrations.<br>**Tetratopic Carboxylic Acid ($H_4L$) Linkers:**<br>• Tetratopic carboxylic acid addition resulted in various crystal shapes but reproducibility issues and reduced BET surface area, unsuitable for hydrogen storage. | • Crystal size and shape impact storage efficiency.<br>• MOF-5, despite high hydrogen capacities, packs poorly.<br>• -Adjusting metal: ligand ratio and concentration enhances storage.<br>• New methods improve MOF-5's hydrogen storage.<br>• Insights benefit other cubic MOFs, enhancing efficiency. | • High storage densities via innovative methods.<br>• Strategies minimize damage, promising efficient storage.<br>• Principles extend to diverse applications. |
| Zhang et al. (2007) [119] | 1-IRMOF-1<br>2-MOF-I1<br>3-MOF-I2<br>4-MOF-I3<br>5-MOF-I4<br>6-MOF-I5<br>*Where "I" is a New Organic Linker* | Different<br>Host:<br>$Zn_4O$(1,4-benzodicarboxylate)$_3$ | • Develop a computer tomography for materials (mCT) method to study hydrogen adsorption sites in MOFs and design new high-capacity MOFs | • mCT method combined with Grand canonical Monte Carlo (GCMC) simulations | • mCT reveals hydrogen's preferential adsorption sites in MOFs. New MOFs designed with this method show better storage than IRMOF-1. | • The mCT method provides insights into hydrogen adsorption mechanisms in MOFs and facilitates the design of high-performance materials. |
| Frost et al. (2006) [120] | IRMOF-1, IRMOF-4, IRMOF-6, IRMOF-7, IRMOF-8, IRMOF-9, IRMOF-10, IRMOF-12, IRMOF-14, IRMOF-16, IRMOF-18 | Different | • Examine effects of structural properties on hydrogen uptake in MOFs | • GCMC simulations over a range of pressures at 77 K; Correlation analysis | • Hydrogen adsorption correlates with heat of adsorption at low pressures, surface area at intermediate pressures, and accessible volume at high pressures | • Structural properties significantly influence hydrogen storage in MOFs, with correlations observed at various pressures, providing insights for predictive models |
| Frost and Snurr (2007) [121] | IRMOF-1, IRMOF-9, IRMOF-10, IRMOF-14, IRMOF-16, CuBTC | Different | • Determine correlations between hydrogen adsorption and structural properties. | • GCMC simulations at different temperatures; Correlation analysis | • Hydrogen adsorption correlates with heat at low and surface area at high pressures. | • Correlations between structure and hydrogen uptake aid MOF design for storage. |
| Hao Li et al. (2019) [122] | MOF-5<br>NOTT-112<br>NU-111<br>NU-100/PCN-610[94]<br>MOF-210<br>IRMOF-20<br>Ni2(*m*-dobdc)<br>SNU-16<br>MOF-200<br>MOF-205<br>Mg-MOF-74<br>PCN-46<br>NOTT-115<br>Mn-BTT | Temperature: 77 K–160 K<br>Pressure: 5 bar–100 bar | • Reviewed 14 MOFs for total gravimetric and volumetric hydrogen storage capacity. | • Analyzed experimental data and computational predictions.<br>• Experimental validated: MOFs' H2 storage capacities. | • MOF structure correlates with $H_2$ storage capacities.<br>• Efficient $H_2$ storage at near-ambient temperatures remains challenging.<br>• Computational screening finds promising MOFs.<br>• Ni2 (*m*-dobdc) shows high volumetric $H_2$ storage. | • MOFs promise $H_2$ storage but face near-ambient challenges.<br>• Computational methods help select better materials.<br>• Advancements inspire more $H_2$ storage research. |

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**Table 4** (*continued*)

| Author(s) (Year) | MOFs Type(s) | Structural Properties | Research Objective | Methodology | Key Findings | Conclusion |
|---|---|---|---|---|---|---|
| Emmanouel Klontzas et al. (2008) [123] | MOFs modified by lithium alkoxide groups:<br>• Li-alkoxide benzene<br>• Li-alkoxide-naphthalen<br>• dicarboxylate *(IRMOF-8 linker)*<br>• Li-alkoxide-pyrene-dicarboxylate *(IRMOF-14 linker)* | Using MOF as a host for Li, substituting with the *O*–Li group under varied thermodynamic conditions. | • Investigating hydrogen storage in lithium alkoxide-modified MOFs using quantum and classical calculations. | • Ab initio calculations found stronger hydrogen interaction with lithium alkoxide groups in MOFs.<br>• Monte Carlo simulations confirmed these trends. | • Lithium alkoxide modification boosted hydrogen interaction energies, confirmed by quantum calculations and GCMC simulations.<br>• Lithium-modified MOFs achieved ten wt % at 77 K and 100 bar and 4.5 wt% at room temperature. | • The modification effectively enhanced hydrogen storage in MOFs.<br>• Stronger interaction energies and high gravimetric capacities → practical hydrogen storage feasibility. |
| Seung Jae Yang et al. (2010) [124] | Pt-loaded MWCNTs@MOF-5 known as [Zn4O (benzene-1,4-dicarboxylate)3] | • MWCNT@MOF-5 composite synthesized at 105 °C.<br>• Hybrid: nanoporous MOFs + Pt-loaded MWCNTs@MOF-5.<br>• Crystalline structure with 2000 $m^2/g$ surface area.<br>• HSC: 1.25 wt% at room temperature (100 bar); 1.89 wt% at cryogenic temperature (1 bar). | • Pt-loaded MWCNTs@MOF-5 synthesis enhances room-temperature hydrogen storage. | • PXRD examined morphology.<br>Measuring:<br>• Gravimetric $H_2$ storage: 280 K, 100 bar.<br>• Volumetric $H_2$: ASAP 2020 at 77 K, 1 bar.<br>• Nitrogen adsorption: ultra-high purity grade (99.9999%) | • Pt-MWCNTs preserve MOF-5 structure.<br>• Pt-MOFMCs efficiently receive hydrogen spillover, boosting storage.<br>• Pt-MOFMCs show superior $H_2$ storage enhancement.<br>• Compare $H_2$ storage of Pt-MOFMC and Pt-MWCNT. | • Incorporating Pt-loaded MWCNTs into MOF-5 increases hydrogen storage (298 K–77 K) |
| Henrietta W. Langmi et al. (2013) [21] | Summarized 111 MOFs, detailing structures, surface areas, hydrogen uptake, and volumetric capacities at various pressures. | • Hydrogen storage capacity: 0.5–1 wt. %-room temperature; 3–4 wt.% for some structures.<br>• Volumetric capacities: less than 15 g $L^{-1}$. | Enhancing MOFs for hydrogen storage involves optimizing metal sites, ligands, and nanoparticle integration for improved low-temperature storage. | • Synthesize and characterize MOFs.<br>• Measure hydrogen adsorption at different temperatures.<br>• Explore hybrid MOF systems.<br>• Develop surface modifications, considering economic feasibility. | **Factors Affecting Hydrogen Storage in MOFs:**<br>• Metal sites enhance $H_2$ adsorption heat and binding; 'guest' ions affect surface, volume, and storage.<br>• Aromatic ligands increase $H_2$ interaction.<br>**Effect of Metal Nanoparticles:**<br>• Pt or Pd nanoparticles improve hydrogen storage by adsorption.<br>• High metal content may reduce surface area and pore volume.<br>**Pore Size and Nanoconfinement:**<br>• Small pores enhance RT $H_2$ adsorption; catenation and nanoconfinement improve storage by constraining pore size.<br>**MOF Hybrid Materials:**<br>• Nanoconfinement in MOFs improves high-temp $H_2$ storage, enhancing physisorption and chemisorption synergistically. | **Challenges and Ideal Characteristics:**<br>• Room-temperature hydrogen storage in MOFs poses challenges.<br>• Ideal MOFs: cost-effective, high adsorption, large surface areas, and proper pore sizes. |

concerns persist, particularly regarding extreme pressure-related issues and energy consumption [28,42]. Due to molecular hydrogen's larger size, physical storage methods struggle to match the high volumetric densities of chemical storage. Safe operation requires robust vessel designs to handle high pressures and prevent hazards like leakage and fire. More research is needed to optimize physical hydrogen storage.

*2.5.2.1. MOFs.* MOFs, formed by metal ions or clusters linked with organic ligands, offer vast surface areas exceeding 5000 $m^2/g$, yet hydrogen uptake primarily occurs at cryogenic temperatures, limiting their storage capacity [7,60,116]. While impregnation enhances volumetric uptake, gravimetric uptake benefits from impregnation at low pressures [70]. MOFs demonstrate excellent hydrogen storage properties at around 77 K, enabling rapid adsorption and efficient refueling

**Table 5**
A literature review of prominent research on some carbon-based materials for hydrogen storage.

| Carbon-based Material for Hydrogen Storage | Pioneer | Author | Experiment | Result | Advantages | Application | Feature | References |
|---|---|---|---|---|---|---|---|---|
| Carbon nanotubes (CNTs) | Iijima et al., -1991 | Kim and Levesque | •Modified the tube diameter and the inter-tube spacing to assess optimizing adsorbent structure. | •Development of synthetic methods of CNs<br>•Characterizing Nanotubes into SWNT and MWNT | •Enhances electronic, mechanical, and physical properties.<br>•Acid treatment and surface modification improve carbon nanotubes' hydrogen sorption. | •Energy storage<br>•Biomedical<br>•Optoelectronics<br>•Fuel cell<br>•Secondary battery<br>•Supercapacitor | •Long-range order carbon hexagons | [38,125] |
| Graphite nanofibers (GNFs) | Chambers et al. | Chambers et al. | •Tested structures in custom apparatus for hydrogen absorption. | •Graphite nanofibers show high hydrogen sorption and retention.<br>•Storage: 120 atm, 25 °C, over 20 L (STP) hydrogen per gram of carbon. | •High reversible adsorption. | •Automotive hydrogen storage | •Produced from the dissociation of carbon gases.<br>•Graphite layers parallel to the nanofiber axis over selected metal surfaces. | [126–128] |
| Activated Carbons (Acs) | Kidnay and Hiza | Dogan et al. | •Synthesized samples characterized by X-ray diffraction, SEM/EDX, and zeta sizer nano S90 using the Emmett and Teller method. | •At 77 K, hydrogen adsorption correlates with surface area and synthesis method.<br>•Hydrogen Storage Capacity in Activated Carbons at 77 K and 80 bar:<br>-In medium: 0.38 g/g<br>-Without ultrasonic waves: 0.43 g/g<br>-With ultrasonic waves: 1.14 g/g | •Adsorption capacity can be modified by pore size distribution at room temperature.<br>•High surface area | •Secondary stationery.<br>•Mobile hydrogen storage systems | •Irregular form of graphite. | [129–132] |
| Graphene | Elias et al., -2008 | Guo et al. | •Graphene sheets are made by electric discharge in hydrogen using graphite rods. | •Graphene sheets have few layers, wide spacing, and wrinkled morphology. | •Good thermal conductivity<br>•High-carrier mobility and elasticity | •Metal-free catalyst support for fuel cell | •Large surface metal<br>•Flexible for hydrogen module integration<br>•-Graphene easily adsorbs hydrogen | [129,133,134] |
| Carbon nano-onions (CNOs) | Ugarte-1992 | Zhang et al. | •Synthesized carbon nano-onions using CVD with Fe–Ni alloy catalysts + SEM image. | •Cyclic voltammetry confirms hydrogen adsorption-oxidation behavior, indicating good electrochemical activity and storage. | •Good electrical conductivity<br>•Short charging time<br>•Large power density | •Li-ion battery supercapacitor<br>•Drug delivery<br>•Field effect transistors | •Spherical nested fullerenes with multiple graphitic layers surrounded by a bucky layer. | [69] |
| Carbon nanofibers (CNFs) | Ugarte-1992 | Xing et al. | •Nano-casting technique<br>•SEM image<br>•BET surface area analysis on mesoporous carbon nanofibers. | •The material's discharge capacity is calculated and compared to the ordered mesoporous carbon. | •High surface-to-volume ratio.<br>•More significant chemical and physical properties among carbon materials.<br>•High thermal stability and electrical conductivity | •Textiles<br>•Engineering<br>•Medical | •Nearly spherical graphite with cavities and defects. | [135,136] |
| Single-walled carbon nanohorns (SWCNs) | Iijima et al., 1998. | Group of researchers | •Optimizing hydrogen storage in carbon nanohorns and metal clusters. | • Calculation of:<br>- Surface area<br>- Binding energy<br>- Storage densities at different temperatures<br>- Volumetric storage densities. | •Adjustable external and internal pore sizes<br>•Single-wall structures maximize surface area.<br>•Economical construction via simple chemical procedures. | •Gas adsorption capacitors<br>•Sensing applications<br>•Catalytic supports<br>•Composite materials<br>•Drug delivery system carriers | •Tubular structure: graphene-like single-walled carbon nanotubes with cone-shaped tips (20° angles) and large diameters (2–5 nm). | [127,137,138] |

