

Hydrogen Applications and Solid-State Storage Materials: A Critical Review of Mechanisms, Material Innovations, and Prospects Toward Practical Hydrogen Energy Systems

Icha Amelia^{1*}, Dedi Rohendi², and Yollanda Nurcholifah¹

¹ Department of Chemistry, Faculty of Science and Engineering, Universitas Bangka Belitung, Balunijuk, Kepulauan Bangka Belitung, 33172, Indonesia

² Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indralaya, South Sumatera, 30662, Indonesia

*Corresponding Author: icha-amelia@ubb.ac.id

Abstract

Hydrogen has significant potential as a clean energy carrier to support the transition toward sustainable energy systems. However, the widespread implementation of a hydrogen economy is still limited by challenges associated with safe, efficient, and high-capacity hydrogen storage technologies. In general, hydrogen storage systems are classified into physical storage, chemical storage, and solid-state storage. This review article systematically discusses various hydrogen storage technologies, with a particular focus on solid-state hydrogen storage, including metal hydrides, complex hydrides such as alanates, and chemical hydrides encompassing borohydrides and liquid organic hydrides. Each class of materials is evaluated in terms of storage capacity, thermodynamic and kinetic characteristics, as well as issues related to reversibility and regeneration. The review highlights that, despite considerable progress, no single hydrogen storage system currently satisfies all practical requirements. Therefore, a fundamental understanding of hydrogen–material interactions, along with material design and catalytic strategies, is essential for advancing hydrogen storage technologies toward practical applications.

Keywords: Hydrogen storage; Solid-state hydrogen storage; Metal hydrides; Chemical hydrides; Thermodynamic and kinetic properties

Article Info

Received 25 December 2025

Received in revised 26 February 2026

Accepted 27 February 2026

Available Online 28 February 2026

Abstrak (Indonesian)

Hydrogen memiliki potensi besar sebagai pembawa energi bersih untuk mendukung transisi menuju sistem energi berkelanjutan. Namun, tantangan utama dalam implementasi ekonomi hidrogen secara luas terletak pada pengembangan teknologi penyimpanan hidrogen yang aman, efisien, dan berkapasitas tinggi. Secara umum, sistem penyimpanan hidrogen diklasifikasikan menjadi penyimpanan fisik, penyimpanan kimia, dan penyimpanan *solid-state*. Artikel ulasan ini membahas secara sistematis berbagai teknologi penyimpanan hidrogen dengan penekanan pada penyimpanan *solid-state*, termasuk hidrida logam, hidrida kompleks seperti alanat, serta hidrida kimia yang mencakup borohidrida dan *liquid organic hydrides*. Setiap kelas material dievaluasi berdasarkan kapasitas penyimpanan, karakteristik termodinamika dan kinetika, serta tantangan dalam aspek reversibilitas dan regenerasi. Ulasan ini menunjukkan bahwa meskipun kemajuan signifikan telah dicapai, belum ada satu sistem penyimpanan yang sepenuhnya memenuhi seluruh persyaratan aplikasi praktis. Oleh karena itu, pemahaman fundamental mengenai interaksi hidrogen–material serta pengembangan strategi material dan katalis menjadi kunci untuk meningkatkan kinerja teknologi penyimpanan hidrogen di masa depan.

Kata Kunci: Penyimpanan hidrogen; Penyimpanan hidrogen keadaan padat; Hidrida logam; Hidrida kimia; Sifat termodinamika dan kinetika

INTRODUCTION

Hydrogen has emerged as one of the most promising clean energy carriers to support the transition toward sustainable, decarbonized global energy systems [1-3]. In the context of the global commitment to achieve net-zero emissions by 2050, hydrogen is increasingly regarded as a strategic solution for decarbonizing hard-to-abate sectors such as steel production, cement manufacturing, heavy-duty transport, aviation, and chemical industries [4]. Several global energy transition scenarios project a substantial increase in hydrogen demand by 2050 under net-zero pathways [5,6], underscoring its critical role in deep decarbonization strategies. Hydrogen possesses a high gravimetric energy density (120–142 MJ kg⁻¹), produces zero greenhouse gas emissions during use in energy conversion systems, and is compatible with fuel cells for efficient electricity generation [1]. These attributes allow hydrogen to play a pivotal role in transportation, stationary power, industrial processing, and large-scale energy storage [7].

Traditional storage methods—compressed gas (350–700 bar) [8] and cryogenic liquid hydrogen (–253°C) [5], present several limitations, including high energy consumption for compression or liquefaction, boil-off losses, and concerns regarding safety and long-term storage stability. Consequently, solid-state hydrogen storage has attracted considerable research interest due to its potential to store hydrogen at moderate temperatures and pressures with improved safety and volumetric density [9].

Solid-state hydrogen storage mechanisms include physisorption, chemisorption, Kubas interactions, and spillover effects. These mechanisms differ fundamentally in binding strength, reversibility, and temperature dependence. Physisorption involves weak van der Waals interactions with low adsorption enthalpies (≈ 4 –10 kJ mol⁻¹ H₂), resulting in highly reversible adsorption but generally requiring low temperatures to achieve significant hydrogen uptake [10]. In contrast, chemisorption forms stronger chemical bonds between hydrogen and the host material, with binding enthalpies typically ranging from ≈ 40 –200 kJ mol⁻¹ H₂, enabling stable storage at ambient conditions but often requiring elevated temperatures for hydrogen release [10,11]. Kubas interactions represent an intermediate bonding mechanism in which molecular hydrogen binds to transition metal centers via σ -donation and π -backdonation, with binding energies generally in the range of 20–70 kJ mol⁻¹ H₂, providing a balance

between stability and reversibility under moderate conditions [12]. Meanwhile, the spillover mechanism involves dissociative chemisorption of hydrogen on a catalytic metal site followed by migration of atomic hydrogen onto a support material, potentially enhancing hydrogen uptake at moderate temperatures [13]. Correspondingly, extensive research has focused on material classes such as metal hydrides, complex hydrides, and chemical hydrides, which exhibit diverse hydrogen storage behaviors and performance characteristics. Each class presents unique advantages and challenges, creating a complex materials landscape that requires systematic evaluation [14-16].

Although many review papers address specific aspects of hydrogen storage, most focus on individual material families or provide limited discussion on the interplay between storage mechanisms, thermodynamic constraints, and kinetic limitations. A systematic and integrative framework that correlates hydrogen–material interaction mechanisms with performance metrics and practical scalability considerations remains insufficiently developed.

In this context, the present review provides a critical and comprehensive assessment of solid-state hydrogen storage materials. Metal hydrides, complex hydrides, and chemical hydrides are comparatively evaluated by correlating material performance with thermodynamic behavior, kinetic barriers, and practical feasibility. Furthermore, key technological challenges and scalability issues are identified, and future research directions are proposed to advance the development of efficient, safe, and application-oriented hydrogen storage systems.

MATERIALS AND METHODS

Materials

This review is constructed using a structured and rigorous literature analysis consistent.

Literature Source

Scientific publications were gathered from: *Scopus*, *Web of Science*, *ScienceDirect*, *SpringerLink*, *ACS Publications*, *IEEE Xplore*, etc. Additional sources include benchmark texts and authoritative reviews in: *International Journal of Hydrogen Energy*, *Journal of Materials Chemistry A*, *Energy Storage Materials*, *Advanced Energy Materials*, *Renewable and Sustainable Energy Reviews*, etc.

The literature survey covered peer-reviewed publications published between 2000 and 2024. While seminal studies published prior to 2000 were considered when relevant to foundational concepts, particular emphasis was placed on research from the

past 10–15 years to reflect recent advances in solid-state hydrogen storage materials and mechanisms.

Literature searches were conducted using keywords such as “solid-state hydrogen storage,” “metal hydrides,” “complex hydrides,” “chemical hydrides,” “physisorption,” “chemisorption,” “Kubas interaction,” “hydrogen spillover,” “thermodynamics,” and “kinetics.” Articles were selected based on their relevance to hydrogen storage mechanisms, material performance, thermodynamic and kinetic analysis, and scalability considerations.

Methods

The gathered literature was categorized into thematic sections covering: *Hydrogen end-use applications*, *Storage technologies*, *Storage mechanisms*, *Material classes*, *Comparative evaluation*, *Challenges and future prospects*. This structure facilitates a systematic analysis, beginning

with hydrogen applications and storage technologies, then examining storage mechanisms and material classes, and concluding with comparative evaluation and future research directions

RESULT AND DISCUSSION

A. Hydrogen

Hydrogen is the most abundant element in nature; however, only a small fraction exists freely on Earth. On Earth, hydrogen is predominantly found in compound forms, such as water (11.1%), hydrocarbons including natural gas (25%) and petroleum (14%), as well as carbohydrates such as starch (6%) [17]. The physical properties of hydrogen are presented in **Table 1**. Hydrogen, as an energy carrier, possesses a significantly higher energy content compared to various other fuels, as shown in **Table 2**.

Table 1. Physical properties of hydrogen [17-20].

