

Harnessing Hydrogen: The Next Step in Renewable Energy Evolution

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Abstract: The problem of anthropogenic climate change and its inextricable link to the current and future energy needs of our global society is the greatest challenge facing our planet. Hydrogen is increasingly acknowledged as a crucial element of a potential energy framework for the 21st century, providing a feasible solution for reducing environmental emissions, improving sustainability, and bolstering energy security. Hydrogen offers a low-impact alternative with potential uses in transportation, decentralized heat and power generation, and energy storage systems, which might substantially mitigate environmental damage on both local and global levels. Nonetheless, the shift from a fossil fuel-dependent energy framework to a hydrogen-based economy presents significant scientific, technological, and socio-economic obstacles. This paper seeks to clarify the forces propelling the worldwide interest in hydrogen energy and critically analyzes essential concerns influencing its future as a primary energy vector.

Keywords: Adaptive learning, AI in language education, Chatbots for language learning, Personalized learning, Foreign language acquisition.

INTRODUCTION

Hydrogen is possibly the most elementary element that exists. A hydrogen atom has a single proton and a single electron. It is the most prevalent element in the universe. Notwithstanding its simplicity and prevalence, hydrogen does not exist naturally on Earth in its gaseous form; it invariably bonds with other elements. Water is a chemical composed of hydrogen and oxygen (H₂O). Hydrogen is among the most prevalent elements in the Earth's crust. Hydrogen in gaseous form does not occur naturally on Earth and must be synthesized. Data training concluded in October 2023. This occurs because hydrogen gas is less dense than air, causing it to ascend into the atmosphere. Natural hydrogen is invariably found in conjunction with other elements in intricate compounds, including water, coal, and oil.

PROPERTIES AND CHARACTERISTICS OF HYDROGEN

Hydrogen possesses the highest energy density among all conventional fuels. Conversely, hydrogen possesses the lowest energy density by volume. It is the least dense element and exists as a gas under standard temperature and pressure conditions. Hydrogen is present in numerous chemical molecules and in water. It is the most prevalent element on Earth. However, it does not exist naturally in its gaseous form. It consistently interacts with other elements, like as oxygen, to create water. Upon separation from another element, hydrogen can be combusted as fuel or transformed into power. Hydrogen is absent as a gaseous component in the Earth's atmosphere, necessitating its extraction from other substances. The two predominant processes for hydrogen production are electrolysis, often known as water splitting, and steam reforming. Steam reforming is presently the most economical technique for hydrogen production. It is utilized in industry to segregate hydrogen atoms from carbon atoms in methane. As methane is a fossil fuel, the steam reforming process generates greenhouse gas emissions associated with global warming. A different technique for generating hydrogen is electrolysis. Electrolysis entails the passage of an electric



current through water to dissociate it into its fundamental constituents, hydrogen and oxygen. Hydrogen is subsequently gathered at the negatively charged cathode, while oxygen is collected at the positively charged anode. The hydrogen formed through electrolysis is highly pure and emits no pollutants, as electricity may be sourced from renewable energy. Regrettably, electrolysis is presently a highly costly procedure. Hydrogen is present in numerous organic molecules, particularly in hydrocarbons that constitute fuels like gasoline, natural gas, methanol, and propane.

Hydrogen can be extracted from hydrocarbons with the use of heat, a process referred to as reforming. The majority of hydrogen is presently generated from natural gas using this method. Electric current can be utilized to dissociate water into its constituent oxygen and hydrogen elements. This procedure is referred to as electrolysis. Certain algae and bacteria utilize sunlight as an energy source and can release hydrogen under specific conditions. 2 Several experimental techniques for hydrogen production exist, including photo-electrolysis and biomass gasification. Researchers have discovered that certain algae and bacteria utilize sunlight as an energy source to generate hydrogen under specific conditions.

Hydrogen can be sourced from various origins, including renewable (hydropower, wind, wave, sun, biomass, and geothermal) and non-renewable (coal, natural gas, and nuclear) resources. It can be stored as fuel and utilized in transportation and distributed heat and power systems via fuel cells, internal combustion engines, or turbines, with water as the sole by-product at the site of use.