(continued on next page)

Table 5 (*continued*)

| Carbon-based Material for Hydrogen Storage | Pioneer | Author | Experiment | Result | Advantages | Application | Feature | References |
|---|---|---|---|---|---|---|---|---|
| Multi-walled carbon nanotubes (MWCTs) | Kanmani et al. | Mosquera-Vargas et al. | •Purification is performed at room temperature.<br>•Investigated hydrogen storage of purified carbon nanotubes under various pressures (0.39–13.33 kPa).<br>•XRD, TEM, and Raman + BET method. | •The structure of carbon nanotubes affects adsorption; the room temperature storage capacity is 3.46 wt%. | •Low cost and eco-friendly.<br>•Good adsorption and desorption.<br>•Capacity is modifiable. | •Support subtracts for MOFs<br>•Fuel cell technologies | •Multiple layers of graphene sheets | [127,139,140] |

[28]. Tuning MOFs' framework components adjust their hydrogen storage capacities [35]. They also boast large surface areas, with theoretical hydrogen storage capacities ranging from 3100 to 4800 $m^2/g$ [73]. MOFs boast inner surface areas nearing 5000 $m^2$ $g^{-1}$, offering extensive space for hydrogen adsorption. These organic-inorganic hybrid crystalline porous materials, characterized by metal ions or metal oxide clusters linked by organic connectors, provide optimal surfaces for hydrogen adsorption [45].

MOFs or PCPs have expanded in numbers and applications for over two decades. Featuring inorganic SBUs linked by organic connectors, these materials play vital roles in gas storage, energy conversion, and chemical activation and have expanded in numbers and applications for over two decades. Featuring inorganic SBUs linked by organic connectors, these materials play vital roles in gas storage, energy conversion, and chemical activation [117]. MOFs' low-density limits volumetric hydrogen storage, necessitating materials with larger surface areas. Material selection depends on application requirements [45]. Table 4 reviews some studies conducted on MOFs.

Table 4 reviews various MOFs hydrogen storage capabilities, significant advancements and ongoing challenges. The research demonstrates that different MOF types, such as MOF-5, exhibit high potential for hydrogen storage, though performance varies with structural modifications. Adjustments in metal-ligand ratios have been shown to improve hydrogen storage density and efficiency. For instance, MOF-5 with enhanced packing density and modified linkers can achieve better storage, while Pt-loaded MWCNTs@MOF-5 shows improved hydrogen storage at room temperature due to spillover effects. Additionally, lithium alkoxide modifications increase hydrogen interaction energies, leading to higher gravimetric capacities.

The impact of structural properties such as crystal size, shape, and pore size on storage efficiency. Despite advancements, challenges persist, particularly in achieving effective hydrogen storage at near-ambient temperatures. Research emphasizes the need for continued development to address these challenges, optimize MOF designs, and explore hybrid materials. Innovations such as hybrid MOF systems and nanoconfinement are noted for their potential to enhance storage performance. Overall, while MOFs offer promising solutions for hydrogen storage, further research is essential to overcome existing limitations and realize practical applications.

*2.5.2.2. Carbon-based materials.* Carbon substrates like activated carbon, nanotubes, and nanofibers store hydrogen effectively at cryogenic temperatures and high pressures, enabling 5%–10% weight adsorption. Activated carbon adsorbs 1–7 wt% at 77 K and 1–20 bar, with super-activated carbon reaching up to 5 wt% [73]. Microporous carbon materials have high gas adsorption, linked to their BET surface area. Macropores affect gas compression and kinetics. Hydrogen adsorption is governed by physisorption at moderate temperatures, limiting adsorption despite high pressures. Temperature is crucial for hydrogen storage in carbon materials [23,64].

Table 5 reviews some studies done on carbon-based materials in the literature.

The table reveals that carbon-based materials exhibit diverse properties suited for hydrogen storage and other applications. Carbon nanotubes (CNTs) and multi-walled carbon nanotubes (MWCNTs) display enhanced hydrogen storage capacities due to structural modifications and high thermal stability, making them ideal for energy storage and fuel cell technologies. Graphite nanofibers (GNFs) and activated carbons (ACs) offer high sorption capacities and adaptability for both stationary and mobile hydrogen storage systems. Graphene is distinguished by its exceptional thermal conductivity and flexibility, making it an excellent candidate for metal-free catalysts in fuel cells. Carbon nano-onions (CNOs) and carbon nanofibers (CNFs) stand out for their good electrical conductivity and stability, useful in supercapacitors and various other applications. Single-walled carbon nanohorns (SWCNs) offer high surface areas and adjustable pore sizes, beneficial for gas adsorption and catalytic support. Overall, these materials show significant promise in hydrogen storage and other technological applications due to their unique properties and structural advantages.

## 3. Summary

Comparative analysis shows $LH_2$ storage capital costs are two to four times higher than gaseous and LOHC methods. Ammonia and methanol fit existing fuel infrastructure but need more energy and capital than LOHCs. LOHCs are a viable option for large-scale stationary storage [42]. Abdin et al. found that longer storage cycles increase the levelized cost of hydrogen storage (LCHS) despite lower OpEx. $CGH_2$ storage costs range from \$0.33/$kgH_2$ (daily cycles) to \$25.20/$kgH_2$ (4-month cycles). Hydrogen production costs globally range from \$3.2/$kgH_2$ to \$7.7/$kgH_2$, with ammonia and methanol having the highest LCHS at \$3.51/$kgH_2$ and \$2.25/$kgH_2$ [141]. Table 6 compares storage methods, detailing characteristics, challenges, and safety.

The table provides a comprehensive comparison of hydrogen storage methods, highlighting their respective advantages and disadvantages. Compressed Gaseous Hydrogen (CGH2) offers high energy density and is a mature technology suitable for various industries, including transportation and aerospace, but it involves high costs and energy losses due to pressurization. Liquid/Cryogenic Hydrogen Storage achieves medium to high density and allows for fast refueling with lower operational pressures, though it requires extremely low temperatures, leading to significant energy losses and boil-off issues. Cryo-Compressed Hydrogen

**Table 6**
Above-ground Hydrogen storage overview.

| Method | Advantages | Disadvantages | User | Safety | References |
|---|---|---|---|---|---|
| **Compressed gaseous hydrogen ($CGH_2$)** | • High energy density<br>• Mature technology for small/large-scale storage<br>• Versatile applications<br>• Safety | • Pressurizing hydrogen causes energy losses, reducing efficiency.<br>• High tank costs.<br>• Limited applications due to energy needs and tank expenses. | Industries needing reliable, high-density energy, like transportation and aerospace. | Good safety standards exist, but risks like tank leakage and explosions remain challenging. | [73] |
| **Liquid/ Cryogenic Hydrogen Storage** | • Medium-high densities: 7.5% gravimetric, 6.4 MJ/L volumetric.<br>• Low operating pressure enhances safety.<br>• Fast and dependable refueling.<br>• Rapid kinetics in the release process. | • Requires extremely low temperatures for liquefaction.<br>• Liquefaction loses max 40% of energy; compressed hydrogen loses 10%.<br>• Heat transfer causes pressure to rise and boil-off. Larger, spherical tanks reduce boil-off. | Medium/large-scale storage and transport uses, including truck delivery and intercontinental shipping. | Cryogenic vessels have a vacuum jacket. Low adiabatic expansion energy in cryogenic hydrogen reduces explosion risk without ignition. | [4,35] |
| **Cryo-compressed hydrogen gas ($Cc$–$H_2$)** | • Mitigating hydrogen boil-off; high-pressure tank design handles pressure.<br>• Achieving medium-high capacities via compression and cooling.<br>• Maintaining hydrogen as gas for fast refueling.<br>• Achieving high storage density, surpassing cryogenic storage.<br>• Enhanced safety with a vacuum enclosure. | • Elevated compression and liquefaction energy | Aerospace vehicles | This storage method presents safety risks due to high pressures and cryogenic temperatures. | [4,35,142] |
| **Chemical hybrids** | • Chemical hydrides use lighter elements for higher density and hydrogen release ease.<br>• Cost-effective compared to LH2 for storage + transportation.<br>• Efficient energy transport from renewable-rich regions. | • Irreversibility<br>• Typically employed as single-use fuels.<br>• Concerns related to the removal of byproducts. | • On-board hydrogen storage for mobility.<br>• Magnesium-based hydrides for solar thermal.<br>• Interstitial hydrides like AB5 for stationary use. | • Chemical hydrides: hazardous due to toxicity and reactivity.<br>• Vents and hydrogen sensors prevent accidents.<br>• Cold traps prevent pyrophoric diborane formation.<br>• Fatal explosion from uncontrolled hydrogen generation.<br>• Correctly sized pressure-relief systems are needed for safety. | [73,143,144] |
| **Metal hydrides** | • Low cost of maintenance.<br>• High hydrogen mass density.<br>• Exceptional safety standards. | • Turbulence potential from impurities.<br>• Susceptibility to hydride instability.<br>• Drawbacks of high dehydrogenation temps + slow kinetics.<br>• Suboptimal efficiency of MOFs<br>• Energy losses + insulation needed for elevated temperatures.<br>• Safety concerns, like magnesium hydride reactivity. | • Interstitial Hydrides (e.g., TiFe, TiMn2, LaNi5) for stationary use.<br>• Complex Hydrides (e.g., NaAlH4, LiBH_4) for mobile applications. | • Safer absorption-based storage, reducing high-pressure gas risks. Research needed for mobile application safety.<br>• May be toxic. | [28,100,145] |
| **Complex metal hybrids** | • Rich chemistry for versatile functionality.<br>• Certain hydrides: high hydrogen capacity.<br>• Potential for energy efficiency with alternative sources.<br>• Hybridization potential with organics.<br>• Reversible reactions enable de/rehydrogenation without extreme conditions. | • Understanding gaps hinders optimization and application.<br>• Thermodynamic issues affect practicality.<br>• Reactivity complicates handling.<br>• Complex optimization due to compositional alteration.<br>• Catalyst reliance adds complexities.<br>• Challenges in achieving desired kinetics with nanoconfinement. | • Limited reversibility, aided by catalysts like LiBH4.<br>• Mobile applications.<br>• Complex hydrides in catalytic processes.<br>• Improving ion conductivity in solid-state electrolytes. | Ensures safe hydrogen storage, considering stability, toxicity, and controlled thermal conditions. | [84,146–150] |
| **Mg-based metal hybrids** | • High hydrogen capacity ensures efficiency.<br>• Safety and reliability guarantee stability.<br>• Cost-effective solutions.<br>• Abundant magnesium ensures sustainability. | • Slow kinetics hinder practicality.<br>• Challenging high operating temp.<br>• Relatively high activation energy limits efficiency. | • Batteries<br>• Hydrogen Purification + Separation<br>• Grid Energy Storage<br>• Portable Hydrogen Storage<br>• Hydrogen Fueling Stations<br>• Aerospace Applications | Slow kinetics and high storage temperatures challenge system stability. | [151] |