Property	Description
Name, Symbol, Atomic Number	Hydrogen, H, 1
Category	Non-metal
Electrons, Protons, Neutrons	1, 1, 0
Relative Atomic Mass	1.008
Color, Odor	Colorless, odorless
Hazard	Mild asphyxiant
Phase	Gas
Ionization Energy (kJ mol ⁻¹)	1310
Liquid-to-Gas Expansion Ratio	1: 848 (at atmospheric conditions)
Boiling Point / Melting Point	-259.14 °C / -252.87 °C
Higher Heating Value (HHV)	141.9 MJ kg ⁻¹
Lower Heating Value (LHV)	118.8 MJ kg ⁻¹
Octane Number	>130
Density (g cm ⁻³)	0.00009
Flash Point	-253 °C
Critical Temperature	33 K
Atomic Radius (nm)	0.037
Standard Electrode Potential (V)	0
Flammability Range in Air	4–75%

Table 2. Comparison of hydrogen energy with other energy sources [14], [17], [21].

Fuel Type	Energy per Mass (J/kg)	Energy per Volume (J/m ³)	Energy Reserves	Carbon Emissions (kg C/kg)
Liquid Hydrogen	141.90	10.10	1.00	0.00
Gaseous Hydrogen	141.90	0.013	1.00	0.00
Oil	45.40	38.65	0.78	0.84
Gasoline	47.40	34.85	0.76	0.86
Jet Fuel	46.50	35.30	0.75	–

Fuel Type	Energy per Mass (J/kg)	Energy per Volume (J/m ³)	Energy Reserves	Carbon Emissions (kg C/kg)
LPG	48.80	24.40	0.62	–
LNG	50.00	23.00	0.61	–
Methanol	22.30	28.10	0.23	0.50
Ethanol	29.90	23.60	0.37	0.50
Biodiesel	37.00	33.00	–	0.50
Natural Gas	50.00	0.04	0.75	0.46
Coal	30.00	–	–	0.50

B. Hydrogen Applications

Hydrogen plays an increasingly significant role across diverse sectors due to its high energy density, versatility, and compatibility with decarbonization strategies. Its applications can be grouped into four major domains: transportation, power generation or stationary applications, and portable device applications.

Transportation Sector

The transportation industry represents one of the most promising domains for hydrogen utilization [2], [16]. Hydrogen Fuel Cell Electric Vehicles (FCEVs) offer quick refueling times, long driving ranges, and zero-emission profiles [22,23]. Several commercial vehicles, including passenger cars, buses, trucks, and forklifts, have adopted fuel cell technology. Compared to lithium-ion battery vehicles, FCEVs exhibit advantages in heavy-duty applications where weight and long-range performance are critical.

Currently, many major automotive companies such as GM, Honda, Hyundai, and Toyota are actively developing large-scale hydrogen programs. Over the past decade, BMW, Nissan, Volkswagen, and several small and medium-sized companies have also introduced hydrogen-powered concept vehicles to the public [18], [24]. Hydrogen mobility is increasingly considered competitive with battery-electric mobility [22].

Recent peer-reviewed analyses indicate that global deployment of fuel cell electric vehicles (FCEVs) has increased steadily over the past decade, exceeding 70,000 units worldwide by the early 2020s, with major markets concentrated in South Korea, Japan, China, the United States, and Germany [25].

In parallel, the number of hydrogen refueling stations (HRS) has surpassed 1,000 globally, with Asia leading infrastructure expansion, followed by Europe and North America [26]. Furthermore, hydrogen mobility markets are projected to experience substantial growth under decarbonization

pathways, supported by policy incentives, infrastructure investments, and advances in fuel cell technologies [25]. These quantitative trends demonstrate that hydrogen mobility is transitioning from demonstration phases toward early commercialization.

Several key limitations associated with batteries in electric vehicles include their low power density per unit mass, which is approximately 35 Wh/kg for lead–acid batteries, 65 Wh/kg for NiH₂, and 93 Wh/kg for lithium-ion batteries. In addition, electric vehicles require very heavy battery packs, often exceeding 200 kg, and take around 5–7 hours to recharge. Achieving a charging time of less than 10 minutes would require charging equipment with extremely high power capacity.

Hydrogen mobility is capable of combining the advantages of both hydrogen and electric mobility, offering driving range and refueling times comparable to those of conventional vehicles, smaller hydrogen storage and lower fuel cell capacity requirements than fully hydrogen-powered vehicles, and reduced battery capacity requirements compared to battery electric vehicles [27]. The comparison between electric vehicles and hydrogen-fueled vehicles is presented in **Table 3**.

The application of hydrogen as a vehicle fuel can be distinguished based on the form of hydrogen bonding and the type of energy converter employed. Hydrogen stored in its molecular (pure) form can be used directly by transportation systems without requiring further conversion into another energy carrier. In this context, hydrogen can be utilized in both internal combustion engines and fuel cell systems [27].

Despite these advantages, the widespread deployment of hydrogen-powered transportation systems critically depends on the development of safe, lightweight, and high-capacity hydrogen storage technologies that can meet stringent onboard requirements.

Table 3. Comparison between electric vehicles and hydrogen-fueled vehicles [28].

Vehicle Type	Electric Vehicle	Hydrogen-Fueled Vehicle
Example	BYD E6, Cina	Honda Clarity, Japan
L x W x H (m)	4.55 x 1.82 x 1.63	4.83 x 1.85 x 1.47
Weight (kg)	2100	1600
Maximum power (kW)	115-200	100
Maximum speed (km/h)	160	160
Driving range (km)	>300 ^a	4300 ^b
Energy storage type	Lithium-ion battery	Hydrogen (350 bar)
Energy capacity (kWh)	>60	136 (4.1 kg H ₂)
Refill time:		
Home	>20 h	-
Fast	50% (10 min)	2-3 min

Notes: ^a Rounded to 400 km; detailed information on operating conditions is not available (n/a); ^b Based on the combined EPA driving cycle with an average speed of 48 km/h.

Stationary Applications

Stationary hydrogen fuel cells (SHFCs) are a promising application of fuel cell technology beyond hydrogen-powered vehicles. These systems electrochemically convert chemical energy into electrical energy, with heat and water as by-products, enabling both residential power supply and heat utilization. SHFCs provide clean and reliable off-grid electricity, are suitable for telecommunications and utility applications, do not require backup batteries, and involve relatively simple maintenance [29]. Solid oxide fuel cells (SOFCs) are commonly used due to their long operational lifetime and stable performance [30]. In Indonesia, PEMFC-based stationary hydrogen fuel cell systems have been commercially deployed as backup power sources for numerous base transceiver stations [31].

Portable Device Applications

Portable electronic devices, including mobile phones, laptops, and power banks, have garnered increasing attention due to their potential to enhance safety, convenience, and operational reliability. This interest is particularly pronounced in military and defense applications, which rely heavily on advanced electronic equipment such as communication radios, night-vision systems, and portable computing devices [32,33]. These applications require power sources that are compact, lightweight, and capable of providing long operational durations without frequent replacement or recharging [34].

Conventional battery technologies are often inadequate for high-power and long-duration portable applications because of their limited specific energy and restricted operating time [35]. As a result, hydrogen-based fuel cells have emerged as a promising alternative to batteries. Fuel cells offer several advantages, including rapid refueling,

independence from electrical grids, extended operational lifetimes, relatively low operating temperatures, favorable anode reaction kinetics, and environmentally benign by-products, primarily water [32-34]. These attributes position hydrogen fuel cells as a viable energy solution for next-generation portable power systems.

Despite its significant advantages, hydrogen deployment faces several critical challenges that must be addressed to ensure its large-scale adoption. The development of hydrogen refueling infrastructure remains limited and capital-intensive, with high investment requirements for production, storage, transportation, and dispensing systems [36]. In addition, the production cost of green hydrogen via water electrolysis is still considerably higher than that of conventional fossil-based hydrogen, primarily due to electricity prices and electrolyzer capital costs [6].

Furthermore, the overall well-to-wheel efficiency of hydrogen energy systems—considering electrolysis efficiency (~60–70%), compression or liquefaction losses, distribution, and fuel cell conversion (~50–60%)—is generally lower than that of direct electrification pathways such as battery electric vehicles [37,38]. These systemic challenges highlight the need for technological innovation, cost reduction, and integrated system optimization to fully realize hydrogen's role in a sustainable energy transition.

These systemic challenges highlight the need for technological innovation, cost reduction, and integrated system optimization to fully realize hydrogen's role in a sustainable energy transition. In this context, a closer examination of quantitative performance indicators—such as efficiency, power density, durability, and storage capacity—provides a clearer understanding of the remaining technical and economic barriers to large-scale deployment.

Proton exchange membrane fuel cells (PEMFCs), which are widely used in hydrogen mobility applications, typically achieve electrical efficiencies of approximately 50–60% under automotive operating conditions, with optimized systems exceeding 60% [39]. In terms of durability, automotive PEMFC systems have demonstrated operational lifetimes of 5,000–8,000 hours, whereas stationary systems may exceed 40,000 hours, depending on degradation mechanisms and operating conditions [40].