HYDROGEN AS AN ENERGY SOURCE

Hydrogen's potential to substitute fossil fuels in the transportation sector may address a significant global environmental issue (Jacobson et al. 2005). Vehicle emissions are presently among the foremost contributors to air pollution globally, particularly in metropolitan environments, and they also play a substantial role in the world's carbon dioxide emissions. Hydrogen can serve as a storage medium for electricity produced from continuous renewable sources, including solar, wind, wave, and tidal power, so addressing a primary challenge of sustainable energy: the issue of consistent supply. Hydrogen is considered a genuinely "green" fuel when derived from non-fossil fuel feedstocks. Moreover, domestic hydrogen production facilitates the utilization of renewable energy within the transportation sector, possibly yielding significant economic and energy security benefits, together with the advantages of new infrastructure grounded in distributed generation. The pivotal aspect of hydrogen's energy storage capability establishes a robust connection between sustainable energy technologies and a sustainable energy economy, sometimes referred to as the "hydrogen economy" (Muradov and Veziroglu 2005). The significance of hydrogen as a prospective energy carrier has markedly risen during the past decade, attributed to swift advancements in fuel cell technology. Hydrogen-powered fuel cells possess the potential to serve as important catalysts for the transition to a sustainable energy system characterized by low carbon emissions.

FUTURE PROSPECTS OF HYDROGEN ENERGY

Numerous nations are already formulating strategies for the advancement of fuel cells and hydrogen technologies, frequently accompanied with explicit numerical objectives. The primary emphasis of hydrogen research and development has been on the transportation sector, where the majority of the world's leading automakers have made substantial investments in fuel cell vehicle research initiatives. Figure 1 depicts the pivotal function of hydrogen as an energy carrier, integrating diverse hydrogen production techniques and a range of end-user applications. A primary appeal of hydrogen as an energy carrier is the diverse array of manufacturing methods derived from various sources.



Hydrogen can be generated from coal, natural gas, and other hydrocarbons through multiple methods, including electrolysis of water, photolytic decomposition, high-temperature thermochemical cycles, biomass, and municipal garbage. The variety of production sources substantially enhances energy supply security. A conventional energy chain for hydrogen encompasses the production, distribution, transportation, storage, and eventual utilization of hydrogen. ³ The energy chain for sustainable hydrogen energy encompasses the capture of solar or alternative energy sources to produce hydrogen as an energy carrier, its storage for utilization in fuel cells or combustion-based devices, and its delivery. The eventual establishment of a hydrogen-based economy may yield significant environmental and economic advantages, as well as improved energy supply security. The most persuasive rationale for a sustainable hydrogen economy is its capacity to significantly diminish global carbon emissions.

CHALLENGES AND BARRIERS TO A HYDROGEN ECONOMY

The shift from a carbon-based (fossil fuel) energy system to a hydrogen-based economy presents considerable scientific, technological, and social obstacles to establishing hydrogen as the future clean energy source. In 2004, the United States National Research Council and the National Academy of Engineering, in their report “The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,” identified four principal obstacles to realizing the concept of a hydrogen economy. Design and implement efficient, sustainable, secure, and ecologically preferable fuel cell systems and hydrogen storage solutions. Establish the infrastructure to supply hydrogen to light-duty vehicle operators. Significantly decrease the expenses associated with hydrogen production from renewable energy sources. Capture and sequester CO₂, a byproduct of hydrogen synthesis derived from coal and natural gas. Decentralized generation of heat and power via local or broader hydrogen supply networks. The subsequent sections outline several problems encountered in the transition to a hydrogen economy.