(*continued on next page*)

**Table 6** (*continued*)

| Method | Advantages | Disadvantages | User | Safety | References |
|---|---|---|---|---|---|
| | • Lower temps higher absorption/desorption rates. | | | | |
| **LOHC** | • Convenient ambient management.<br>• Carbon-free storage + release.<br>• Reusable, non-toxic liquid carrier.<br>• Low storage pressure, abundant availability.<br>• Easy handling, high volumetric density. | • Limited hydrogen capacity constrain LOHCs (max 7.2 % wt).<br>• Rapid noble metal catalyst deterioration.<br>• High dehydrogenation temps lack system compactness.<br>• Costly, high operating temperatures.<br>• Requires diverse catalysts for optimal performance.<br>• High molecular weight compared to stored hydrogen. | • Mobile applications.<br>• Enables long-term, large-scale hydrogen storage. | • High safety.<br>• Efficient catalysts and refining techniques are needed.<br>• Mitigating high dehydrogenation is crucial for energy efficiency.<br>• Developing stable, cost-effective catalysts essential for processes. | [2,4,22,35,73,152] |
| **MOF** | • Substantial surface area, low hydrogen binding energy.<br>• Accelerates charging, discharging kinetics, and cost-effective materials.<br>• Addresses thermal management's remarkable cyclability.<br>• Enables rapid refueling, high-purity gas, and high storage capacities. | • Carrier material weight affects the system.<br>• Low hydrogen density.<br>• Insulated tanks are used for cold and high pressures, which increase weight and reduce density.<br>• Limited MOF thermal conductivity complicates management.<br>• Inefficiency at cryogenic temperatures.<br>• Risks with pressure vessels.<br>• Cryogenic conditions and high pressure hinder widespread adoption. | • FCVs<br>• Compact, lightweight hydrogen storage for electronics.<br>• Storing excess renewable energy.<br>• On-site hydrogen storage for chemical synthesis metal processing.<br>• Aerospace, aviation, including spacecraft propulsion. | • Safety concerns primarily with pressurized vessels.<br>• Ensuring thermal conductivity and structural integrity for safe storage. | [4,28,35,73,153] |
| **Carbon-based materials** | • Enhanced hydrogen storage beyond absorption methods.<br>• Versatile carbon materials: activated carbon, graphite, nanotubes, nanofibers.<br>• Potential for improvement via synthesis treatment. | • Reliance on surface area, micropore distribution.<br>• Limited room temperature storage capacities.<br>• Theoretical predictions may not align with experiments. | • FCVs<br>• Hydrogen devices.<br>• Integration with renewables.<br>• Chemical manufacturing.<br>• Aerospace hydrogen storage. | • Thermal treatments and metal doping are required.<br>• Ensures good safety and durability. | [19,154] |

Gas (*Cc*–H2) combines the benefits of high density and safety with vacuum enclosures but requires substantial energy for compression and liquefaction, posing safety risks. Chemical Hybrids are cost-effective and efficient for energy transport, though they face irreversibility and byproduct removal issues, with safety concerns related to toxicity and uncontrolled hydrogen generation. Metal Hydrides are known for low maintenance and high hydrogen mass density with good safety standards but suffer from high dehydrogenation temperatures and instability. Magnesium-Based Metal Hybrids offer high capacity and cost-effectiveness but are hampered by slow kinetics and high operational temperatures. Liquid Organic Hydrogen Carriers (LOHC) provide ease of handling and high volumetric density but are limited by capacity and high costs. Metal-Organic Frameworks (MOFs) feature substantial surface area and rapid kinetics but face challenges with low hydrogen density and inefficiencies at cryogenic temperatures. Carbon-Based Materials show potential through surface area and advanced treatments but are limited by their room temperature storage capacities. While choosing for application, all limits should be considered.

Lastly, Table 7 compares all mentioned hydrogen storage methods. Compressed Gas Storage operates at 293 K and up to 700 bars, offering a gravimetric energy density of 5.7 wt% and a volumetric energy density of 4.9 MJ/L. It is noted for its simplicity and reliability but faces high energy demands and lower density compared to other methods. Liquid Hydrogen Storage at 20K and 0 bars achieves a gravimetric energy density of 7.5 wt% and a volumetric energy density of 6.4 MJ/L, with high volumetric density but challenges including significant energy loss during cooling and high costs. Cryo-compressed Hydrogen combines high density with low storage efficiency due to its cooling and compression requirements. Magnesium-based Alloys like $Mg_2Ni$ offer a high hydrogen storage capacity (6.2 wt%) but require high temperatures and face slow kinetics. MOFs (e.g., NOTT-112), with a gravimetric density of 10 wt% and 6.036 MJ/L volumetric density, show rapid kinetics but are sensitive to low temperatures and synthesizing conditions. LOHCs provide a compact, liquid-phase storage solution but suffer from high raw material costs and limited hydrogen capacity. Metal Hydrides such as $MgH_2$, with a high volumetric density of 13.2 MJ/L, are safe and compact but have high decomposition temperatures. Complex Hydrides like $LIBH_4$ offer high storage densities (18.5 wt%) but face poor reversibility and high regeneration costs. Chemical Hydrides have high storage rates but struggle with irreversibility and cost. PIMs/PIM-1 and Covalent Organic Frameworks (COF-102), while promising in terms of porosity and capacity, face limitations related to desorption behavior and activation processes, respectively.

## 4. Hydrogen storage applications

Hydrogen is a low-emission fuel suitable for transportation, heating, cooling, and storing excess electricity, unifying transport and power sectors. Hydrogen storage applications fall into stationary and mobile categories, as shown in Fig. 7.

Stationary methods store hydrogen on-site, while mobile applications transport it [4]. Hydrogen powers transportation and various sectors globally [15,29,38].

Transportation applications require high capacity, moderate pressure, fast kinetics, and cost-effective infrastructure [73]. Hydride challenges include low gravimetric density (<2%wt $H_2$) with L $H_2$ favored

**Table 7**
Comparative analysis of hydrogen storage material and methods.

| Storage Method/ Candidate | Storage Conditions | Gravimetric Energy Density (wt %) | Volumetric Energy density | Advantages | Disadvantages | User | Remarks and Limitations | References |
|---|---|---|---|---|---|---|---|---|
| Compressed Gas (cylinder) | T = 293 K<br>P = Max 700 bars | 5.7 | 4.9 MJ/L | • Technical Simplicity<br>• High reliability<br>• Extensively researched- max 200 bars<br>• Relatively low cost | • High energy demand<br>• Lower storage energy density compared to $LH_2$, gasoline, and diesel. | • Transportation<br>• Used in mobile applications for vehicles at 350 bars and 700 bars. | • Limitation:<br>- The need for assessment of tank material and gas compatibility<br>• Improvement:<br>- Newly produced composite materials for tanks. | [29,45,54, 68,155, 156] |
| Liquid (tank) | T = 20 K<br>P = 0 bars | 7.5 | 6.4 MJ/L | • Higher volumetric energy density<br>• Increased transport capacity<br>• Short-term storage capability<br>• Efficient<br>• Well-researched<br>• Compact gas storage volume | • The cooling process takes a 1/3 of Hydrogen's chemical energy<br>• Boil-off<br>• High cost of materials<br>• The energy is less than that of fossil fuels. | • Transport<br>- rockets.<br>• Airplane fuel | • Limitations:<br>- Requires strongly isolated storage tank with vacuum layer and Aluminum Foil<br>- Needs external protective jacket + inner pressure vessel<br>- Stored in an open system<br>• Improvements:<br>- Minimized thermal conductivity with perlite or aluminum film wrapping<br>- Utilizes well-insulated cryo-genic container | [7,38,41, 45,155, 157] |
| Cryo-compressed | T = Max 30 K<br>P = 300 bars | 5.4 | 4.0 MJ/L | • Attainable higher energy density in optimal conditions | • Low Storage efficiency<br>• Cooling and compression require energy<br>• Boil-off<br>• High costs of hydrogen production and pressurized/cryogenic tanks. | • Mobile applications | • Limitation:<br>- Need for strongly Isolated storage tank<br>• Improvements:<br>- Changes to composite used in vessels | [38,45] |
| Magnesium-based alloys/ Mg– $Mg_2Ni$-graphite hydride | T = 573.15 K<br>P = ~3.5 bars | 6.2 | NM | • Relatively high hydrogen storage capacity<br>• Fast hydrogen absorption Kinetics<br>• Mg's reliability and low-cost<br>• Excellent cyclic stability | • High reaction temperature<br>• Slow progress reactions<br>• Poor kinetics | • On-board applications | • Limitations:<br>- Requires thermal management<br>- Low kinetic<br>- Poor reversibility<br>• Improvements:<br>- Kinetic<br>Nano structuring<br>Using catalysts<br>- Thermodynamic<br>- Alloy<br>- Altering reaction pathway | [7,23,60, 158] |
| MOFs/NOTT-112 | T = 77 K<br>P = 77 bars | 10 | 6.036 MJ/L | • Effortless reversible cycle<br>• Fast kinetics<br>• High-rate hydrogen adsorption<br>• Low density<br>• High surface area and enthalpy<br>• Large porous volume | • Desirable density at low temperatures<br>• Need to purify unloaded | • Vehicular hydrogen stores<br>• Aerospace industry<br>• On-board hydrogen storage | • Limitations:<br>- Needing to optimize the mass density and surface area based on usage<br>- Sensitive to synthesizing process and atmosphere<br>- Needing cryogenic temperature<br>• Improvements:<br>- Using metal-supported | [23,64, 116, 159–163] |