From a storage perspective, light-duty fuel cell vehicles typically store 5–6 kg of hydrogen at 700 bar, enabling driving ranges above 500 km [8]. However, compressing hydrogen to such high pressures requires additional energy input equivalent to approximately 10–15% of its lower heating value, thereby reducing overall system efficiency [37].

Economically, although the cost of PEMFC stacks has declined to approximately $\$70\text{--}80\text{ kW}^{-1}$ at scale, further reductions toward long-term targets below $\$30\text{ kW}^{-1}$ are necessary to achieve full

competitiveness [41]. In addition, high-pressure composite storage tanks remain a major cost component due to the extensive use of carbon fiber materials [8].

Collectively, these quantitative indicators demonstrate that while hydrogen technologies have reached significant technological maturity, improvements in efficiency, durability, storage density, and cost reduction remain critical for large-scale commercialization.

C. Hydrogen Storage Technologies

Hydrogen storage remains a fundamental challenge in the realization of a full hydrogen economy. Existing storage systems are categorized into physical storage, chemical storage, and solid-state storage. Although solid-state hydrogen storage is sometimes regarded as a subset of chemical storage, it is frequently discussed as a distinct category due to its unique hydrogen–material interaction mechanisms and technological characteristics, as illustrated in Figure 1.

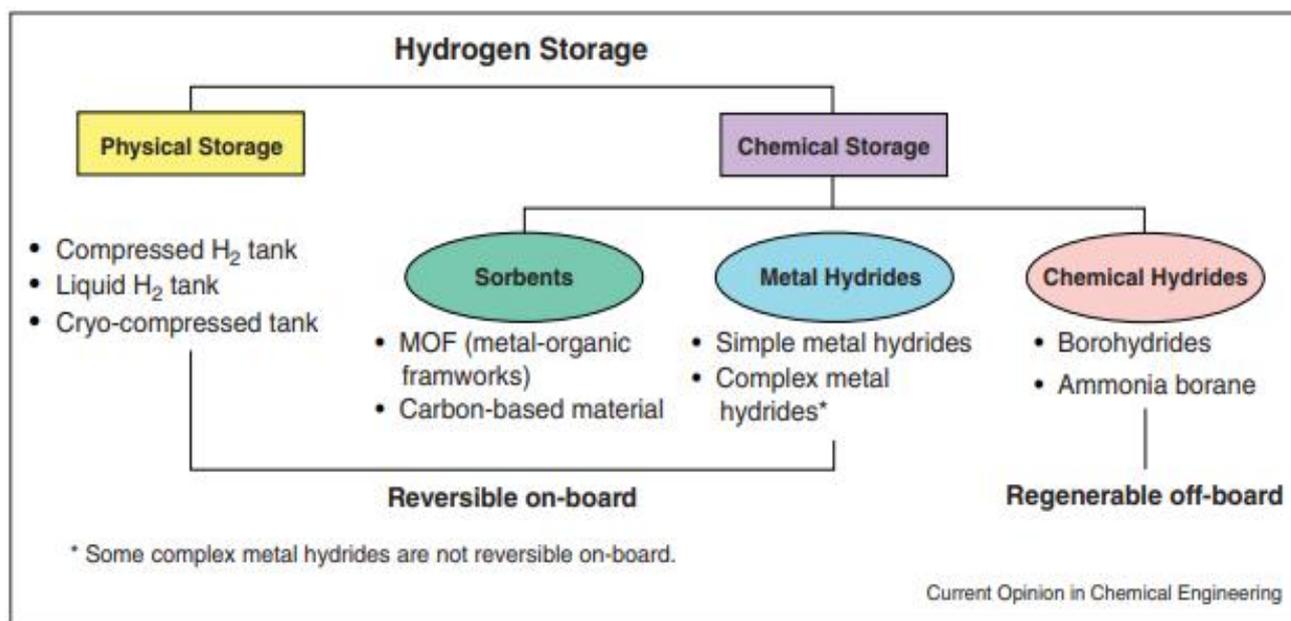


Figure 1. General methods of hydrogen storage [42].

Physical Hydrogen Storage

Physical hydrogen storage involves storing hydrogen without altering its chemical structure, typically in gaseous or liquid form. Compressed hydrogen stored at pressures of 350–700 bar is the most mature storage method. Modern Type-IV composite tanks offer good mechanical strength and relatively long lifetimes. However, high-pressure storage systems pose safety risks, require energy-intensive compression (approximately 10–15% of

hydrogen's energy content), and provide limited volumetric energy density [8].

To achieve higher hydrogen density, hydrogen can also be stored in liquid form through cryogenic liquefaction at -253 °C . Cryogenic tanks are commonly used in aerospace, heavy transportation, and industrial storage applications. Nevertheless, liquid hydrogen storage is associated with high energy consumption during liquefaction (approximately 30–40% of hydrogen's energy

content), boil-off losses over time, and the need for sophisticated insulation systems [3].

Chemical Hydrogen Storage

Chemical storage involves materials that release hydrogen through catalytic decomposition or hydrolysis. Common examples include ammonia (NH_3), formic acid (HCOOH), metal–organic liquids, and chemical hydrides such as ammonia borane (NH_3BH_3). These systems offer high gravimetric capacity but often suffer from limited reversibility and complex regeneration processes [9].

Solid State Hydrogen Storage

Solid-state hydrogen storage materials have attracted significant research interest due to their high volumetric density, improved safety, and potential for onboard hydrogen technologies. Based on the interaction between hydrogen and host materials, solid-state systems can be categorized into adsorption-based porous materials, metal hydrides (including complex hydrides), and chemical hydrides [9,43].

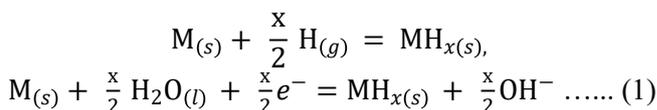
These categories differ in the fundamental nature of hydrogen–material interactions. In adsorption-based porous materials, hydrogen is stored via weak van der Waals forces (physisorption) with low enthalpy change (ΔH), resulting in fast and reversible storage but typically requiring low temperatures or high pressures to achieve significant capacity [44]. In contrast, metal hydrides involve chemisorption through the formation of metal–hydrogen bonds, leading to stronger binding energies and higher volumetric hydrogen density [45]. Complex and chemical hydrides store hydrogen through stronger ionic or covalent bonding within their crystal structures, which often provides high gravimetric capacity but may require elevated temperatures and careful thermodynamic management for hydrogen release [46].

1. Adsorption in Porous Materials

Hydrogen storage using porous materials has been extensively investigated. This method offers several advantages, including relatively high gravimetric capacity and fast adsorption–desorption kinetics. However, it also presents several limitations, such as metal clustering, the requirement for low operating temperatures or high pressures, and relatively weak interactions between the adsorbent material and hydrogen molecules [47]. Porous materials commonly employed for hydrogen storage via adsorption include carbon nanotubes (CNTs) [48–52], metal–organic frameworks (MOFs) [53–63], and zeolites [64–69].

2. Metal Hydrides

Metal hydrides are considered promising materials for hydrogen storage due to their high hydrogen storage capacity, flexible applicability, rapid charging and discharging characteristics, and high operational safety [70–72]. Hydrogen storage in metal hydrides typically occurs at relatively low temperatures and pressures, making these materials suitable for fuel cell applications. Metal hydrides are reversible chemical compounds formed through the reaction between metal alloys and hydrogen gas, in which hydrogen absorption is an exothermic process, while hydrogen desorption is endothermic [73]. A representative example is LaNi_5H_6 , which has been applied in proton-exchange membrane fuel cell (PEMFC) systems under operating pressures of 1–10 bar and temperatures ranging from 25 to 100 °C [42,71]. The formation reaction of metal hydrides can be seen in Reaction (1).



Beyond hydrogen storage, metal hydrides have been explored for various applications, including large-scale solid-state hydrogen storage combined with thermal energy storage, solar heat storage systems, sensing and smart window technologies based on reversible optical properties, and energy systems for transportation and underwater applications [74]. Among the diverse classes of metal hydrides, alkali and alkaline earth alanates as well as magnesium hydride (MgH_2) are regarded as particularly promising hydrogen storage media due to their high storage capacities and potential for practical implementation [75]–[77].

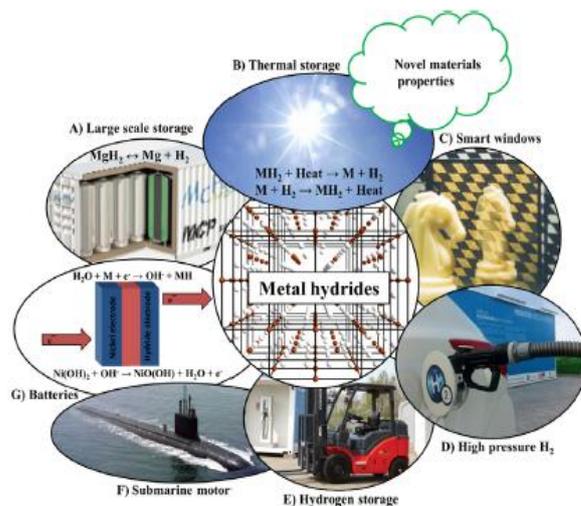


Figure 2. Schematic illustration of metal hydride applications [74].