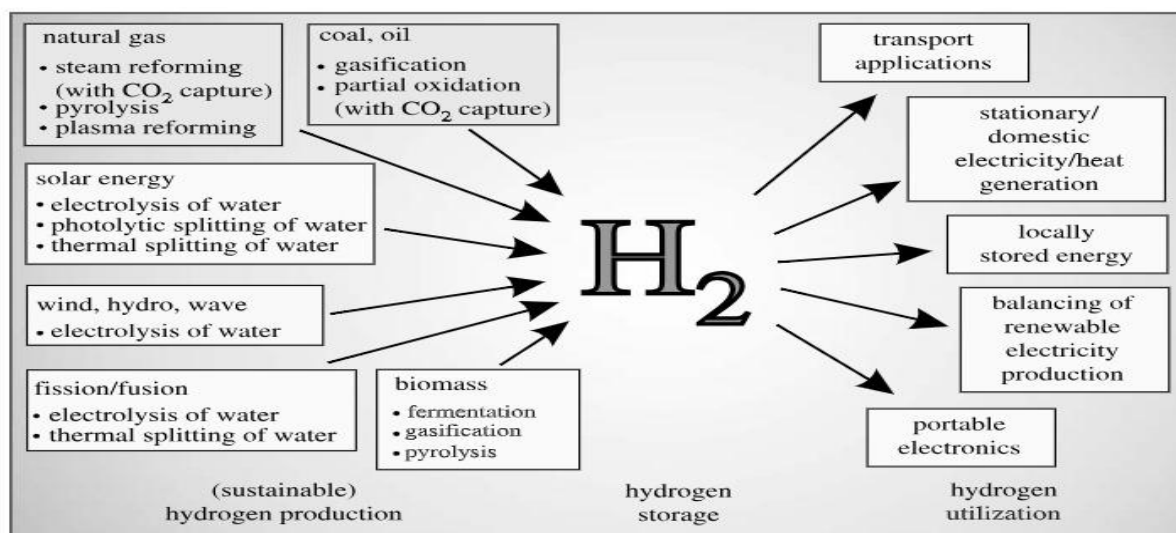


Figure 1. Hydrogen as an energy carrier links multiple hydrogen production methods to various end users through storage. Shadow production routes can involve significant carbon dioxide (by-product) production.

Hydrogen generation and dissemination. Hydrogen ranks as the third most prevalent chemical element in the Earth's crust, however it is perpetually combined with other elements in chemical compounds. Consequently, it must be synthesized from alternative hydrogen-containing sources utilizing energy, such as electricity or thermal energy. Hydrogen is presently generated in substantial volumes from fossil fuels

using the steam reforming of natural gas and the partial oxidation of coal or heavy hydrocarbons (see to Sigfusson 2007). These methods can leverage economies of scale and are presently the most cost-effective and well-established ways for large-scale hydrogen production. They can be utilized in the short to medium term to satisfy the demand for hydrogen fuel and to facilitate the testing and validation of technology related to hydrogen production, storage, distribution, safety, and utilization. In the long term, it is evidently unsustainable for the hydrogen economy to rely on hydrogen sourced from hydrocarbons. The generation of hydrogen from fossil fuels via reforming and gasification processes invariably results in the emission of carbon dioxide as a by-product. Carbon dioxide emissions, a primary contributor to global climate change, are produced in large-scale facilities via a process known as carbon capture, which entails the underground capture, liquefaction, transportation, and storage of carbon dioxide, such as in depleted natural gas and oil wells or geological formations. Nonetheless, all sequestration procedures are energy-intensive, expensive, and possibly harmful to the environment. The primary risk arises from the unpredictable long-term environmental effects of carbon dioxide sequestration. A more advantageous method for hydrogen production devoid of carbon dioxide emissions is the high-temperature pyrolysis of hydrocarbons, biomass, and municipal solid waste, resulting in hydrogen and solid carbon black, which may be readily utilized or sequestered industrially. The expense of this technique is presently considerably more than that of steam reforming of natural gas. To realize the advantages of a genuinely sustainable hydrogen energy system, it is imperative to transition to hydrogen production from non-fossil resources, such as water (Turner 2004; P. P. Edwards et al. 1046 Phil. Trans. R. Soc. A (2007) Sheriff et al. 2005; Penner 2006). Hydrogen can be generated by dissociating water via several methods, including electrolysis, photoelectrolysis, high-temperature decomposition, and photobiological water splitting. The commercial production of hydrogen using water electrolysis attains an efficiency of 75%; yet, the cost of hydrogen is presently many times greater than that of fossil fuels (Dutton 2002; Ewan & Allen 2005; International Energy Agency 2006). Electricity generated by renewable energy sources (such as wind, wave, and tidal) can satisfy local hydrogen requirements; nevertheless, it will undoubtedly fall short of fulfilling the global demand for hydrogen as a prevalent energy source. The generation of hydrogen through biological reformation and fermentation of biomass utilizing microorganisms is evidently appealing, provided it can be shown that this method can yield the substantial quantities of hydrogen needed. This process emits carbon dioxide, which can be mitigated by enhancing biomass, rendering it carbon dioxide neutral. Nevertheless, prudence is important; the utilization of fertilizers for cultivating plants or biomass inevitably incurs a "CO₂ cost," as ammonia is required for fertilizer synthesis, and this ammonia is produced from hydrogen and nitrogen, with the former being derived from hydrocarbons. 4 The ultimate objective of hydrogen generation is the effective, direct conversion of sunlight using a photocatalytic process to dissociate water into its constituent elements, hydrogen and oxygen, without employing energy. This optimal manufacturing method harnesses solar energy to extract water from the oceans, resulting in "solar hydrogen." A new analysis from the US Department of Energy (DoE) indicates that solar water splitting is the sole significant, long-term, CO₂-free method for the mass generation of the substantial quantities of H₂ required for the establishment of a hydrogen economy. U.S. Department of Energy, Office of Science (2003). Attaining cost-effective and efficient solar hydrogen production necessitates the advancement of creative materials, novel physical phenomena, new synthetic methodologies, and wholly original design concepts. Current nuclear (fission) technology generates electricity that can facilitate hydrogen production through the electrolysis of water. Advanced nuclear reactors are being designed to facilitate high-temperature water electrolysis (independent of power) or thermochemical cycles that utilize heat and chemical processes to dissociate water. If successfully developed, fusion power might serve as a substantial source of clean, abundant, and carbon-free hydrogen generation. The existing transportation infrastructure for distributing conventional fuels to