(continued on next page)

**Table 7** (*continued*)

| Storage Method/ Candidate | Storage Conditions | Gravimetric Energy Density (wt %) | Volumetric Energy density | Advantages | Disadvantages | User | Remarks and Limitations | References |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | catalysts through a carbon bridge | |
| LOHCs/2- (n-Methylbenzyl Pyridine) | T = 293 K<br>P = 0 bars | 6.15 | Not Specified | • Compact hydrogen storage<br>• Liquid-phase storage enables gasoline-like transport and handling<br>• No need for high-pressure or low-temperature<br>• Chemical reversibility without decomposition in consecutive cycles<br>• Chemical and thermal stability | • Need to purify unloaded hydrogen for PEM<br>• High raw material price<br>• Toxicity | • LOHCs hold promise for large-scale energy transport, storage, and mobile applications.<br>• MBP is favorable for transport<br>• Train<br>• FCEV | • Limitations:<br>- Heat management<br>- Needing a proper catalyst<br>• Improvements:<br>- Further study into catalysts.<br>- Changes to the structure by adding N into the benzo ring. | [15,104, 105,110, 164] |
| Metal Hydrides/ $MgH_2$ | T = 260–425 K<br>P = 20 bars | 7.60 | 13.2 MJ/L | • Advantages of solid-state storage.<br>• Safe, compact hydrogen storage.<br>• Higher volume compared to other methods.<br>• Excellent security reversible cycle performance.<br>• Reusable thermal effect in subsystems. | • Absorb impurities, reducing hydrogen capacity and tank lifetime.<br>• High decomposition temperature and pressure.<br>• Poor sorption and desorption kinetics.<br>• Solid waste, degradable. | • Storage media for concentrating solar thermal power stations | • Limitations:<br>- Storage temperature below operating temperature<br>- The need for heat management<br>• Improvements:<br>- Using Catalyst<br>- Using ball milling to change the particle size<br>- Alloying | [23,38,68, 70,155] |
| Complex Hydrides/ $LiBH_4$/ $NaAlH_4$ | T = 380–600 K (P 35)<br>P = 200 bars | 18.5 | 17.17 MJ/L | • High storage and capacity density.<br>• Highest room temperature hydrogen density. | • Costly regeneration for some compounds.<br>• Poor reversibility and stability, requiring high temperatures in Alanates and borohydrides. | • Onboard energy carrier applications<br>• Transportation | • Limitations:<br>- The need for high desperation temperature.<br>- Materials must be stored in a moisture-free inert atmosphere<br>• Improvements:<br>- Enhancing reversible capacity via the BMAS process<br>- Utilizing dopants or catalysts<br>- Adding SiO2 to improve hydrogen desorption properties<br>- Employing nanostructuring | [23,38,60, 165] |
| Chemical Hydrides/ $NH_3B_3$ (AB) | T = 358–373 K<br>P = 20 bars | 19.6 | 146 $g.H_2/L$ | • High hydrogen storage rate<br>• Easy decomposition<br>• Storage under ambient or near-ambient conditions | • Irreversibility<br>• Impurity absorption<br>• Reaction kinetics<br>• Cost<br>• High storage capacity<br>• Safety<br>• Moderate operating temperatures<br>• By-products hinder regeneration; recycling needs improvement | • Mobile applications<br>• Onboard hydrogen storage. | • Limitations:<br>- Regeneration methods vital<br>- Additive costs<br>- Hydrogen release needs other stimuli.<br>• Improvements:<br>- Storage tech integration enhances performance, range<br>- Catalysts enhance kinetics. | [7,41,68, 166–169] |

(*continued on next page*)

**Table 7** (*continued*)

| Storage Method/ Candidate | Storage Conditions | Gravimetric Energy Density (wt %) | Volumetric Energy density | Advantages | Disadvantages | User | Remarks and Limitations | References |
|---|---|---|---|---|---|---|---|---|
| PIMs/PIM-1 | T = 77 K<br>P = 10 bars | 2.7 | 4.4 MJ/L | • High porosity for hydrogen storage<br>• Versatile with easy film casting<br>• Promising hydrogen adsorption, especially at higher pressures<br>• Reproducible mechanical tests, good thermal stability | • Expensive; requires cost-effectiveness optimization<br>• Desorption behavior requires further study. | • Hydrogen storage tank | • Limitations:<br>- Mechanical differences may result from film properties.<br>- Needing study on mesoporosity's impact on hydrogen adsorption.<br>- Potential for future hydrogen storage with enhancements. | [23,170] |
| Covalent organic frameworks/ COF-102 | T = 77 K<br>P = 35 bars | 7.16 | 40.4 g.$H_2$/L | • COF-102: High porosity, low density for exceptional hydrogen storage.<br>• Pd impregnation: Increases capacity 2–3 times.<br>• Reversible hydrogen uptake:<br>• Enables recyclable storage.<br>• Tailorable structures:<br>• Optimize performance. | • Limited storage capacities compared to alternatives.<br>• Time-consuming activation process.<br>• Stability issues under certain conditions. | • FCVs<br>• Portable power sources | • Remarks:<br>- Photocatalytic performance for hydrogen generation needs enhancement.<br>• Limitations:<br>- Challenges in optimizing properties. | [171–174] |

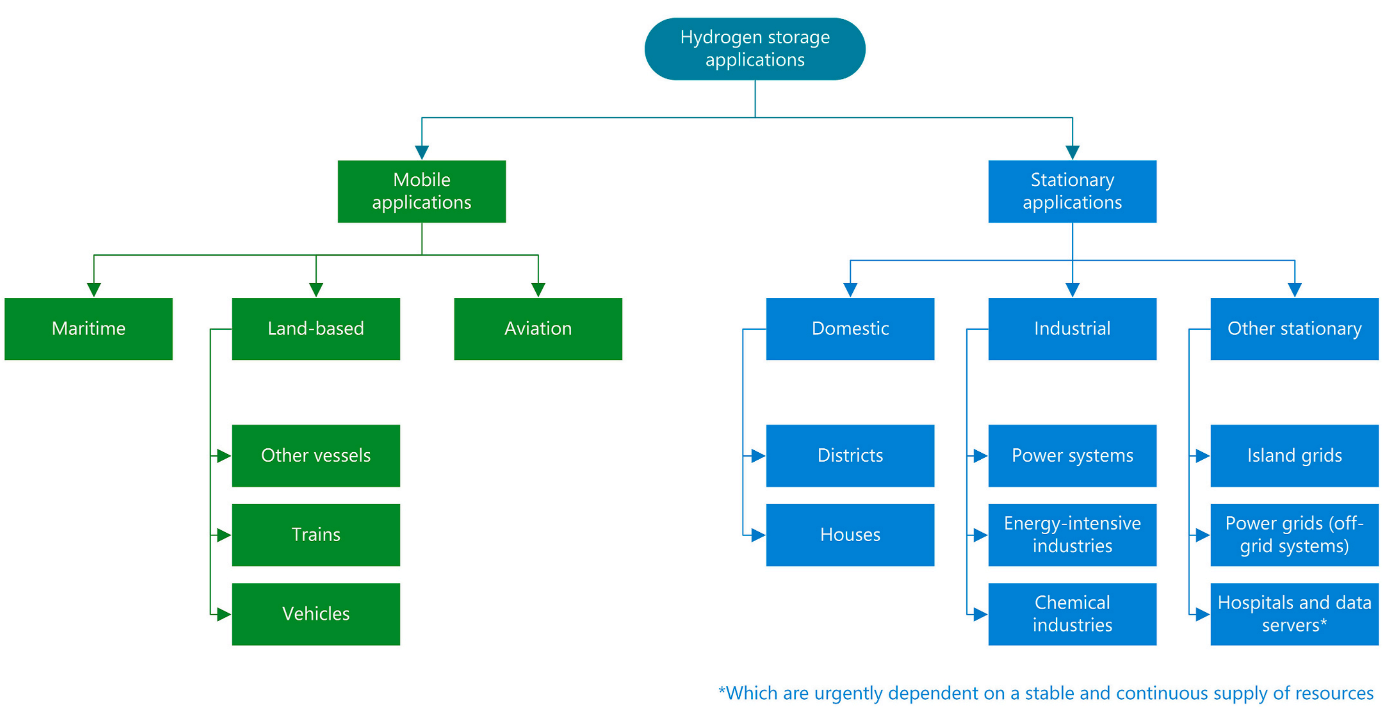


**Fig. 7.** Hydrogen storage applications overview (inspired by Ref. [95]).

for aircraft [35,175,176].

Hydrogen storage methods depend on volume, duration, discharge speed, and cost [177]. The following sections discuss mobile and stationary applications.

### 4.1. Mobile applications

Hydrogen boasts a specific energy of 120 MJ/kg, surpassing diesel and gasoline. Mobility options include $CGH_2$, $LH_2$, cryo-compressed, MHs, complex hydrides, MOF adsorption, and LOHC [41]. $LH_2$ offers an extended range and higher energy content but requires cryogenic cooling, increasing weight and costs [142,178]. MHs suit submarines, canal boats, trains, and mine vehicles. $Ti_{0.065}Zr_{0.35}$ (Fe, Cr, Mn, Ni)$_2$ suits heavy-duty applications, while $AB_2$ alloys are preferred for light passenger vehicles [73]. MHs suit specific applications, needing attributes like high storage density [179]. Sodium alanate (NaAlH4) shows potential due to its high capacity and affordability but faces challenges in mobile applications [178].

Dimethyl Ether (DME) enhances diesel engine efficiency, replacing diesel with minor adjustments and reducing particulate emissions significantly [68]. Hydrogen mobility relies on safe, rapid, mature, viable, efficient, and sustainable storage [35]. Two mobile application technologies considered [180].

- Electricity stored in batteries/supercapacitors.
- Chemical energy stored as $H_2$ in hydrogen fuel cells.

Hydrogen fuel cell (HFC) technologies offer energy densities of 0.33–0.51 kWh/L, varying with $H_2$ storage methods, compared to rechargeable Li-ion batteries achieving up to 0.14 kWh/L [180]. HFC electric vehicles (FCEVs) significantly reduce $CO_2$ emissions, enhance energy security, and mitigate local air pollution and noise levels, aligning with transport sector goals [30]. Hydrogen and fuel cell tech decarbonize heavy-duty transport like trucks, large vehicles, and coaches. Large vehicles are expected to break even by 2030 [181].

Vehicular hydrogen storage options encompass low-pressure gas, compression, or solid absorption, each with distinct advantages and considerations [182]. Light-duty vehicles need onboard hydrogen storage for a 300+ mile range [82]. Efficient hydrogen utilization requires compact storage. Air transport consumes the most energy, followed by road and rail. Water electrolysis needs minimum voltage, consuming around 47 kWh/kg [13,183]. Vehicles decide between continuous energy supply or on-board storage. Off-board regeneration is unfeasible due to energy-intensive hydride recovery [54]. The following sections detail typical mobile applications.