Metal hydrides can also be applied in various other applications, as illustrated in **Figure 2**. Among the various classes of metal hydrides, complex hydrides particularly alanes have attracted significant attention due to their high gravimetric hydrogen storage capacity and potential for practical solid state hydrogen storage applications.

3. Alanates

Alanates are aluminum based complex hydrides that have attracted considerable attention as solid state hydrogen storage materials due to their high gravimetric hydrogen storage capacity and favorable thermodynamic characteristics. The most widely studied alanates include aluminum hydride (AlH_3), sodium alanate (NaAlH_4), and lithium alanate (LiAlH_4). **Figure 3** compares the gravimetric and volumetric hydrogen storage densities of various metal hydrides, highlighting the favorable hydrogen storage performance of alanates such as AlH_3 , NaAlH_4 , and LiAlH_4 relative to conventional metal hydrides [77-79].

Aluminum hydride (AlH_3) is a metastable crystalline solid at room temperature with an exceptionally high volumetric hydrogen density of approximately $148 \text{ g H}_2 \text{ L}^{-1}$ and a gravimetric hydrogen density exceeding 10 wt%. AlH_3 also exhibits a relatively low reaction enthalpy and fast hydrogen release at temperatures below $100 \text{ }^\circ\text{C}$, making it attractive for hydrogen storage applications [68]. However, its practical use is limited by the lack of direct hydrogen reversibility, despite favorable thermodynamic properties [80-82].

Sodium alanate (NaAlH_4) has been extensively investigated because it offers a promising balance between hydrogen storage capacity and potential

reversibility. Nevertheless, NaAlH_4 suffers from slow reaction kinetics and requires elevated temperatures and pressures for hydrogen desorption [84]. The addition of catalysts, particularly titanium based and other transition metal compounds, has been shown to significantly improve reaction kinetics, lower desorption temperatures, and enable reversibility under practical conditions [14][39, [85] [86] [87] [88]. NaAlH_4 can be synthesized through mechanical milling followed by hydrogenation assisted by catalysts or dopants [89].

Lithium alanate (LiAlH_4) exhibits a higher theoretical gravimetric hydrogen storage capacity of approximately 10 wt% compared to NaAlH_4 [90]. It is classified as a kinetically stabilized hydride with relatively low reaction enthalpy and high equilibrium hydrogen pressure at moderate temperatures [91]. However, similar to NaAlH_4 , LiAlH_4 is limited by slow hydrogen absorption and desorption kinetics, primarily due to high activation energy barriers and sluggish solid-state diffusion during its multi-step decomposition reactions, as well as high desorption temperatures. Strategies such as ball milling and the incorporation of titanium based catalysts, carbon based materials, and metal halides have been widely applied to enhance its hydrogen desorption behavior [14][39, [92] [93]–[106]. Overall, alanates provide significantly higher gravimetric hydrogen storage capacities than conventional metal hydrides such as MgH_2 and FeTi , but challenges related to kinetics, desorption temperature, and reversibility remain. Continued development of catalytic and nanostructuring strategies is therefore essential for their practical application.

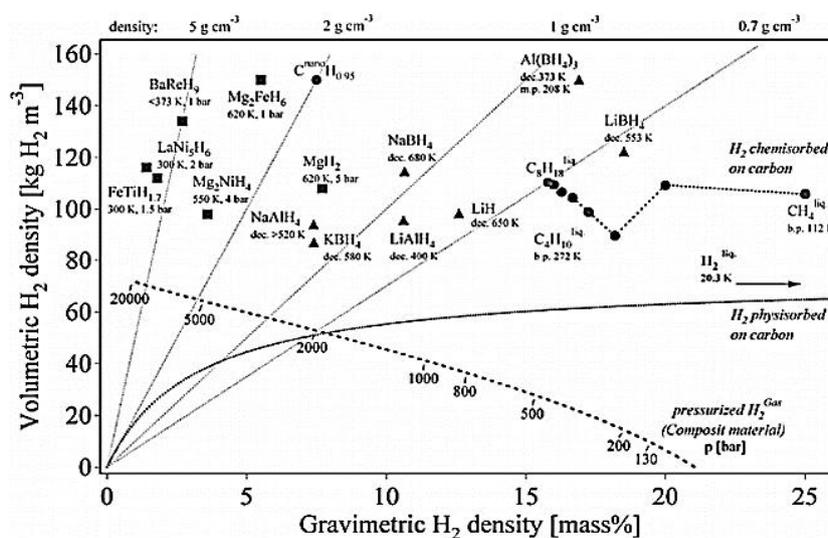


Figure 3. Curves of several metal hydrides in terms of gravimetric and volumetric hydrogen density [83].

4. Chemical Hydrides

Chemical hydrides that are currently being intensively investigated include amides and borohydrides. Within this class of materials, borohydrides and liquid organic hydrides have attracted significant attention due to their high hydrogen storage capacities and their potential applicability in fuel cell systems. Chemical hydrides offer good volumetric hydrogen storage capacity at ambient conditions and enable hydrogen release at relatively low temperatures and pressures when appropriate catalysts are employed [107]. However, their practical implementation is still challenged by the lack of feasible on board regeneration and the requirement for efficient thermal management systems. Consequently, the development of energy efficient and cost effective regeneration processes remains a critical issue [108]. Within this category, borohydrides and liquid organic hydrides represent two major classes of chemical hydrides, distinguished by their hydrogen bonding characteristics and hydrogen release mechanisms

Borohydrides

Among various chemical hydrides, borohydrides are regarded as promising hydrogen storage materials due to their exceptionally high hydrogen content, which often exceeds 10 wt%. For example, LiBH_4 exhibits a theoretical hydrogen storage capacity of up to 18 wt%, while NaBH_4 also possesses a high hydrogen content; however, its practical application is limited by challenges associated with regeneration processes [109].

Ammonia borane (NH_3BH_3) is one of the most extensively studied borohydrides owing to its very high hydrogen content of approximately 19.6 wt%, as well as the relatively low flammability and toxicity of its spent fuel products [74]. NH_3BH_3 decomposes through multiple reaction steps, releasing hydrogen at moderate temperatures. Nevertheless, its practical use is constrained by irreversible hydrogen release, by-product formation, and complex regeneration chemistry.

Hydrogen can also be generated from ammonia borane via catalyzed hydrolysis, which is initiated by the controlled addition of water. Despite this advantage, borohydrides generally suffer from high dehydrogenation temperatures, formation of thermodynamically stable intermediates, and poor reversibility resulting from strong B–H bonds [109]. To address these limitations, chemical hydride fuel systems have been developed using high-energy ball milling of ammonia borane with Ni–Co/r-GO

catalysts, which has been shown to significantly enhance hydrogen generation performance [107].

Liquid Organic Hydrides

Liquid organic hydrides constitute another important category of chemical hydrides for hydrogen storage applications. Cycloalkanes are considered suitable hydrogen carriers due to their relatively high gravimetric hydrogen storage capacity of approximately 6.5 wt% and high volumetric hydrogen density of about $60.62 \text{ kg H}_2 \text{ m}^{-3}$ [110]. Hydrogen storage using liquid organic hydrides is based on reversible catalytic dehydrogenation of cycloalkanes such as methylcyclohexane, cyclohexane, and decalin, coupled with the corresponding hydrogenation of aromatic compounds. Aromatic hydrogenation is a well established industrial process, making liquid organic hydride systems a promising approach for hydrogen storage, transportation, and on demand hydrogen supply for proton exchange membrane fuel cell applications [110].

Despite the promising hydrogen storage capacities and practical advantages offered by chemical hydrides such as borohydrides and liquid organic hydrides, their real world application is ultimately governed by thermodynamic and kinetic limitations. The efficiency of hydrogen release and uptake, operating temperature, reaction reversibility, and overall system performance are strongly influenced by the thermodynamic stability of the hydride and the kinetics of hydrogenation and dehydrogenation reactions. Therefore, a fundamental understanding of thermodynamic and kinetic properties is essential for evaluating and optimizing hydrogen storage materials, regardless of their chemical classification.

Hydrogen diffusion in metal hydrides primarily occurs through interstitial sites within the metal lattice and is strongly affected by microstructural defects such as vacancies, dislocations, and grain boundaries, which can act as trapping sites and modify the effective hydrogen diffusivity [111]. In addition, reducing particle size to the nanoscale shortens diffusion pathways and increases surface to volume ratio, thereby lowering activation energy barriers and enhancing hydrogen absorption–desorption kinetics [112]. The overall phase transformation kinetics in metal hydrides are governed by nucleation and growth mechanisms, where interfacial energy and phase boundary migration can introduce significant kinetic limitations during hydrogenation and dehydrogenation processes [113]. Moreover, interfacial engineering strategies have been demonstrated to facilitate hydrogen transport across

phase boundaries and improve reaction kinetics in composite hydride systems [114].