customers is not readily adaptable for hydrogen use. Hydrogen transportation methods encompass compressed gas (200 bar) in steel tube cylinders, liquid hydrogen tanks, and localized hydrogen pipeline networks, among others. All of these alternatives are costly and substantially increase the expense of hydrogen for consumers. Innovative strategies will be essential to minimize delivery expenses while upholding stringent safety standards, from manufacturing to end-user refilling. Consequently, the primary elements of the hydrogen delivery infrastructure must be established immediately to facilitate local hydrogen recharging stations for transportation—commonly regarded as the inaugural significant foray into the hydrogen economy. Subsequently, the elements of a national hydrogen delivery and distribution network that guarantees a dependable supply of economical hydrogen must be established. Establishing a new hydrogen network necessitates substantial investment, along with research and development of innovative materials, cost-effective compressor technology, seals, sensors, and controls, in addition to the filling station infrastructure essential for the safety of any hydrogen transport system. A decentralized framework Hydrogen production for localized energy and hydrogen filling stations will be centralized in small-scale facilities, necessitating entirely new specifications for dimensions, manufacturing costs, and other parameters. In regions without natural gas, hydrogen can be optimally generated on-site from water, methanol, or ammonia, utilizing electricity—preferably sourced from renewable energy, such as wind, solar, or biofuels. Local hydrogen production may align more well with the distribution of available fuels; nevertheless, CO₂ sequestration may be less efficient compared to large-scale centralized production. Upon the successful integration of hydrogen into the energy sector, the optimal long-term solution for hydrogen distribution would entail a network of pipelines linking centralized hydrogen production facilities to stationary consumers and mobile refueling stations. Nonetheless, in certain regions, like remote refueling stations or residences utilizing water electrolysis, efficient small-scale reforming facilities, or alternative sophisticated hydrogen production techniques, local hydrogen production may remain more cost-effective.

HYDROGEN STORAGE TECHNOLOGIES

Live hydrogen storage is regarded by many as one of the most significant and technically demanding challenges to the extensive adoption of hydrogen as an effective energy carrier (Crabtree et al. 2004; Harris et al. 2004). Hydrogen possesses a higher energy density by weight than any other material. Regrettably, being the lightest chemical element in the periodic table, it possesses a markedly low energy density per unit volume (Table 1). The hydrogen economy necessitates two categories of hydrogen storage systems: one for transportation and another for stationary purposes. Both possess distinct requirements and constraints. The transportation industry is anticipated to be the initial significant consumer of hydrogen in the forthcoming hydrogen economy. The hydrogen storage criteria for transportation applications are more rigorous than those for stationary uses. The operational specifications for an optimal hydrogen storage system for transportation applications encompass:— multi-state hydrogen uptake/release reversibility (minimum of 500 cycles),— low operating pressure (below 4 bar),— operating temperature range from 50 K to 150 °C,— rapid hydrogen uptake/release kinetics,— elevated gravimetric and volumetric hydrogen density (minimum of 9% by weight and at least 70 g H₂ per liter of storage system), — safety parameters and public acceptance during operation, and — hydrogen storage system cost below £15/kg. Storage systems are nonexistent. Figure 2 illustrates a facet of the issue with on-board hydrogen storage, depicting the volume and weight of 4 kg of hydrogen storage across several systems (4 kilogram of hydrogen is adequate to propel a fuel cell car for 500 km). In stationary applications, the limits of weight and volume for hydrogen storage are less critical than in vehicular contexts; stationary hydrogen storage systems can utilize extensive space, function at elevated temperatures and pressures, and provide supplementary power to offset sluggish kinetics. Nonetheless, hydrogen storage for stationary applications presents a significant