#### 4.1.1. Polymer electrolyte membrane fuel cells

Fuel cells convert hydrogen into electricity through low-temperature electrochemical processes, which is crucial for a low-CO2 energy system [184]. The hydrogen economy relies on solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs), each facing efficiency, cost, and application-specific challenges [17]. High-temperature fuel cells face limitations for all-electric aircraft but can complement other propulsion systems, leveraging temperature compatibility with turbomachines [35].

HFCs, notably PEMFCs, use environmentally friendly materials like polymers and graphite, excluding platinum (Pt) [184]. PEMFCs use Pt catalysts and Nafion proton conductors with thin polymer electrolyte sheets [185]. They convert hydrogen's energy into electricity directly, needing humidification and operating best below 100 °C, with water exiting around 90 °C to aid hydrogen release from storage devices [7].

PEMFCs offer low noise, rapid startup, high efficiency, and simple control, commercialized in transportation, stationary power, and portable markets [54,186]. Liquid $NH_3$ is a promising hydrogen carrier with high storage capacity, approximately 17.8 wt%, and 10.7 kg. $H_2$/100 L at 1 MPa and 298 K [187]. PEMs are essential for transport and stationary/portable systems, with stack sizes from 1 to 100 kW [17,41,184,185]. PEMFCs face flow and thermal challenges, with ongoing research to boost performance and durability [17]. Fig. 8 shows a fuel cell system with green hydrogen.

Table 8 compares SOFCs and PEMFCs, noting power density, fuel variety, operating temperature, efficiency, compactness, CO tolerance, and materials. Applications vary due to differing advantages and limitations.

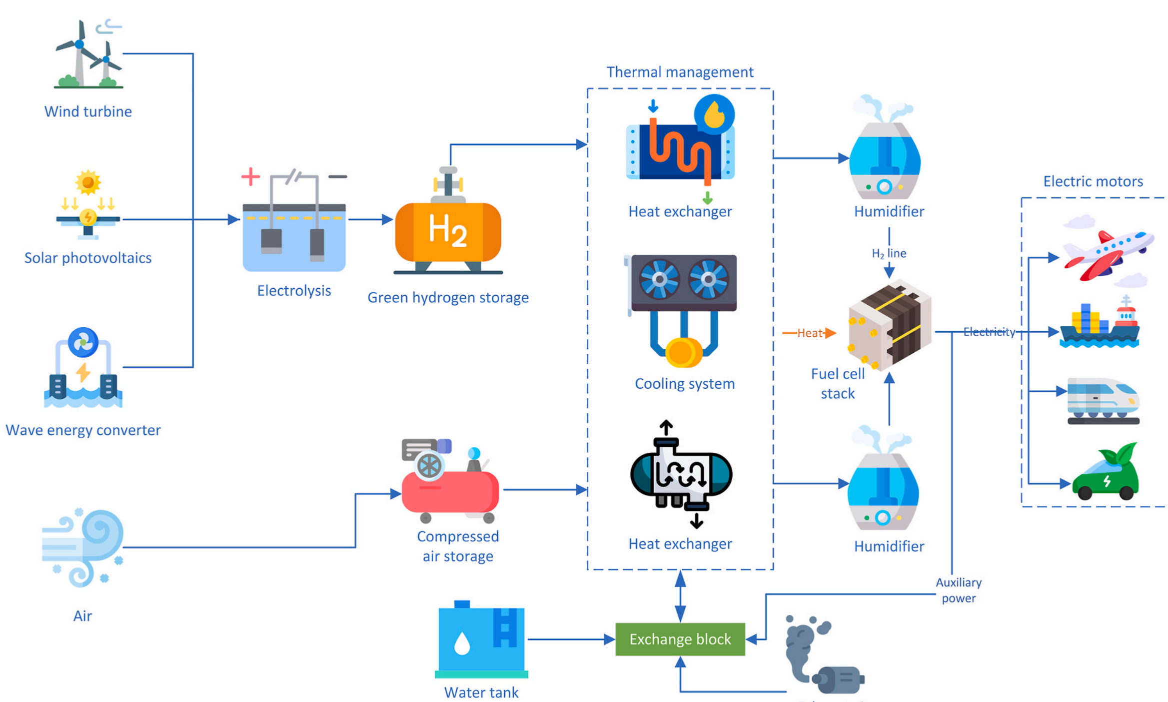


**Fig. 8.** Scheme of a fuel cell system run by green hydrogen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 8**
Comparison between SOFCs and PEMFCs [188–190].

| Feature | PEMFCs | SOFCs |
|---|---|---|
| Power Density | Lower compared to SOFC | Better than PEMFC |
| Fuel Variety | Limited variety of fuels for operation | Versatile types of fuels |
| Operating Temperature | Lower temperatures operation | Higher temperatures operation |
| Hydrocarbon Usage | Requires pre-processing unit for hydrocarbons | Direct consumption of hydrocarbons |
| Maintenance | Lower for lower temperatures | Elevated temperatures may cause coarsening |
| Efficiency | Higher efficiency than SOFC | Lower efficiency than PEMFC |
| Compactness | Packable in a compact form factor | Unpackable in a compact form factor |
| CO Tolerance | Needs pure hydrogen with no CO | Can use CO + hydrogen as fuel |
| Insulator Technology | Insulation and heat dispersion | Cheaper insulators |
| Thermal Management | Complex | Better |
| Start-up Time | Quick | Long |
| Materials | Need for optimization of components for efficiency | Limited selection of materials stable at high temps |
| Typical Operating Temperature Range | 70–90 °C | 600–1100 °C |
| Cogeneration Capability | No | Yes |

*4.1.2. Aviation*

Testing biodiesel and hydrogen as jet fuel substitutes showed biodiesel's cost inefficiency and hydrogen's space efficiency. Gas turbines remain primary [191,192]. Hydrogen adoption in aviation demands aircraft and engine modifications, with fuel storage behind the cabin altering the plane's center of gravity [192].

$LH_2$ challenges include low density, redesign, extreme temperatures, and evaporation [193–196]. Storage consumes 35% of hydrogen's energy, which is ideal for flight and space due to its high energy density despite its higher consumption [73].

$LH_2$ aircraft tanks face challenges in lifetime, stability, maintenance, and design integration [197]. $LH_2$ aircraft costs hinge on production and storage [195]. PEMFCs are favored for aircraft due to their lightweight, efficiency, lifespan, and rapid startup [35].

Indicators for comparative analysis among aircraft storage methods include [35].

1. Gravimetric density: Aerodynamic efficiency.
2. Volumetric density: Spatial constraints.
3. Storage conditions alignment: Handling and auxiliary systems.
4. Operational condition disparity insights: Auxiliary system sizing.
5. Specific energy: Cooling/heating needs.
6. Kinetics: Swift release.
7. Safety paramountcy.
8. Maturity level: Technological potential.

Hydrogen, 2.6 times more energy dense than kerosene, requires four times the volume for storage. Specialized cooling is vital due to its −253 °C boiling point. Tanks, usually spherical or cylindrical, must maintain a slight pressure differential for insulation [198].

Airbus targets hydrogen-powered aircraft by 2035, exploring hybrid fuel cells and direct combustion, collaborating with ElringKlinger AG on fuel cell stacks [199]. Rolls-Royce and easyJet partner on hydrogen combustion engines for narrow-body planes, targeting net-zero carbon emissions by 2050. Rolls-Royce offers engine expertise; easyJet contributes operational knowledge. Ground tests include Boeing 737 MAX 9 and Airbus A320neo [2,200].

*4.1.3. Maritime*

Hydrogen-powered ships cut emissions in maritime use, employing internal combustion engines and fuel cells, which are ideal for long-distance voyages and auxiliary power. Fuel cells offer efficiency and silence, emitting no pollutants. Towboats and ferries are key candidates [33,195,201].

Analysis of marine hydrogen tank connections is vital for safety and durability. Compressed hydrogen in shipping requires an understanding of fatigue life as maritime hydrogen use expands [194,202]. Di Micco et al. studied replacing an 8.3 MW diesel engine with a PEMFC system on a chemical tanker, finding significant volume and mass reductions [203].

Various hydrogen-powered maritime projects talked about in the Table 9 with unique features provides an overview of progress of the application. Hydroville (Belgium, 2017) is a passenger shuttle using dual fuel (hydrogen and diesel) with 441 kW power, featuring Type III cylinders. BeHydro (Belgium, 2020) is a heavy-duty engine with dual fuel capability and up to 2.6 MW power, aimed at reducing CO2 emissions. MF Hydra (Norway, 2021) uses liquid hydrogen and PEM fuel cells with a total power of 2 × 200 kW and 80 $m^3$ hydrogen storage. HySeas III (UK, 2022) integrates hydrogen fuel cells and batteries, offering 600 kW power and 600 kg hydrogen storage. ELEKTRA (Germany, 2019) is a hydrogen canal tug with 2.5 MWh battery capacity, focusing on inland waterways. Hydrogenesis Passenger Ferry (UK, 2013) combines fuel cells and batteries, achieving speeds of 10 knots with 350 bar hydrogen storage. In conclusion, the challenges and requirements include developing efficient storage and refueling infrastructure, reducing costs, integrating hydrogen with existing technologies, addressing safety and regulatory issues, and enhancing environmental performance for zero-emission goals.

*4.1.4. Fuel-cell electric vehicles*

Introduced in 2014, PEMFC-equipped fuel-cell vehicles (FCVs) revolutionized electric vehicles, converting hydrogen and oxygen's chemical energy into electricity [187]. Key components include the fuel cell stack, electric motor, motor drive, and voltage regulator/converter, favoring compact, lightweight stacks [142,221]. FCEVs primarily use hydrogen gas from diverse energy sources [221].

Hydrogen fuel-powered vehicles, favored for their reliability and quality, surpass Battery Electric Vehicles (BEVs) due to lower vehicle cost and shorter refueling times facilitated by hydrogen [181,195]. However, new studies into batteries such as sodium-ion batteries (SIBs), which even have potential as a substitute for graphite as a great way of large-scale energy storage, despite the need for further optimization to address challenges such as low ion diffusion rates [88]. Well-suited for replacing heavy-duty internal combustion vehicles, FCEVs benefit from hydrogen's high energy density, offering longer driving ranges [221]. Hydrogen vehicles have distinct advantages over battery-powered vehicles. They boast significantly faster refueling times compared to battery recharging. Additionally, they tend to be lighter, which is particularly beneficial for heavy vehicles like trucks and buses [184]. Fig. 9 compares BEVs and FCEVs.

In fuel cell applications, managing storage and refilling involves addressing heat leakage, especially in compressed and liquid storage. Rapid consumption can mitigate temperature rise, while thermal storage devices in cryo-compressed systems offer a solution [223]. Future hydrogen storage may involve cryogenic liquefaction of atomic hydrogen [224], which faces high energy costs and boil-off losses. MOFs present potential solutions [180]. On-board $H_2$ storage is crucial for FCVs, with considerations for volume, weight, safety, and cost [66]. Hydrogen storage infrastructure spans production, utilization, and fueling [20]. Hydrogen vehicles, with fast refueling times and lower weight, are attractive for high-loading vehicles, advancing the green economy [193].