D. Thermodynamic and Kinetic Properties

The thermodynamic and kinetic properties of hydrogen storage materials can be improved by controlling particle size and employing suitable catalysts [115]. From a thermodynamic standpoint, the dehydrogenation temperature can be reliably estimated using the enthalpy change ΔH and entropy change ΔS of the dehydrogenation reaction [83]. The thermodynamic behavior of metal hydrides is commonly described by the van't Hoff relationship [72,116,117]:

$$\ln P = -\frac{\Delta S^\circ}{R} + \frac{\Delta H^\circ}{RT} \dots \dots \dots (2)$$

where P is the equilibrium hydrogen pressure, T is the temperature, ΔH° is the standard reaction enthalpy, ΔS° is the standard reaction entropy, and R is the universal gas constant [43,64,70,72,116]. This equation highlights the intrinsic trade off between equilibrium pressure and operating temperature during hydrogen absorption and desorption processes. Accordingly, the thermodynamic behavior of hydrogen itself plays a critical role in storage system design. Selected thermodynamic properties of hydrogen at 25 °C and 1 atm are therefore presented in **Table 5** for reference.

Table 5. Thermodynamic Properties of Hydrogen at 25 °C and 1 atm

Property	Value
Specific volume (m ³ /kg)	12.1
Density of liquid at atmospheric pressure (kg/m ³)	71.0
Absolute viscosity (centipoise)	0.009
Speed of sound in gas (m/s)	1315
Specific heat, c_p (kJ/kg·K)	14.310
Specific heat ratio, c_p/c_v	1.405
Gas constant, R (kJ/kg·K)	4.126
Thermal conductivity (W/m·°C)	0.182
Boiling point at saturation pressure of 1 atm (K)	20.4
Latent heat of evaporation at boiling point (kJ/kg)	447
Freezing or melting point at 1 atm (°C)	-259.1
Latent heat of fusion (J/kg)	58,000
Critical temperature (°C)	-240.0
Critical pressure (MN/m ²)	1.30
Critical volume (m ³ /kg)	0.033
Heat of combustion (kJ/kg)	144,000

In addition to thermodynamics, reaction kinetics play a decisive role in determining the practical usability of hydrogen storage systems. The kinetics of hydrogenation and dehydrogenation reactions are governed by the activation energy barrier and the reaction rate constant, which follows the Arrhenius relationship [21]. High activation energies and low operating temperatures significantly slow reaction rates, thereby limiting hydrogen release and uptake under practical conditions.

For hydrogen storage applications operating at relatively low temperatures, minimizing the activation energies for both dehydrogenation and hydrogenation reactions is therefore essential [83]. This can be achieved through catalytic doping and hydride destabilization strategies, which effectively lower energy barriers and enhance reaction kinetics [115]. While thermodynamic improvements have been realized through approaches such as hydride coupling,

partial cation substitution, and stabilization of decomposition products [3,33]. these methods often have limited impact on kinetics. As a result, the incorporation of suitable catalysts is frequently required to further reduce activation energy barriers and achieve fast and reversible hydrogen storage behavior [115].

CONCLUSION

Hydrogen has considerable potential as a clean energy carrier, yet its large-scale deployment is primarily constrained by limitations in hydrogen storage technologies. Conventional physical storage methods, including compressed and liquid hydrogen, face challenges related to safety, energy efficiency, and volumetric density. Consequently, solid-state hydrogen storage has gained increasing attention as a promising alternative capable of operating under safer and more compact conditions.

This review has discussed key classes of solid-state hydrogen storage materials, including adsorption-based materials, metal hydrides, complex hydrides such as alanates, and chemical hydrides encompassing borohydrides and liquid organic hydrides. Each class exhibits distinct advantages and limitations in terms of storage capacity, thermodynamic stability, kinetic behavior, and reversibility. Despite significant progress, no single material system currently fulfills all practical requirements. Therefore, future advancements in hydrogen storage will depend on a fundamental understanding of thermodynamic and kinetic processes, coupled with material design strategies and catalytic approaches to achieve efficient, safe, and scalable hydrogen storage systems.

ACKNOWLEDGMENT

The authors would like to thank the University of Bengkulu and the Faculty of Mathematics and Natural Sciences for the permission and full support given to the author in conducting this research in the Physical Chemistry Laboratory.

REFERENCES

- [1] R. A. Varin, T. Czujko, Z. S. Wronski, P. Prachi, M. M. Wagh, and G. Aneesh, "Chapter 2 ' Heart ' of Solid State Hydrogen Storage," *Advance in Energy Power*, vol. 4, no. 2, pp. 11–22, 2009.
- [2] B. Sakintuna, Lamari-Darkrim, Farida, and M. Hirscher, "Metal hydride materials for solid hydrogen storage: A review," *International Journal of Hydrogen Energy*, vol. 32, no. 9, pp. 1121–1140, 2007.
- [3] M. Hirscher, V. A. Yartys, M. Baricco, J. B. von Colbe, D. Blanchard, R. C. Bowman, Jr., D. P. Broom, C. E. Buckley, F. Chang, P. Chen, Y. W. Cho, J.-C. Crivello, F. Cuevas, W. I. F. David, P. E. de Jongh, R. V. Denys, M. Dornheim, M. Felderhoff, Y. Filinchuk, G. E. Froudakis, D. M. Grant, E. M. A. Gray, B. C. Hauback, T. He, T. D. Humphries, T. R. Jensen, S. Kim, Y. Kojima, M. Latroche, H.-W. Li, M. V. Lototsky, J. W. Makepeace, K. T. Møller, L. Naheed, P. Ngene, D. Noréus, M. M. Nygård, S.-i. Orimo, M. Paskevicius, L. Pasquini, D. B. Ravnsbæk, M. V. Sofianos, T. J. Udovic, T. Vegge, G. S. Walker, C. J. Webb, C. Weidenthaler, and C. Zlotea, "Materials for hydrogen-based energy storage – Past, recent progress and future outlook," *J. Alloys Compd.*, p. 153548, 2019.
- [4] I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah, and K. R. Ward, "Environmental Science The role of hydrogen and fuel cells in the global energy system," *Energy and Environmental Science*, no. 12, p. 463, 2018.
- [5] A.M. Sadeq, R.Z. Homod, A. K. Hussein, H. Togun, A. Mahmoodi, H. F. Isleem, A. R. Patil, and A. H. Moghaddam, "Hydrogen energy systems: Technologies, trends, and future prospects," *Science of the Total Environment*, vol. 939, no. April, p. 173622, 2024.
- [6] G. Glenk and S. Reichelstein, "hydrogen," *Nature Energy*, 2017.
- [7] A. Saeedmanesh, M. A. Mac Kinnon, and J. Brouwer, "Hydrogen is essential for sustainability," *Current Opinion in Electrochemistry*, vol. 12, pp. 166–181, 2018.
- [8] R. K. Ahluwalia, T. Q. Hua, and J. K. Peng, "On-board and Off-board performance of hydrogen storage options for light-duty vehicles," *International Journal of Hydrogen Energy*, vol. 37, no. 3, pp. 2891–2910, 2012.
- [9] G. Walker, *Solid-state hydrogen storage*. 2010.
- [10] S. Kumar and H. Oh, "Sustainable Energy & Fuels," vol. 10, no. 4, 2026.
- [11] F. Ding and B. I. Yakobson, "Challenges in hydrogen adsorptions : from physisorption to chemisorption," *Frontiers of Physics*, vol. 6, no. 2, pp. 142–150, 2015.
- [12] K. Soni and N. L. Panwar, "Emergence of carbonaceous material for hydrogen storage : an overview," vol. 8, no. 4, pp. 147–168, 2024.
- [13] H. Cheng, L. Chen, A. C. Cooper, and G. P. Pez, "Hydrogen spillover in the context of hydrogen storage using solid-state materials," pp. 338–354, 2008.
- [14] C. Milanese, S. Garroni, F. Gennari, A. Marini, T. Klassen, M. Dornheim, and C. Pistidda, "Solid state hydrogen storage in alanates and alanate-based compounds: A review," *Metals (Basel)*, vol. 8, no. 8, pp. 1–15, 2018.
- [15] M. Lototsky, I. Tolj, Y. Klochko, M. W. Davids, D. Swanepoel, and V. Linkov, "Metal hydride hydrogen storage tank for fuel cell utility vehicles," *International Journal of Hydrogen Energy*, 2019.
- [16] V. Stavila, R. K. Bhakta, T. M. Alam, E. H. Majzoub, and M. D. Allendorf, "Reversible hydrogen storage by NaAlH₄ confined within a titanium-functionalized MOF-74(Mg) nanoreactor," *ACS Nano*, vol. 6, no. 11, pp. 9807–9817, 2012.