scientific and technical barrier, particularly concerning storage materials. 5 Presently, hydrogen storage methods rely on high-pressure gas cylinders or cryogenically liquefied hydrogen. Conventional steel cylinders may contain hydrogen at 200 bar and possess a gravimetric density of around 1 wt% (1 wt% of stored hydrogen corresponds to a reserve energy of 186 Wh kg⁻¹). Recently engineered ultra-high-density composite cylinders constructed from premium carbon fiber can contain hydrogen at pressures between 700 and 1000 bar, achieving a gravimetric hydrogen density of up to 10 wt%. Nonetheless, these high-pressure cylinders are costly and necessitate intricate and costly filling apparatus. Storing hydrogen as a cryogenic liquid provides a markedly greater gravimetric density compared to compressed gas, with liquid hydrogen exhibiting a density of 70.8 g L⁻¹ at 252.88°C and 1 bar. Nonetheless, this density remains 14 times inferior to that of water. Cryogenic liquid containers necessitate highly effective insulation to maintain hydrogen in its liquid state. Despite optimal insulation, the evaporation rate for small transport tanks is no less than 1% per day. Although compressed and liquid storage options for hydrogen are accessible, these methods fail to satisfy numerous aforementioned requirements, as well as the medium- and long-term objectives established for transportation hydrogen storage systems (U.S. Department of Energy, Office of Science 2003).

This collection of rigorous and integrated requirements presents a significant scientific obstacle for the advancement of dependable hydrogen storage for transportation; at now, hydrogen storage devices capable of concurrently satisfying all these criteria are nonexistent. Figure 2 illustrates a facet of the on-board hydrogen storage challenge, depicting the volume and mass of 4 kg of hydrogen across several storage technologies (4 kilogram of hydrogen suffices to propel a fuel cell vehicle for 500 kilometers). In stationary applications, the limits of weight and volume for hydrogen storage are less critical than in cars; stationary hydrogen storage systems can utilize extensive space, function at elevated temperatures and pressures, and provide supplementary power to offset sluggish kinetics. Storing hydrogen for stationary applications is a significant scientific and technical problem, particularly regarding storage materials. Presently, hydrogen storage alternatives rely on high-pressure gas cylinders or cryogenically chilled liquid hydrogen. Conventional steel cylinders may contain hydrogen at 200 bar and possess a gravimetric density of around 1 wt% (1 wt% of stored hydrogen corresponds to a reserve energy of 186 Wh kg⁻¹). Recently, ultra-high-performance carbon fiber tubes have been created.

These technologies incur a substantial energy penalty, requiring up to 20% of hydrogen's energy content for gas compression and up to 30% for liquefaction. A significant concern for high-pressure and cryogenic storage facilities is the public perception and acceptance of compressed gas and liquid hydrogen storage. Hydrogen storage necessitates a significant technological advancement, which is anticipated to occur in Azerbaijan. The most feasible alternative to compressed and liquid hydrogen is the storage of hydrogen in solid or liquid forms. The advancement of novel solid-state hydrogen storage materials may signify a transformative shift in hydrogen storage technology and significantly influence the transition to a hydrogen economy (Crabtree et al. 2004; Harris et al. 2004). Figure 3 illustrates the gravimetric and volumetric energy densities of chemically stored hydrogen employing diverse storage techniques. Neither cryogenic nor high-pressure hydrogen storage methods seem capable of fulfilling the Department of Energy's medium-term objectives for transportation applications (U.S. Department of Energy, Office of Science 2003). Solid-state hydrogen storage utilizing ionic-covalent hydrides of light elements, including lithium, boron, sodium, magnesium, and aluminum (or their combinations), is increasingly acknowledged as the sole method capable of attaining the requisite gravimetric and volumetric target densities. A solid-state storage material appropriate for transportation must have a high gravimetric and volumetric hydrogen density while rapidly



absorbing and desorbing hydrogen at or near ambient temperature and pressure. Ideally, this material should be synthesized from cost-effective substances using an energy-efficient preparation technique, exhibit resistance to contamination from trace impurities, possess excellent thermal conductivity in both loaded and unloaded states, ensure safety and reusability in atmospheric contact, be recyclable, and facilitate straightforward recycling processes. This chart illustrates a notably demanding array of qualifications for an optimal storage material; as present, no material satisfies all of these criteria.