Some companies adopting hydrogen technology include Toyota with its Mirai (2014), Honda with the Clarity (2016), Hyundai with the Nexo

**Table 9**
Some ship companies and projects utilizing hydrogen technology.

| Features | Project | | | | | |
|---|---|---|---|---|---|---|
| | Hydroville | BeH$_2$ydro | MF Hydra | HySeas III | ELEKTRA | Hydrogenesis Passenger Ferry |
| **Type** | Passenger Shuttle | Engine Technology | Passenger Ferry | Ferry | Hydrogen Canal Tug | Passenger Ferry |
| **Fuel** | Hydrogen: 36 kg<br>Diesel: 2 × 260 L | • Dual fuel $H_2$ (85% hydrogen gas + 15% conventional fuel)<br>• Mono fuel $H_2$ | LH2 | Hydrogen | Hydrogen | Hydrogen |
| **Operator** | Belgian ship owner CMB | A joint venture between CMB and Anglo Belgian Corporation | Norled | HySeas III Consortium - Supported by the European Union's Horizon 2020 framework program | TU Berlin - EBMS | Bristol Hydrogen Boats |
| **Capacity** | 13 passengers, 2 crew members | – | 300 passengers + 80 cars | 120 passengers | – | 12 passengers, 2 crew |
| **Service Entry** | 2017 | 2020 | 2021 | 2022 | 2019 | 2013 |
| **Engine Technology** | Dual Fuel (Diesel/$H_2$) | Dual Fuel (Hydrogen/Liquid Fuel) | Fuel Cells (PEM) and Hydrogen | Fuel Cells and Hydrogen | Fuel Cells, Batteries, Hydrogen | Fuel Cells (Auriga Energy) |
| **Power** | 441 kW | 600 kW - 2.6 MW | • Fuel cells 2 × 200 kW<br>• Generators: 2 × 440 kW | • PEMFC: 600 kW<br>• Li-ion BESS: 768 kWh | • Battery package: 242 DNV-approved modules, total capacity 2.5 MW h.<br>• Three maritime fuel cells (NT-PEMFC): 100 kW peak power each | 12 kW unchanging continuous power at 48 V |
| **Geometry** | • Length: 14 m<br>• Beam: 4.2 m<br>• Draft: 0.65 m | – | • Length: 82.4 m | • Length: 40 m<br>• Beam: 10 m<br>• Depth: 4 m | • Length: 20 m<br>• Beam: 8.2 m<br>• Draft: 1.25 m | • Length: 11 m<br>• Width: 3.6 m wide |
| **Emission** | $CO_2$: 58% | • Dual fuel: Max 85% $CO_2$ reduction<br>• Mono fuel: $CO_2$ free | Max 95% carbon reduction | Zero emissions | Zero emission | Zero emissions |
| **Country** | Belgium | Belgium | Norway | United Kingdom | Germany | United Kingdom |
| **Aim/Function** | • Hydroville began as a commuter vessel, easing peak traffic.<br>• It now serves as an exhibition venue and meeting space.<br>• Summer excursions to explore wind parks | • Designed for heavy-duty tasks<br>• BeHydro focuses on shipping, railways, and power. | • Advancing green maritime solutions<br>• Meeting emission reduction targets by 2030, 2050. | • Successful fuel cell integration<br>• Include marine hybrid electric propulsion<br>• Integrate hydrogen storage and bunkering. | • Creating eco-friendly ship energy for inland waterways.<br>• Evaluating ELEKTRA's project for economic feasibility. | • HFC viability. |
| **Additional Information** | • Cylinder:<br>- Type: Type III<br>- Weight: 66 kg<br>- Lifetime: 20 years<br>- Water volume: 205 L<br>• Pressure:<br>- Service pressure: 200 bar<br>- Maximum pressure: 260 bar<br>- Test pressure: 300 bar<br>• Capacity per tank: 3 kg<br>• Number of tanks: 12<br>• Working temperature: 40 °C to +82 °C<br>• Performance:<br>- Max. Speed: 27 knot<br>- Cruising speed: 18–22 knot | • Lifetime: Over 200,000 running hours<br>• Cylinder Options: Inline 6 or 8 cylinders; V configuration with 12 or 16 cylinders<br>• A 1 MW BeHydro hydrogen-powered engine reduces CO2 emissions by 3500 tonnes/year.<br>• It can convert 13,600 diesel locomotives in Europe to H2 operation.<br>• The engine produces as much energy as one 3 MW wind turbine or 36,000 solar panels. | • First ship sailing on LH2<br>• Hydrogen storage tank capacity: 80m3<br>• Maximum speed: 9 knots | • Hydrogen storage: 600 kg at 350 bar<br>• Operates on local renewable hydrogen<br>• PEM fuel cells in HySeas III have 30,000+ operating hours. | • Elektra: 100 km range over 16 h<br>• 21,200 kWh electric power capacity<br>• Battery: Green Orca<br>• Electric mode: 65 km in 8 h | • Speed: 6 kt s - 10 kt s<br>• All-weather operability<br>• H2 storage: max 350 bar<br>• Refueling every 4 days<br>• Hydrogen sourced from Air Products plastic factory waste<br>• 10-min fuel cell recharge |
| **References** | [204–206] | [207–211] | [212,213] | [214–217] | [218,219] | [220] |

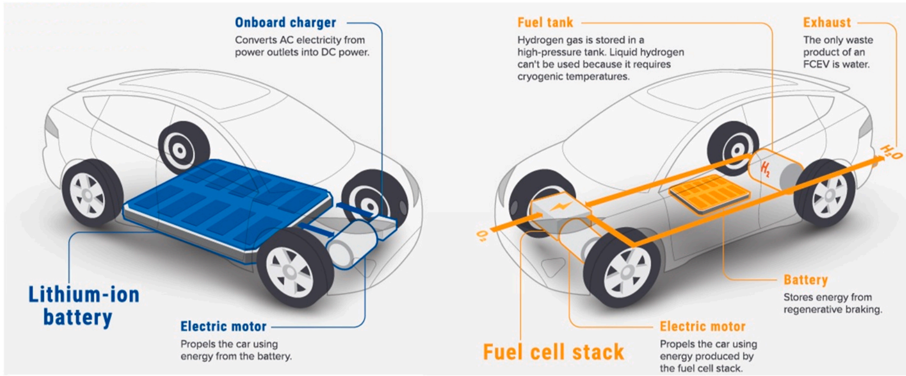


**Fig. 9.** Schematic of FCEVs and BEVs [222].

(2018), as well as China's BAIC, Yutong, Changan, and GAC [225].

With a look at Table 10, the growing commitment to hydrogen technology and its increasing adoption in the mobile sector becomes evident. Advances such as the Toyota Mirai, which boasts a driving range of up to 850 km and features high-pressure tanks and advanced safety measures, highlight significant progress in fuel cell efficiency and user convenience. The BMW iX5 Hydrogen, launched in 2023, underscores this trend with its 504 km range and quick refueling time, showing how hydrogen vehicles are becoming more practical for everyday use. Hyundai's 2023 NEXO Fuel Cell and the upcoming N Vision 74 illustrate further advancements, with the NEXO offering a driving range of 380 miles and the N Vision 74 promising over 600 km, alongside sophisticated cooling systems. Honda's forthcoming CR-Ve combines hydrogen fuel with electric power for a range of 270 miles and the added benefit of powering small appliances. These developments reflect a robust momentum towards hydrogen vehicles, addressing challenges such as range and refueling speed while enhancing environmental sustainability. There seems a promising shift in the automotive industry towards cleaner, hydrogen-powered mobility solutions.

**Table 10**
Companies manufacturing FCEVs.

| Company | Product name | Launch Date | Performance | Information on Storage | Facts | References |
|---|---|---|---|---|---|---|
| Toyota | Toyota Mirai | Launched in 2014 | • Maximum speed: ~ 175 km/h<br>• Driving range: max 850 km<br>• Volume power density: 3.1 km/L<br>• Maximum power productivity: 144 kW<br>• Power: 134 kW (182 PS)/6940 r.p.m. | • High-pressure tanks × 3<br>• Filling pressure: 70 MPa<br>• Capacity: 141 L<br>• PEMFC | • Advanced Toyota Safety Sense for enhanced safety measures<br>• Smooth and powerful driving performance<br>• Maintains operability akin to gasoline-powered vehicles<br>• Extended cruising range enhances convenience. | [195,226,227] |
| | Toyota Hydrogen HiLux | The project began in early 2022 | • Driving range: More than 365 miles | • High-pressure tanks × 3<br>• Capacity: 7 L | • Toyota prototypes prioritize durability and reliability.<br>• Mirai's decade-long technology ensures reliability.<br>• FC operation produces zero tailpipe emissions. | [228,229] |
| BMW | BMW iX5 Hydrogen | Launched in 2023, after four years of development | • Maximum speed: 60 mph<br>• Driving range: 504 km<br>• Power: Max 295 kW | • Hydrogen tanks (hydrogen - gaseous) × 2<br>• Capacity: 6 kg<br>• Refueling time: 3–4 min | • Combining precision engineering and agility with a hydrogen propulsion drivetrain.<br>• Long-distance range capacity.<br>• Emission-free driving experience. | [230–232] |
| Hyundai | 2023 NEXO Fuel Cell | 2023 | • Maximum speed: 111 mph<br>• Driving range: Max 380 miles<br>• Power: 120 kW | • Capacity: 6.33 kg<br>• Refueling time: less than 5 min | • Equipped with a 360-degree sensor array for autonomous parking.<br>• Features a sleek, refined design with clean lines.<br>• Highly aerodynamic shape boosts driving range. | [233,234] |
| | Hyundai N Vision 74 | Set to enter production by 2026, albeit in limited quantities | • Maximum speed: Over 250 kph<br>• Driving range: Over 600 km<br>• Power: Over 500 (Rear) kW | • Capacity: 4.2 kg<br>• Refueling time: 5 min | • Incorporates individual cooling systems for stack and battery.<br>• 3-channel cooling enhances PE system heat management.<br>• Motorsport-inspired details improve aerodynamics. | [235,236] |
| Honda | 2025 Honda CR-V e:FCEV | 2024 | • Electric motor<br>- Power: 174 hp<br>- Torque: 229 l b-ft<br>• Driving range: Max 270 miles | • Fuel: Compressed Hydrogen Gas<br>• Tank pressure: 10,000 psi<br>• Tank capacity: 4.3 kg<br>• Refueling time: in minutes | • Honda Power Supply Connector: Max 1500 W.<br>• CR-V e: FCEV can power small appliances.<br>• Aerodynamic features enhance driving range. | [237–239] |