- [17] K. Z. Patil, *Hydrogen*, vol. 38, no. 10, 1997.
- [18] A. Keçebaş and M. Kayfeci, "Hydrogen properties," *Sol. Hydrog. Prod. Process. Syst. Technol.*, pp. 3–29, 2019.
- [19] S. W. Lee, H. S. Lee, Y. J. Park, and Y. S. Cho, "Combustion and emission characteristics of HCNG in a constant volume chamber," *Journal of Mechanical Engineering Science and Technology*, vol. 25, no. 2, pp. 489–494, 2011.
- [20] K. Mazloomi and C. Gomes, "Hydrogen as an energy carrier: Prospects and challenges," *Renewable and Sustainable Energy Review*, vol. 16, no. 5, pp. 3024–3033, 2012.
- [21] M. D. and G. C. Vincent, B., Gregg R., "Size effects on the hydrogen storage properties of nanostructured metal hydrides: A Review," *International Journal of Energy Research*, vol. 31, no. 4, pp. 637–663, 2007.
- [22] V. Ananthachar and J. J. Duffy, "Efficiencies of hydrogen storage systems onboard fuel cell vehicles," *Solar Energy*, vol. 78, no. 5, pp. 687–694, 2005.
- [23] J. Sarkar and S. Bhattacharyya, "Application of graphene and graphene-based materials in clean energy-related devices Minghui," *Archives of Thermodynamics*, vol. 33, no. 4, pp. 23–40, 2012.
- [24] R. A. Felseghi, E. Carcadea, M. S. Raboaca, C. N. Trufin, and C. Filote, "Hydrogen fuel cell technology for the sustainable future of stationary applications," *Energies*, vol. 12, no. 23, 2019.
- [25] L. Wang, Y. Hong, E. Liu, Z. Wang, J. Chen, S. Yang, J. Wang, X. Lin, and J. Shi, "ScienceDirect Rapid polymerization synthesizing high- crystalline g-C 3 N 4 towards boosting solar photocatalytic H 2 generation," *International Journal of Hydrogen Energy*, no. xxxx, 2020.
- [26] A. M. Hussein, K. Kadirgama, and M. M. Noor, "Nanoparticles suspended in ethylene glycol thermal properties and applications : An overview," *Renew. Sustain. Energy Rev.*, no. June 2015, pp. 0–1, 2016.
- [27] C. Mansilla, C. Bourasseau, C. Cany, B. Guinot, A. Le Duigou, and P. Lucchese, *Hydrogen applications: Overview of the key economic issues and perspectives*. Elsevier Ltd., 2018.
- [28] F. Zhang and P. Cooke, "Hydrogen and fuel cell development in China: A review," *European Planning Studies*, vol. 18, no. 7, pp. 1153–1168, 2010.
- [29] K. Volkart, M. Densing, R. De Miglio, T. Priem, S. Pye, and B. Cox, *The Role of Fuel Cells and Hydrogen in Stationary Applications*. Elsevier Inc., 2017.
- [30] S. C. Singhal, "Solid oxide fuel cells for stationary, mobile, and military applications," *Solid State Ionics*, vol. 152–153, pp. 405–410, 2002..
- [31] O. Abdul Rosyid, "Infrastruktur Hidrogen Untuk Aplikasi Fuel Cell," pp. 1–2, 2009, [Online]. Available: <https://media.neliti.com>.
- [32] P. Ferreira-Aparicio and A. M. Chaparro, *Why portable electricity with hydrogen fuel cells?* Elsevier Inc., 2018.
- [33] Q. Lai, M. Paskevicius, D. A. Sheppard, C. E. Buckley, A. W. Thornton, M. R. Hill, Q. Gu, J. Mao, Z. Huang, H. K. Liu, Z. Guo, A. Banerjee, S. Chakraborty, R. Ahuja, and K.-F. Aguey-Zinsou, "Hydrogen Storage Materials for Mobile and Stationary Applications: Current State of the Art," *ChemSusChem*, vol. 8, no. 17, pp. 2789–2825, 2015.
- [34] P. P. Kundu and K. Dutta, *Hydrogen fuel cells for portable applications*, no. c. Elsevier Ltd., 2016.
- [35] Colpan, "Portable fuel cells – fundamentals, technologies and applications C. O. Colpan 1 , I. Dincer 2* , and F. Hamdullahpur 1 1," 2008.
- [36] A. R. Kalidindi, R. Taspinar, S. Litster, and E. C. Kumbur, "A two-phase model for studying the role of microporous layer and catalyst layer interface on polymer electrolyte fuel cell performance," *International Journal of Hydrogen Energy*, vol. 38, no. 22, pp. 9297–9309, 2013.
- [37] H. J. Ā, Y. Jiang, Y. Wang, Z. Ma, and Y. Yao, "An experimental study on a modified air conditioner with a domestic hot water supply (ACDHWS)," vol. 31, pp. 1789–1803, 2006.
- [38] D. D. Demir, A. Salcı, and R. Solmaz, "ScienceDirect Fabrication of Mo-modified carbon felt as candidate substrate for electrolysis : Optimization of pH , current and metal amount *," *International Journal of Hydrogen Energy*, pp. 1–9, 2018.
- [39] R. Alamian, R. Shafaghat, S. J. Miri, and N. Yazdanshenas, "Evaluation of technologies for harvesting wave energy in Caspian Sea," *Renewable and Sustainable Energy Review*, vol. 32, pp. 468–476, 2014.
- [40] H. Kreutzer, V. Yarlalagadda, and T. Van Nguyen, "Performance Evaluation of a

- Regenerative Hydrogen-Bromine Fuel Cell*," vol. 159, no. 7, 2012, doi: 10.1149/2.086207jes.
- [41] O. J. Vickers, D. Peterson, K. Randolph, E. Miller, and S. Satyapal, "Table 1 – Hydrogen costs for PEM electrolysis from H₂A with associated inputs of electricity cost, capacity factor, and uninstalled system capital cost. 4," pp. 5–9, 2020.
- [42] H. T. Hwang and A. Varma, "Hydrogen storage for fuel cell vehicles," *Curr. Opin. Chem. Eng.*, vol. 5, pp. 42–48, 2014.
- [43] S. State and H. Storage, *Handbook of Hydrogen Storage*. 2011.
- [44] S. S. A. Al Kareem, Q. Hassan, H. F. Fakhruddin, T. M. Hanoon, F. I. Jabbar, S. Algburi, and D. H. Khalaf, "A review on physical and chemical hydrogen storage methods for sustainable energy applications," *Unconventional Resources*, vol. 8, no. June, p. 100235, 2025.
- [45] E. Nemukula, C. B. Mtshali, and F. Nemangwele, "Review Article Metal Hydrides for Sustainable Hydrogen Storage: A Review," vol. 2025, 2025.
- [46] M. Altaf, U. B. Demirci, and A. K. Haldar, "Review of solid-state hydrogen storage: Materials categorisation, recent developments, challenges and industrial perspectives," *Energy Reports*, vol. 13, no. January, pp. 5746–5772, 2025.
- [47] S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and perspectives," *Renewable and Sustainable Energy Review*, vol. 50, pp. 457–469, 2015.
- [48] S. M. Lee and Y. H. Lee, "Hydrogen storage in single-walled carbon nanotubes," *Applied Physics Letters*, vol. 76, no. 20, pp. 2877–2879, 2000.
- [49] Seung Mi Lee, Kay Hyeok An, Young Hee Lee, G. Seifert, and T. Frauenheim, "A hydrogen storage mechanism in single-walled carbon nanotubes," *Journal of the American Chemical Society*, vol. 123, no. 21, pp. 5059–5063, 2001.
- [50] Y. Chen, D. T. Shaw, X. D. Bai, E. G. Wang, C. Lund, W. M. Lu, and D. D. L. Chung, "Hydrogen storage in aligned carbon nanotubes," *Appl. Phys. Lett.*, vol. 78, no. 15, pp. 2128–2130, 2001.
- [51] C. Liu, Y. Chen, C. Z. Wu, S. T. Xu, and H. M. Cheng, "Hydrogen storage in carbon nanotubes revisited," *Carbon N. Y.*, vol. 48, no. 2, pp. 452–455, 2010.
- [52] E. Yoo, L. Gao, T. Komatsu, N. Yagai, K. Arai, T. Yamazaki, K. Matsuishi, T. Matsumoto, and J. Nakamura, "Atomic hydrogen storage in carbon nanotubes promoted by metal catalysts," *Journal of Physical Chemistry B*, vol. 108, no. 49, pp. 18903–18907, 2004.
- [53] Y. Li and R. T. Yang, "Significantly enhanced hydrogen storage in metal-organic frameworks via spillover," *Journal of the American Chemical Society*, vol. 128, no. 3, pp. 726–727, 2006.
- [54] P. Rahayu and W. W. Lestari, "Study of Synthesis and Characterization of Metal-Organic Frameworks Mof-5 As Hydrogen Storage Material," *ALCHEMY J. Penelitian Kimia*, vol. 12, no. 1, p. 14, 2016.
- [55] A. Blomqvist, C. M. Araújo, P. Srepusharawoot, and R. Ahuja, "Li-decorated metal-organic framework 5: A route to achieving a suitable hydrogen storage medium," *Proceedings of the National Academy of Sciences U.S.A.*, vol. 104, no. 51, pp. 20173–20176, 2007.
- [56] X. Gu, Z. H. Lu, H. L. Jiang, T. Akita, and Q. Xu, "Synergistic catalysis of metal-organic framework-immobilized au-pd nanoparticles in dehydrogenation of formic acid for chemical hydrogen storage," *Journal of the American Chemical Society*, vol. 133, no. 31, pp. 11822–11825, 2011.
- [57] N. L. Rosi, J. Eckert, M. Eddaoudi, D. T. Vodak, J. Kim, M. O'Keeffe, and O. M. Yaghi, "Hydrogen Storage in Microporous Metal-Organic Frameworks," *Science (80-.)*, vol. 73, no. 1973, pp. 12–15, 2002.
- [58] L. Xia, Z. Bo, Q. Liu, X. Zhang, and Y. Pei, "Li-doped and functionalized metal-organic framework-519 for enhancing hydrogen storage: A computational study," *Computational Materials Science*, vol. 166, no. April 2019, pp. 179–186, 2019.
- [59] J. Li, S. Cheng, Q. Zhao, P. Long, and J. Dong, "Synthesis and hydrogen-storage behavior of metal-organic framework MOF-5," *Int. J. Hydrogen Energy*, vol. 34, no. 3, pp. 1377–1382, 2009.
- [60] Y. E. Cheon and M. P. Suh, "Enhanced hydrogen storage by palladium nanoparticles fabricated in a redox-active metal-organic framework," *Angew. Chemie - Int. Ed.*, vol. 48, no. 16, pp. 2899–2903, 2009.