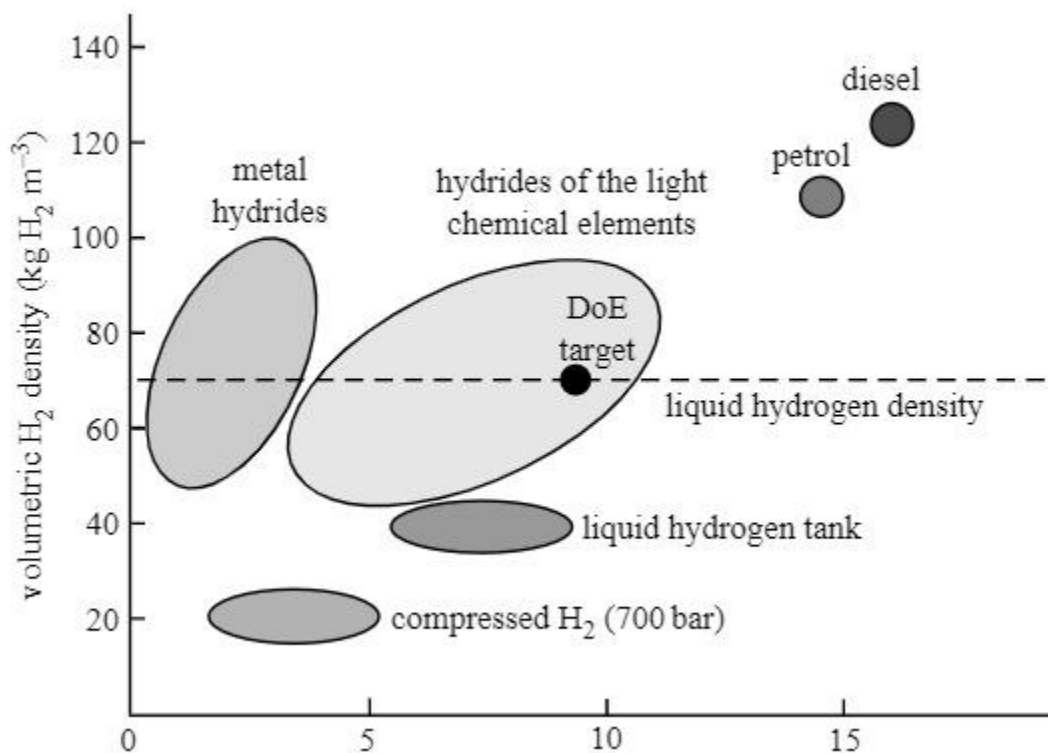


Figure 2. Gravimetric and bulk densities of various hydrogen storage options (note: the weight and volume of the storage container are included). The “DoE target” reflects the U.S. Department of Energy’s target for the “ideal” hydrogen storage material for 2015. Metal hydrides are traditional, heavy metal hydrides, such as LaNi_5 , etc.

The inherent characteristics and behavior of hydrogen storage materials are contingent upon the specific nature of the hydrogen interaction with the host material. Various types of interactions exist, including:— physical adsorption of H_2 molecules on the material's surface (either external or internal),— chemical absorption of hydrogen by the material resulting in the formation of chemical bonds (along with hydrogen dissociation), and— the creation of “chemical hydrides” distinguished by diverse covalent bonds. The physical processes that dictate hydrogen-material interactions are essential for the significant advancements required in this domain. Physical adsorption is the weakest kind of hydrogen bonding. Hydrogen molecules generally create a monolayer on the surface, necessitating a material with an exceptionally high surface area to attain a significant hydrogen storage capacity (Figure 4). A variety of high-surface-area materials have been examined, including zeolites, metal-organic frameworks, and several forms of carbon. The maximum hydrogen storage capacity is attained in carbon spheres processed with 8 wt% hydrogen.

Nonetheless, effective hydrogen storage in carbon necessitates low temperatures (1968°C) and high pressures (up to 50 bar); furthermore, the ball milling process is protracted and energy-intensive.