**Table 11**
Hydrogen applications implemented in real projects.

| Application | Project name | Duration | Aim | Other information | Results | References |
|---|---|---|---|---|---|---|
| Aviation | ENABLE$H_2$ | 2018–2021 | • Advance $LH_2$ propulsion for zero $CO_2$, ultra-low NOx emissions.<br>• Address safety, infrastructure, economics, and community acceptance.<br>• Research better combustor design fuel system heat management for NOx reduction, efficiency, and $LH_2$ volume reduction. | • Studied technologies:<br>- H2 Micromix combustion.<br>- Fuel system heat management.<br>• Storage: LH2. | • Hydrogen transition complements air transport research.<br>• Exceeds aviation's long-term environmental goals. | [142,243] |
| | WESTKÜSTE100 | 2020–2025 | • Oxygen from electrolysis is used in oxyfuel combustion at the Lägerdorf cement plant.<br>• Wind energy sources industrial green hydrogen.<br>• Byproducts (waste heat, CO2, oxygen) recycled. | • Establishing a large-scale hydrogen economy in the Schleswig-Holstein region.<br>• Storage type: Caverns | • Project ongoing. Post-completion, electrolysis to enable industry decarbonization, generating hundreds of megawatts. | [142,244,245] |
| Power generation, steelmaking, mobility sector | Green Hydrogen Catapult | 2020-Present | • Green hydrogen aligns with fossil fuel displacement for net-zero emissions and a 1.5 °C limit.<br>• Testing green ammonia for power generation.<br>• Targeting industry energy revolution costs below \$2/kg. | • Installed 80 GW of new electrolyzers, 45 GW pledged by Catapult members. | • Scaled green hydrogen production by 50×.<br>• Achieved 50% cost reduction, aiming for sub-\$2/kg green hydrogen. | [246–248] |
| Utility vehicles (such as forklifts) + refueling systems | HYDRIDE4MOBILITY | 2017–2022 | • Advance MH materials for $H_2$ storage.<br>• Develop high-performance, mass-producible MH containers.<br>• Integrate $H_2$ storage and compression with refueling.<br>• Test systems with PEMFCs to boost efficiency. | • Storage type: MOFs | • Zr/Ti-based Laves type alloys are effective for high-pressure $H_2$ storage.<br>• Competitiveness hinges on materials, system design, and integration. | [180] |
| Shipping and chemical industries | Highly Innovative Fuels (HIF) | 2016-Present | • Substituting fossil fuels for existing engines.<br>• Using renewables for hydrogen production.<br>• Capturing $CO_2$ from various sources. | • Synthesizing green hydrogen with captured CO2.<br>• 2035 goals:<br>• 150 k barrels of eFuel daily.<br>• Recycling 25 MM tonnes of $CO_2$ yearly.<br>• Deploying 5 MM low-carbon vehicles. | • The final result is low-carbon eFuel. | [249–252] |
| Maritime | HyShip | 2021–2025 | • Cutting costs for liquid green hydrogen ship propulsion in Europe.<br>• Building a sustainable $LH_2$ supply chain and bunkering infrastructure. | • Storage type: $LH_2$ | • The project has not yet concluded. | [253–255] |
| | MARANDA | 2017–2021 | • Developing an emission-free PEMFC hybrid powertrain.<br>• Testing freeze start of 165 kW system with battery. | • Validated three 82.5 kW power output systems on test benches and aboard the research vessel Aranda.<br>• Mobile $H_2$ storage container refills at $H_2$ station −350 bar. | • New MEAs improve stack durability.<br>• Dry air temp affects humidifier performance.<br>• Land tests succeed, but challenges remain in maritime FC integration. | [254,256,257] |
| | e-SHyIPS | 2021–2024 | • Providing experimental data for safety criteria on hydrogen-fueled vessels.<br>• Creating an EU maritime roadmap for hydrogen fuel adoption. | • e-SHyIPS prioritizes vessel-independent risk assessment methods.<br>• Its goal is to update the IGF code for passenger ships with hydrogen fuels. | • Employing lean agile methods for passenger ship risk management by 2024. | [258–260] |
| Iron and steel, mobility + fertilizer industry | Blue Danube | 2014–2030 | • Off-grid green hydrogen production in Southeast Europe using renewables. | • Phase One: Establishing green hydrogen in Austria and neighboring Bavaria. | • The project has not yet concluded. | [261–263] |

(continued on next page)

**Table 11** (*continued*)

| Application | Project name | Duration | Aim | Other information | Results | References |
|---|---|---|---|---|---|---|
| | | | • Hydrogen transportation via the River Danube to users in the region.<br>• Developing hydrogen infrastructure along TEN-T core corridors in participating states. | • Phase Two: Generating green hydrogen in Southeastern Europe.<br>• Storage: LOHC. | | |
| Transportation technologies | TransHyDE | 2021–2025 | • Developing and assessing hydrogen transport and storage technologies.<br>• Goal: Identify optimal technology for each application. | • Transporting methods: pipelines, high-pressure containers, LH, and chemically stored options like ammonia or LOHC. | • The TransHyDE project guides national hydrogen infrastructure through regulatory analysis, standards review, certification, and gap identification. | [264,265] |

#### 4.1.5. *Heavy-duty vehicles*

Fuel cell technology, powered by green hydrogen, reduces greenhouse gas emissions from heavy-duty vehicles (HDVs), meeting modern logistics demands and integrating renewable energies [240]. Hydrogen fuel cells excel in heavy-duty utility applications, offering rapid refueling, enhanced performance, and zero emissions for indoor operations [180,241]. While battery-electric trucks gain traction, hydrogen-powered heavy-duty trucking promises faster refueling and greater range, as demonstrated by the Hyundai Xcient Fuel Cell [95]. Transitioning HDVs to hydrogen fuel cells can curb $CO_2$ emissions, yet high costs and R&D hurdles persist, requiring gradual integration and renewable fuel sources [242].

The projects scrutinized in Table 11 demonstrate significant advancements and diverse applications of hydrogen technology across various sectors. For aviation, the ENABLEH2 projectfocused on optimizing $LH_2$ propulsion to achieve zero $CO_2$ and ultra-low NOx emissions, improving combustor design and fuel system management. WESTKÜSTE100 aims to integrate wind energy-driven green hydrogen into cement production, utilizing electrolysis and cavern storage. In power generation, the Green Hydrogen Catapult seeks to scale up green hydrogen production while reducing costs below $2/kg. HYDRIDE4-MOBILITY explores advanced metal hydride materials for hydrogen storage in utility vehicles, while Highly Innovative Fuels (HIF) works on synthesizing low-carbon eFuel from renewable hydrogen and $CO_2$. Maritime projects like HyShip and MARANDA are developing $LH_2$ propulsion systems and emission-free hybrid powertrains. The e-SHyIPS project focuses on safety criteria for hydrogen-fueled vessels, and Blue Danube aims to establish a green hydrogen infrastructure along the River Danube. Lastly, TransHyDE is evaluating various hydrogen transport and storage technologies to optimize their application. The covered projects indicate that advancements are happening rapidly by focusing on emission reduction, cost efficiency, and diverse applications across sectors.

### 4.2. *Stationary applications*

Stationary hydrogen storage systems primarily involve compressed hydrogen storage in pressurized tanks or underground facilities, with pressures ranging from 100 to 400 bar. $LH_2$ storage, while less common, utilizes cryogenic technology with storage volumes reaching many cubic meters. Companies like Hydrogenious GmbH, $H_2$-Industries AG, Areva $H_2$Gen, Hynertech, Chiyoda Corporation, and Hydrogenia Pty Ltd are leading LOHC-based storage initiatives. Typically, two tanks suffice for stationary applications, with capacities varying based on the specific storage method and scale [42].

Hydrogen storage in metal hydrides offers advantages for stationary applications, including high volumetric energy density and lower operating pressure. Metal hydrides can also be compressors and heat storage units in the stationary sector. Unlike in transportation, where lower temperatures prevail, stationary applications can accommodate metal hydrides with several hundred degrees Celsius desorption temperatures. Metal hydrides capable of reversibly storing hydrogen under ambient conditions are a practical choice for stationary hydrogen storage [95,100,266]. Efficient storage and transportation of liquid hydrogen require careful vessel design and auxiliary equipment. In stationary storage, tanks come in various shapes, with cylindrical and spherical structures being common choices. Spherical tanks are advantageous because they reduce evaporation losses, provide mechanical strength, and ensure uniform stress distribution [267].

Currently, stationary hydrogen storage systems have mainly been incorporated into standalone hybrid energy systems, where hydrogen production and storage are demonstrated at a small scale [141]. Hydrogen stationary applications encompass backup power supply, off-grid power supply, and residential power generation. Key considerations in these applications include hydrogen supply cost and pressure cycle life [29]. The primary types of fuel cells used for stationary applications are polymer electrolyte membranes and phosphoric acid variants. Despite economic challenges, researchers view these systems as reliable and durable [69]. In stationary applications, weight constraints are typically less stringent, allowing for more flexibility in hydrogen storage systems. Since these systems are usually placed on solid ground, weight is primarily restricted by the volume of hydrogen needed for storage [78,175,193,268].

#### 4.2.1. *Power generation system*

For hydrogen to aid clean energy transitions, it must penetrate sectors like transport, buildings, and power generation. It is a top option for renewable energy storage [269]. Stationary power outputs range from 0.1 to 10 kW for small applications to several megawatts for large-scale power generation [69]. Hydrogen integration diversifies energy systems, offering balancing support and regulatory flexibility within the source-grid-load framework, reducing emissions, and addressing power system challenges [270]. Hydrogen power generation gained traction, reaching 1 GW global capacity in 2015 [271].

#### 4.2.2. *Off-grid supply stations*

Unlike high-pressure systems, off-grid systems in remote areas demand user-friendly operation and minimal maintenance. While diesel generators have historically powered such locations, the trend is shifting towards off-grid renewable energy technologies. However, intermittency in renewable sources poses challenges, highlighting the need for effective storage solutions. As demonstrated by recent projects, metal hydride-based hydrogen storage devices emerge as promising options for off-grid power generation and energy storage [78]. In stationary applications, volume and weight considerations take a back seat to factors like waste heat utilization and temperature thresholds. Off-grid systems, however, show variability in volume importance due to diverse application needs [95,272].

Gray et al. explored the integration of intermittent renewable energy sources for off-grid electricity consumers, emphasizing the role of hydrogen storage alongside PEM electrolyzers and PEMFCs. Metal-hydride storage, particularly Mischmetal-based AB5 alloys, was favored over Li-ion batteries due to its potential for compact packaging [273]. Hybrid battery-hydrogen systems offer a solution for robust and economical off-grid renewable energy systems. Research explores diverse energy management strategies, including environmental performance evaluation of fuel cells, monitoring hybrid systems and home energy usage, minimizing energy loss and generation costs, and optimizing domestic load scheduling [73].

#### 4.2.3. Power backups

Hydrogen fuel cells (HFCs) present a promising solution for reliable, eco-friendly backup power, offering clean and efficient energy generation, scalability, and compatibility with renewable sources. However, safety, cost, infrastructure, and integration must be addressed for widespread adoption [274]. Integrating solid-state hydrogen storage with fuel cells offers a versatile solution for reliable power supply in industrial parks, data centers, and hospitals. Unlike traditional diesel generators, fuel cells provide faster response times, silent operation, and zero emissions. Solid-state hydrogen storage and fuel cells can utilize industrial tail gas for hydrogen production, offering cleaner and more efficient alternatives for backup power in industrial parks [275]. Meticulously designed charging-discharging protocols enable MOFs coupled with electrolyzers and fuel cells to demonstrate economic competitiveness akin to incumbent energy storage technologies in backup power scenarios [276].