- [61] M. Dincă, W. S. Han, Y. Liu, A. Dailly, C. M. Brown, D. A. Neumann, and J. R. Long, "Hydrogen storage in a microporous metal-organic framework with exposed Mn²⁺ coordination sites," *Journal of the American Chemical Society*, vol. 128, no. 51, pp. 16876–16883, 2006.
- [62] Q.-R. Fang, G.-S. Zhu, Z. Jin, Y.-Y. Ji, J.-W. Ye, M. Xue, H. Yang, Y. Wang, and S.-L. Qiu, "Mesoporous Metal-Organic Framework with Rare etb Topology for Hydrogen Storage and Dye Assembly," *Angew. Chemie*, vol. 119, no. 35, pp. 6758–6762, 2007.
- [63] P. Krawiec, M. Kramer, M. Sabo, R. Kunschke, H. Fröde, and S. Kaskel, "Improved hydrogen storage in the Metal-Organic Framework Cu₃(BTC)₂," *Advanced Engineering Materials*, vol. 8, no. 4, pp. 293–296, 2006.
- [64] A. Pacuła and R. Mokaya, "Synthesis and high hydrogen storage capacity of zeolite-like carbons nanocast using as-synthesized zeolite templates," *Journal of Physical Chemistry C*, vol. 112, no. 7, pp. 2764–2769, 2008.
- [65] H. Nishihara, P. X. Hou, L. X. Li, M. Ito, M. Uchiyama, T. Kaburagi, A. Ikura, J. Katamura, T. Kawarada, K. Mizuuchi, and T. Kyotani, "High-pressure hydrogen storage in zeolite-templated carbon," *Journal of Physical Chemistry C*, vol. 113, no. 8, pp. 3189–3196, 2009.
- [66] N. P. Stadie, J. J. Vajo, R. W. Cumberland, A. A. Wilson, C. C. Ahn, and B. Fultz, "Zeolite-templated carbon materials for high-pressure hydrogen storage," *Langmuir*, vol. 28, no. 26, pp. 10057–10063, 2012.
- [67] Y. Xia, R. Mokaya, D. M. Grant, and G. S. Walker, "A simplified synthesis of N-doped zeolite-templated carbons, the control of the level of zeolite-like ordering and its effect on hydrogen storage properties," *Carbon N.Y.*, vol. 49, no. 3, pp. 844–853, 2011.
- [68] Z. Yang, Y. Xia, X. Sun, and R. Mokaya, "Preparation and Hydrogen Storage Properties of Zeolite-Templated Carbon Materials.pdf," *Journal of Physical Chemistry B*, vol. 110, pp. 18424–18431, 2006.
- [69] Z. Yang, Y. Xia, and R. Mokaya, "Enhanced hydrogen storage capacity of high surface area zeolite-like carbon materials," *Journal of the American Chemical Society*, vol. 129, no. 6, pp. 1673–1679, 2007.
- [70] O. Bernauer, "Development of hydrogen-hydride technology in the F.R.G.," *Int. J. Hydrogen Energy*, vol. 14, no. 10, pp. 727–735, 1989.
- [71] M. Bhourri, M. Linder, and I. Bürger, "Metal hydride reactor for dual use: Hydrogen storage and cold production," *International Journal of Hydrogen Energy*, vol. 43, no. 52, pp. 23357–23371, 2018.
- [72] L. Pickering, F. Barbir, V. Yartys, M. V. Lototskyy, I. Tolj, and C. Sita, "The use of metal hydrides in fuel cell applications," *Progress in Natural Science: Materials International*, vol. 27, no. 1, pp. 3–20, 2017.
- [73] K. Malleswararao, A. N. S. Srinivasa Murthy, and P. Dutta, "Performance prediction of a coupled metal hydride based thermal energy storage system," *International Journal of Hydrogen Energy*, vol. 45, no. 32, pp. 16239–16253, 2020.
- [74] M. B. Ley, L. H. Jepsen, Y. S. Lee, Y. W. Cho, J. M. Bellosta von Colbe, M. Dornheim, M. Rokni, J. O. Jensen, M. Sloth, Y. Filinchuk, J. E. Jørgensen, F. Besenbacher, and T. R. Jensen, "Complex hydrides for hydrogen storage - New perspectives," *Materials Today*, vol. 17, no. 3, pp. 122–128, 2014.
- [75] J. Andersson and S. Grönkvist, "Large-scale storage of hydrogen," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 11901–11919, 2019.
- [76] S. V. Alapati, J. K. Johnson, and D. S. Sholl, "Identification of destabilized metal hydrides for hydrogen storage using first principles calculations," *Journal of Physical Chemistry B*, vol. 110, no. 17, pp. 8769–8776, 2006.
- [77] J. Graetz, J. J. Reilly, V. A. Yartys, J. P. Maehlen, B. M. Bulychev, V. E. Antonov, B. P. Tarasov, and I. E. Gabis, "Aluminum hydride as a hydrogen and energy storage material: Past, present and future," *Journal of Alloys Compound*, vol. 509, no. SUPPL. 2, pp. S517–S528, 2011.
- [78] J. Wang, A. D. Ebner, and J. A. Ritter, "On the reversibility of hydrogen storage in novel complex hydrides," *Adsorption*, vol. 11, no. 1 SUPPL., pp. 811–816, 2005.
- [79] C. P. Baldé, B. P. C. Hereijgers, J. H. Bitter, and K. P. De Jong, "Sodium alanate nanoparticles - Linking size to hydrogen storage properties," *Journal of the American Chemical Society*, vol. 130, no. 21, pp. 6761–6765, 2008.
- [80] S. Orimo, Y. Nakamori, T. Kato, C. Brown,