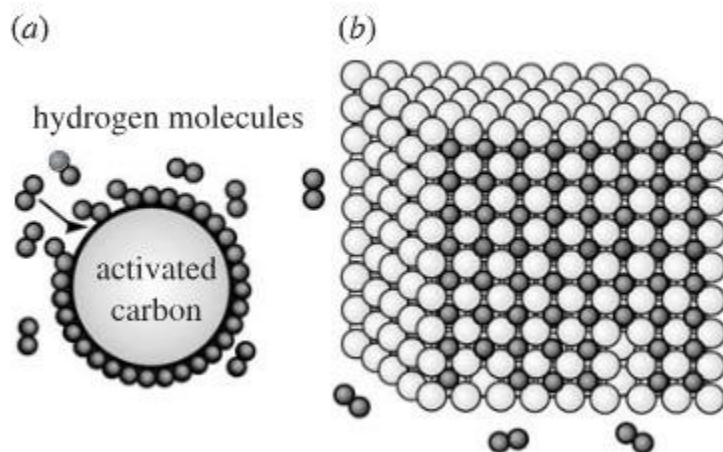


Figure 3. Schematic of (a) adsorption (physisorption) and (b) absorption (chemisorption) of hydrogen. In adsorption, hydrogen molecules remain intact; in chemisorption, molecular hydrogen dissociates and occupies interstitial spaces in the metal matrix (erosion).

The highest hydrogen storage capacity of chemically adsorbed hydrogen in prevalent metal hydrides (e.g., LaNi_5H_6 , $\text{FeTiH}_{1.7}$, MgNiH_4) is approximately 4 wt%. These metal hydrides may securely and effectively retain hydrogen within their crystalline structure. Hydrogen is initially absorbed into the substance and subsequently released through regulated heating of the solid. Despite the increased bulk density of hydrogen in these materials compared to liquid hydrogen (Figure 2), the weight of the materials renders them impractical for on-board hydrogen storage in automobiles. Consequently, elevated gravimetric hydrogen densities can alone be attained by the hydrides of the lighter chemical elements in the periodic table. The most promising hydrogen storage materials are ionic-covalent hydrides composed of light elements, including lithium, boron, sodium, magnesium, and aluminum. [6] Hydrogen absorption and desorption in these materials often include high-temperature solid-state phase changes that were previously deemed irreversible; nevertheless, NaAlH_4 appears to function as a reversible storage medium with appropriate catalysts. Recently, novel chemical pathways have been established to facilitate hydrogen uptake and release under mild conditions (Johnson 2005), and new promising hydrogen storage materials have been identified (Chater et al. 2006). Nevertheless, further fundamental study is essential to comprehend the physical and chemical processes that regulate hydrogen storage and release, as well as to enhance the hydrogen absorption and desorption characteristics of these materials to satisfy hydrogen storage demands.

CONCLUSION

Hydrogen energy presents a transformative opportunity for addressing the challenges of climate change, energy security, and sustainability. As the most abundant element in the universe, hydrogen offers a high energy density and the potential to replace fossil fuels across multiple sectors, including transportation, power generation, and industrial applications. However, realizing a hydrogen-based economy requires overcoming significant scientific, technological, economic, and infrastructural barriers.

The current reliance on fossil fuel-based hydrogen production methods, such as steam reforming, continues to contribute to carbon emissions, underscoring the urgency for cleaner alternatives like electrolysis powered by renewable energy. Advances in hydrogen storage, particularly in solid-state materials, will be essential for making hydrogen a viable energy carrier. Additionally, the expansion of hydrogen infrastructure, including production facilities, storage systems, and refueling stations, must be prioritized to facilitate large-scale adoption.

Despite these challenges, global investment and research into hydrogen technologies are rapidly accelerating. Governments, industries, and scientific communities are working collaboratively to develop cost-effective and sustainable hydrogen production, storage, and distribution methods. With continuous technological advancements and supportive policies, hydrogen has the potential to play a pivotal role in the global transition to a cleaner and more sustainable energy future.

While a full hydrogen economy remains an ambitious goal, the progress made in recent decades suggests that hydrogen will be an integral part of future energy systems. Continued innovation, investment, and policy support will be critical in ensuring hydrogen's successful integration into the global energy landscape, ultimately contributing to a low-carbon and sustainable world.

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