Hang Zhang et al. analyzed MH hydrogen storage using a thermodynamic model to understand pressure, composition, and temperature dynamics. Their study confirmed the feasibility of using this system as a backup power source, sustaining a 5 kW workload demand with an operating current of up to 80 A. At 291 K, hydrogen absorption and release rates were 0.29 MPa and 0.21 MPa, respectively. This research indicates promising market potential for fuel cell backup power systems in various applications [277].

#### 4.2.4. Combined system with renewable energy sources

The primary goal of hydrogen energy storage is to demonstrate its effectiveness in integrating renewable energy sources into current energy systems. This involves optimizing hydrogen storage, handling, and distribution to enable storage at centralized and decentralized production facilities, ensuring efficient customer delivery [78]. Integrating hydrogen from renewable sources like solar and wind energy with fuel cell technology presents a promising avenue for creating a more efficient and sustainable energy source. These integrated hydrogen renewable systems signify a significant advancement in electricity production, offering substantial potential for sustainable energy generation [69]. Integrating various energy storage systems holds promise for meeting complex energy storage needs, enabling the development of versatile large-scale stationary energy storage. These systems offer increased capacity, frequent storage with rapid response, and sustained storage without losses [267]. Hybrid energy systems, utilizing multiple energy sources, outperform single-source systems in terms of cost-effectiveness and reliability. Thermal recovery without storage emerges as the most cost-effective and reliable approach for supplying residential loads [278].

A distributed energy system (DES) combining hybrid energy storage with renewable energies can enable nearly zero-energy communities. Optimizing DES design, operation, and management enhances system performance [279]. Yuechuan Tao et al. proposed an energy-sharing model combining hydrogen and electricity to address the high capital costs of energy storage systems. The integrated system involves aggregators owning power-to-gas devices and plug-in hybrid electric and hydrogen vehicles, acting as coupling points between electricity and gas networks. Simulations demonstrate the feasibility of obtaining energy-sharing amounts and unified market-clearing prices, reducing system costs and improving system stability [280]. Matteo Marinelli et al. emphasized energy supply challenges in off-grid areas due to infrastructure limitations and costs. They advocate for Power-to-Power (P2P) energy systems to achieve energy independence using renewable sources. P2P systems could mitigate the intermittency of renewables like wind and PV. They focus on a hybrid H2-battery P2P system, emphasizing hydrogen storage [281].

#### 4.2.5. Combined heat and power supply

Combined Heat and Power (CHP) systems, renowned for their simultaneous electricity and heat generation, have gained traction in contemporary energy research for their high efficiency and low carbon emissions. Incorporating hydrogen energy into CHP systems offers opportunities for greater efficiency, reduced emissions, and enhanced reliability, making them attractive for residential, commercial, and industrial energy needs. Consequently, hydrogen-based CHP systems emerge as promising alternatives to fossil-fuel CHP systems [282]. CHPs optimize energy usage by harnessing thermal and electrical energy from a single fuel cell source, ensuring cleanliness and reliability. They come in two types: grid-independent and grid-assisted. While grid-independent systems offer benefits, they are often complex and costly due to managing dynamic load fluctuations. Grid-assisted systems leverage the grid to import electricity during peak demand and export excess electricity during low-demand periods [69]. Renewable power supply growth challenges conventional plants like CHP due to fluctuating electricity prices. Despite this, these plants remain crucial for grid flexibility and reliability, especially given renewables' intermittent nature [283].

Delhomme et al. introduced a 1 kWe SOFC CHP system fueled by pure hydrogen stored in an MgH2 tank, suitable for residential and tertiary applications. Though feasible, integrating the SOFC hot box with the $MgH_2$ tank poses challenges, including maintaining high gas temperatures for efficient heat transfer and addressing pressure drop issues in the air heat exchanger. Coupling tests revealed performance decline due to over-pressure in the SOFC's cathodic side [284]. Boait et al. compared the performance of a PEMFC micro-CHP system to a Stirling engine micro-CHP over a heating season in a UK household. The PEMFC system generated significantly more electricity annually, influenced by electric vehicle charging. Empirical models showed that the PEMFC's value is less affected by building characteristics, occupancy, and climate changes than engine-based micro-CHP. A mixed approach to heat decarbonization, including heat pumps, PEMFC micro-CHP, and hydrogen boilers, may not substantially compromise energy efficiency compared to an all-electric solution and could be more consumer-friendly [285]. Skordoulias et al. examined the technical and economic aspects of integrating PEM electrolyzers to produce hydrogen in a CHP plant. They store electricity from renewables via water electrolysis and use the hydrogen in a thermal power plant for electricity and heat generation. Sensitivity analyses were conducted, varying power-to-H2 plant capacity and the percentage of hydrogen in the fuel mix; substituting hydrogen for thermal energy improved system efficiency, reducing CO2 and CO emissions. With 100% hydrogen substitution, CO2 and CO emissions fell by 100%, and CHP efficiency increased by approximately 0.59% [286].

## 5. Discussion

The current review reveals significant disparities in the cost and efficiency of various hydrogen storage methods. Liquid hydrogen ($LH_2$) is noted for its high density and efficient refueling capabilities, but it comes with prohibitive costs due to extreme cooling requirements and energy losses. Conversely, compressed gaseous hydrogen ($CGLH_2$) is reliable for high-density storage but suffers from high operational costs and energy inefficiencies, particularly during extended storage cycles. Liquid organic hydrogen carriers (LOHCs) present a viable large-scale storage solution that offers ease of handling and integration into existing infrastructure. However, they entail higher capital and operational costs compared to other methods. Ammonia and methanol also offer practical solutions within existing fuel infrastructure, yet higher energy and capital requirements characterize them. This suggests that while these methods are adaptable, they may not be the most cost-effective for hydrogen storage. The high levelized cost of hydrogen storage (LCHS) for ammonia and methanol further highlights the economic challenges associated with their use. Chemical hybrid storage methods, although cost-effective and high-density, face issues related to irreversibility and byproduct management. Metal hydrides, which provide a safe and high-density option, are hindered by inefficiencies related to high temperatures and slow kinetics. Magnesium-based hybrids, known for their high capacity, also struggle with slow kinetics. Meanwhile, metal-organic frameworks (MOFs) and carbon-based materials promise improved storage but encounter density and thermal conductivity challenges.

Hydrogen's diverse applications across various sectors underscore its potential as a transformative energy carrier. In transportation, Fuel Cell Electric Vehicles (FCEVs) offer a compelling alternative to battery electric vehicles (BEVs) due to their faster refueling times and higher energy density. Hydrogen-powered vehicles developed by major automakers such as Toyota, Honda, and Hyundai are critical for reducing $CO_2$ emissions in the transportation sector. In the aviation and maritime sectors, hydrogen's potential is being explored, with $LH_2$ providing high energy density suitable for aircraft despite its storage and cost challenges. Hydrogen-powered ships represent a practical application for reducing emissions, especially in long-distance and auxiliary power scenarios. In stationary applications, hydrogen is increasingly used for power generation, with potential applications in backup power supply, off-grid systems, and combined heat and power (CHP) systems. Integrating hydrogen with renewable energy sources offers a robust energy storage and grid stability solution [287]. Due to its compact nature, off-grid systems benefit from hydrogen's potential for energy storage, with metal hydride-based storage emerging as a viable option. Backup power systems utilizing hydrogen fuel cells provide clean and reliable alternatives to traditional diesel generators, with ongoing research focusing on improving their economic feasibility and integration with renewable sources.

## 6. Conclusion

Hydrogen is increasingly recognized as a pivotal energy carrier in the transition towards sustainable energy systems because of its potential to mitigate the environmental impacts of traditional fossil fuels. However, the efficient storage and utilization of hydrogen remain complex due to various technical and economic challenges. Among these, the choice of above-ground hydrogen storage (AGHS) methods is particularly complex, influenced by user requirements, feasibility, and cost considerations. For instance, compressed hydrogen storage systems, commonly used in mobile applications, require up to 700 bar pressures, significantly raising the energy costs associated with compression. This paper addresses these complexities by examining the current state of AGHS methods and identifying areas where further research and innovation are needed.

Current research indicates a substantial gap in understanding and optimizing AGHS methods, particularly for mobile applications. While material-based technologies, such as metal hydrides (MHs), offer promising solutions, they face significant thermodynamic and kinetic challenges that must be addressed to enhance their practical utility. For example, metal hydrides typically operate within temperature ranges of 300–500 K and require extensive heat management systems to function efficiently. This analysis aims to shed light on the mentioned challenges and underline the directions for future research that can overcome these barriers. Moreover, advancements in AGHS, electrolysis, and fuel cell technologies are crucial for improving energy resilience and supporting the broader adoption of hydrogen as a clean energy source. Hydrogen's potential impact spans multiple sectors, including transportation, where fuel cell vehicles (FCVs) and hydrogen-powered aircraft are making notable strides. The global FCV market is projected to grow at a compound annual growth rate (CAGR) of over 40% from 2023 to 2030, indicating strong future adoption.

Additionally, hydrogen's role in stationary applications, such as power generation and backup power systems, highlights its versatility and integration with renewable energy sources. Stationary hydrogen applications, spanning across sectors like power generation, industrial parks, and off-grid systems, demonstrate the versatility and potential of hydrogen as a key component in the transition to clean energy. The integration of advanced hydrogen storage technologies in these stationary sectors not only enhances energy efficiency but also provides a reliable and sustainable solution to the growing energy demands of the future. Stationary fuel cells, for instance, have already reached efficiencies of up to 60%, with future advancements potentially pushing this figure even higher. Market adoption by leading companies signifies progress, yet ongoing research into infrastructure development and cost-efficiency remains vital. The paper seeks to contribute to the ongoing efforts to make hydrogen a viable and widely adopted energy solution. Future research should focus on several key areas to unlock the full potential of AGHS. This includes integrating AGHS with renewable energy sources, advancing solid-state hydrogen storage technologies, developing more efficient catalysts, and optimizing fuel cell and battery systems. Lastly, assessing the environmental impacts of various AGHS methods is essential to ensure their adoption contributes positively to overall sustainability goals. Life cycle assessments have shown that hydrogen produced via electrolysis from renewable sources can reduce greenhouse gas emissions by up to 90% compared to traditional fossil fuels.

In summary, while hydrogen holds significant promise for a cleaner energy future, realizing its full potential requires comprehensive research and innovation. Advancements towards a more sustainable and resilient energy system could be attained by addressing existing technological gaps, improving infrastructure, and integrating hydrogen with renewable energy sources.

## CRediT authorship contribution statement

**Mahgol Farazmand:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Zahra Saadat:** Conceptualization, Formal analysis, Visualization, Writing – review & editing, Validation. **Mohammad Sameti:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing.

## Declaration of competing interest

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

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