- and C. M. Jensen, "Intrinsic and mechanically modified thermal stabilities of α -, β - and γ -aluminum trihydrides AlH_3 ," *Applied Physics A: Materials Science and Processing*, vol. 83, no. 1, pp. 5–8, 2006.
- [81] G. C. Sinke, L. C. Walker, F. L. Oetting, and D. R. Stull, "Thermodynamic properties of aluminum hydride," *Journal of Chemical Physics*, vol. 47, no. 8, pp. 2759–2761, 1967.
- [82] J. Graetz and J. J. Reilly, "Thermodynamics of the α , β and γ polymorphs of AlH_3 ," *Journal of Alloys and Compounds*, vol. 424, no. 1–2, pp. 262–265, 2006.
- [83] A. Züttel, P. Wenger, S. Rentsch, P. Sudan, P. Mauron, and C. Emmenegger, "LiBH₄ a new hydrogen storage material," *Journal of Power Sources*, vol. 118, no. 1–2, pp. 1–7, 2003.
- [84] K. Manickam, P. Mistry, G. Walker, D. Grant, C. E. Buckley, T. D. Humphries, M. Paskevicius, T. Jensen, R. Albert, K. Peinecke, and M. Felderhoff, "Future Perspectives of thermal energy storage with metal hydrides," *International Journal of Hydrogen Energy*, vol. xxx, no. 1, p. 2, 2018.
- [85] H. Wang, H. J. Lin, W. T. Cai, L. Z. Ouyang, and M. Zhu, "Tuning kinetics and thermodynamics of hydrogen storage in light metal element based systems - A review of recent progress," *Journal of Alloys and Compounds*, vol. 658, pp. 280–300, 2016.
- [86] A. G. Haiduc, H. A. Stil, M. A. Schwarz, P. Paulus, and J. J. C. Geerlings, "On the fate of the Ti catalyst during hydrogen cycling of sodium alanate," *Journal of Alloys and Compounds*, vol. 393, no. 1–2, pp. 252–263, 2005.
- [87] E. H. Majzoub, F. Zhou, and V. Ozoliņš, "First-principles calculated phase diagram for nanoclusters in the Na-Al-H system: A single-step decomposition pathway for NaAlH_4 ," *Journal of Physical Chemistry C*, vol. 115, no. 6, pp. 2636–2643, 2011.
- [88] T. Mueller and G. Ceder, "Effect of particle size on hydrogen release from sodium alanate nanoparticles," *ACS Nano*, vol. 4, no. 10, pp. 5647–5656, 2010.
- [89] B. Bogdanović, R. A. Brand, A. Marjanović, M. Schwickardi, and J. Tölle, "Metal-doped sodium aluminium hydrides as potential new hydrogen storage materials," *Journal of Alloys and Compounds*, vol. 302, no. 1–2, pp. 36–58, 2000.
- [90] M. Resan, M. D. Hampton, J. K. Lomness, and D. K. Slattery, "Effects of various catalysts on hydrogen release and uptake characteristics of LiAlH_4 ," *International Journal of Hydrogen Energy*, vol. 30, no. 13–14, pp. 1413–1416, 2005.
- [91] R. D. Zysler, C. P. Arciprete, and M. I. Dimitrijewits, "Synthesis of α - Fe_2O_3 Nanoparticles," pp. 481–486, 1998.
- [92] S. S. Muir and X. Yao, "Progress in sodium borohydride as a hydrogen storage material: Development of hydrolysis catalysts and reaction systems," *International Journal of Hydrogen Energy*, vol. 36, no. 10, pp. 5983–5997, 2011.
- [93] J. Chen, N. Kuriyama, Q. Xu, H. T. Takeshita, and T. Sakai, "Reversible hydrogen storage via titanium-catalyzed LiAlH_4 and Li_3AlH_6 ," *Journal of Physical Chemistry B*, vol. 105, no. 45, pp. 11214–11220, 2001.
- [94] V. P. Balema, J. W. Wiench, K. W. Dennis, M. Pruski, and V. K. Pecharsky, "Titanium catalyzed solid-state transformations in LiAlH_4 during high-energy ball-milling," *Journal of Alloys and Compounds*, vol. 329, no. 1–2, pp. 108–114, 2001.
- [95] L. Li, F. Qiu, Y. Wang, Y. Xu, C. An, G. Liu, L. Jiao, and H. Yuan, "Enhanced hydrogen storage properties of TiN- LiAlH_4 composite," *International Journal of Hydrogen Energy*, vol. 38, no. 9, pp. 3695–3701, 2013.
- [96] S. Zhou, J. Zou, X. Zeng, and W. Ding, "Effects of REF₃ (RE = Y, La, Ce) additives on dehydrogenation properties of LiAlH_4 ," *International Journal of Hydrogen Energy*, vol. 39, no. 22, pp. 11642–11650, 2014.
- [97] C. Y. Tan and W. T. Tsai, "Catalytic and inhibitive effects of Pd and Pt decorated MWCNTs on the dehydrogenation behavior of LiAlH_4 ," *International Journal of Hydrogen Energy*, vol. 40, no. 32, pp. 10185–10193, 2015.
- [98] J. R. Ares, K. F. Aguey-Zinsou, M. Porcu, J. M. Sykes, M. Dornheim, T. Klassen, and R. Bormann, "Thermal and mechanically activated decomposition of LiAlH_4 ," *Materials Research Bulletin*, vol. 43, no. 5, pp. 1263–1275, 200.
- [99] D. Blanchard, H. W. Brinks, B. C. Hauback, and P. Norby, "Desorption of LiAlH_4 with Ti- and V-based additives," *Materials Science and Engineering B: Solid-State Materials for Advanced Technology*, vol. 108, no. 1–2, pp. 54–59, 2004.

- [100] X. Zheng, X. Qu, I. S. Humail, P. Li, and G. Wang, "Effects of various catalysts and heating rates on hydrogen release from lithium alanate," *International Journal of Hydrogen Energy*, vol. 32, no. 9, pp. 1141–1144, 2007.
- [101] J. R. Ares Fernandez, K. F. Aguey-Zinsou, M. Elsaesser, X. Z. Ma, M. Dornheim, T. Klassen, and R. Bormann, "Mechanical and thermal decomposition of LiAlH_4 with metal halides," *International Journal of Hydrogen Energy*, vol. 32, no. 8, pp. 1033–1040, 2007.
- [102] M. Ismail, Y. Zhao, X. B. Yu, and S. X. Dou, "Effects of NbF_5 addition on the hydrogen storage properties of LiAlH_4 ," *International Journal of Hydrogen Energy*, vol. 35, no. 6, pp. 2361–2367, 2010.
- [103] M. Ismail, Y. Zhao, X. B. Yu, A. Ranjbar, and S. X. Dou, "Improved hydrogen desorption in lithium alanate by addition of SWCNT-metallic catalyst composite," *International Journal of Hydrogen Energy*, vol. 36, no. 5, pp. 3593–3599, 2011.
- [104] Rafi-Ud-Din, L. Zhang, L. Ping, and Q. Xuanhui, "Catalytic effects of nano-sized TiC additions on the hydrogen storage properties of LiAlH_4 ," *Journal of Alloys and Compounds*, vol. 508, no. 1, pp. 119–128, 2010.
- [105] F. Zhai, P. Li, A. Sun, S. Wu, Q. Wan, W. Zhang, Y. Li, L. Cui, and X. Qu, "Significantly improved dehydrogenation of LiAlH_4 destabilized by MnFe_2O_4 nanoparticles," *Journal of Physical Chemistry C*, vol. 116, no. 22, pp. 11939–11945, 2012.
- [106] Z. Li, S. Liu, X. Si, J. Zhang, C. Jiao, S. Wang, S. Liu, Y. J. Zou, L. Sun, and F. Xu, "Significantly improved dehydrogenation of LiAlH_4 destabilized by K_2TiF_6 ," *International Journal of Hydrogen Energy*, vol. 37, no. 4, pp. 3261–3267, 2012.
- [107] R. Lan, J. T. S. Irvine, and S. Tao, "Ammonia and related chemicals as potential indirect hydrogen storage materials," *International Journal of Hydrogen Energy*, vol. 37, no. 2, pp. 1482–1494, 2012.
- [108] B. Sunden, "Hydrogen 3 3.1," pp. 37–55, 2019.
- [109] C. C. Chou, B. H. Chen, and D. J. Lee, "Hydrogen storage in a chemical hydride fuel system containing ammonia borane and Ni-Co/r-GO catalyst," *Energy Procedia*, vol. 61, pp. 142–145, 2014.
- [110] R. B. Biniwale, S. Rayalu, S. Devotta, and M. Ichikawa, "Chemical hydrides: A solution to high capacity hydrogen storage and supply," *International Journal of Hydrogen Energy*, vol. 33, no. 1, pp. 360–365, 2008.
- [111] A. De Silvestri, S. Stendardo, M. Della, and D. Borello, "ScienceDirect Decarbonizing cement plants via a fully integrated calcium looping-molten carbonate fuel cell process: Assessment of a model for fuel cell performance predictions under different operating conditions," *International Journal of Hydrogen Energy*, vol. 46, no. 28, pp. 14988–15007, 2020.
- [112] H. Wan, L. Ran, H. Lu, J. Qiu, H. Zhang, and Y. Yang, "Optimizing microstructure and enhancing hydrogen storage properties in Mg alloy via tailoring Ni and Si element \star ," *Journal of Magnesium and Alloys*, vol. 13, pp. 3784–3797, 2025.
- [113] D. Singh and R. Ahuja, "Theoretical Prediction of a Bi-Doped β -Antimonene Monolayer as a Highly Efficient Photocatalyst for Oxygen Reduction and Overall Water Splitting," *ACS Applied Materials & Interfaces*, vol. 13, no. 47, pp. 56254–56264, 2021.
- [114] T. G. Voskuilen, "Phase field modeling of hydrogen transport and reaction in metal hydrides," vol. 8, 2013.
- [115] S. Bouaricha, J. P. Dodelet, D. Guay, J. Huot, and R. Schulz, "Study of the activation process of Mg-based hydrogen storage materials modified by graphite and other carbonaceous compounds," *Journal of Materials Research*, vol. 16, no. 10, pp. 2893–2905, 2001.
- [116] Y. Liu and H. Pan, *Hydrogen Storage Materials*. Elsevier B.V., 2013.
- [117] V. and Mykhaylo, *An overview of hydrogen storage technologies*, vol. 24, no. 3. 2006.