

Energy density and economic analysis of different hydrogen storage methods

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Abstract. As the importance of hydrogen energy in the global clean energy system becomes increasingly prominent, how to store hydrogen efficiently, safely and economically has become the core bottleneck restricting its large-scale application. This study takes three mainstream hydrogen storage methods, namely high-pressure hydrogen storage, liquid hydrogen storage and solid-state hydrogen storage, as the research objects, and comprehensively compares their advantages and disadvantages in terms of energy density, safety and economy. Through systematic literature review and case analysis, the study finds that high-pressure hydrogen storage has a relatively high mass energy density and technical maturity, and is suitable for mobile transportation scenarios, but its volume efficiency is low and there is a risk of high-pressure leakage; liquid hydrogen storage has the highest volume energy density and is suitable for large-scale transportation, but the liquefaction process has high energy consumption and the equipment cost is expensive; solid-state hydrogen storage performs best in terms of safety and is particularly suitable for portable applications, but the hydrogen storage materials are expensive and the technology is not yet mature. Based on the above comparison, this study proposes suggestions for multi-scenario collaborative optimization and looks forward to the future development direction of hydrogen storage technology.

Keywords: hydrogen energy, high-pressure hydrogen storage, liquid hydrogen storage, solid-state hydrogen storage, energy density

1. Introduction

Hydrogen energy, as a clean and sustainable energy source, is poised to play a pivotal role in the future energy landscape. Its remarkable advantages, such as zero-emissions, high energy density, and renewability, position it as a promising alternative to fossil fuels, especially in mitigating greenhouse gas emissions. Hydrogen fuel cells, the primary application of hydrogen energy, offer distinct advantages and a promising future. They convert hydrogen and oxygen directly into electricity, producing only water as a by-product, which makes them highly efficient and environmentally friendly. However, the storage of hydrogen remains one of the core bottlenecks in the widespread utilization of hydrogen energy. The inherent properties of hydrogen, such as its low volumetric energy density and high flammability, make its storage particularly challenging. To store hydrogen in practice, it must be compressed, liquefied or chemically combined, all of which require specialized technologies. These processes present significant technical and economic obstacles. High-pressure storage involves compressing hydrogen to extremely high pressures, while liquefaction requires cooling hydrogen to low temperatures. Solid-state storage is safer and potentially more efficient, but it requires the development of advanced materials that can store hydrogen at room temperature. Each method has its own complexities, including safety issues, energy losses and high upfront costs, making the effective storage of hydrogen one of the most critical obstacles to achieving its widespread use.

High-pressure hydrogen storage is relatively mature with a simple structure but has low energy density and safety concerns due to high-pressure. Liquid hydrogen storage offers high energy density, yet its liquefaction is energy-consuming and costly. Solid-state hydrogen storage shows potential in safety and energy density but needs to improve economic viability. Currently, high-pressure hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage. High-pressure hydrogen storage is relatively mature and widely used in some applications. It has the advantage of simplicity but faces challenges in terms of low energy density and safety concerns due to high-pressure conditions. Liquid hydrogen storage offers high energy density, yet it requires extremely low temperatures for liquefaction, which is energy-consuming and costly. Solid-state hydrogen storage shows great potential in terms of safety and high energy density, but it still needs further development to improve its economic viability.

The limitations of hydrogen storage technologies directly affect the feasibility of hydrogen as a mainstream energy source. Without efficient storage systems, hydrogen fuel cells that rely on hydrogen storage cannot be deployed on a large scale for applications such as electric vehicles or fixed power generation. Moreover, the lack of reliable and affordable storage methods hinders the development of hydrogen infrastructure, including gas stations and transportation networks. Although significant progress has been made in developing various storage technologies, breakthroughs are still needed to achieve cost-effective, safe, and efficient hydrogen storage solutions that enable hydrogen to compete with traditional fossil fuels in terms of practicality and affordability. Therefore, this research intends to compare these storage technologies and evaluate their practical feasibility and potential in real-world applications. By identifying the strengths and weaknesses of each method, this research seeks to provide theoretical support for technological improvements and policy-making.

From an academic perspective, hydrogen energy research is crucial in disciplines like energy science, chemical engineering, and materials science. The study of hydrogen storage technology can contribute to the development of green energy solutions and fill the academic gaps in this field. In terms of application, the research results can significantly promote the commercialization of the hydrogen energy industry and influence policy-making, thereby facilitating carbon emission reduction and energy transition.

This essay will be divided into three parts. In the part of research review, the basic principles and current development of three major hydrogen storage technologies—high-pressure hydrogen storage, liquid hydrogen storage and solid-state hydrogen storage, which will be comprehensively reviewed to summarize the current research progress and clarify the key issues. In the part of discussion, different hydrogen storage methods will be compared in terms of energy density, safety and economy, and their advantages and limitations will be explored. In the part of conclusion, the main research findings will be summarized, suggestions for optimizing hydrogen storage technologies will be proposed and future research directions will be prospected.

2. Research review

2.1. The development history of hydrogen storage technology

Hydrogen energy, as an important component of the future clean energy system, has undergone a long and tortuous evolution in its storage methods. Starting from the initial experiments on hydrogen storage, to the development of high-pressure, liquid, and solid-state hydrogen storage technologies, each breakthrough has promoted the wide application of hydrogen energy in the energy system. However, due to the physical and chemical properties of hydrogen, the choice of storage methods not only affects energy utilization efficiency but also determines the feasibility and economy of hydrogen energy technology. Therefore, reviewing the development history of hydrogen storage technology not only helps to understand the technical level of different hydrogen storage methods at present, but also provides ideas for the optimization of future hydrogen storage technologies.

In the early 20th century, the research on hydrogen storage technology mainly focused on the storage of hydrogen in high-pressure gas cylinders. Although this method was simple, the problem of low density of hydrogen at normal temperature and pressure made high-pressure storage have poor safety and low hydrogen storage density, limiting its wide application [1]. With the development of cryogenic technology, from the 1950s to the 1970s, liquid hydrogen storage technology gradually became a research hotspot. The density of liquid hydrogen is much higher than that of gaseous hydrogen, so it has been applied in aerospace and other fields. However, liquid hydrogen needs to be stored at extremely low temperatures (-253°C), resulting in high energy consumption and high costs [2]. From the 1970s to the 1990s, metal hydride hydrogen storage technology emerged. Metal hydrides can absorb and release hydrogen under relatively mild conditions, featuring high hydrogen storage density and good safety [3]. At the same time, chemical hydride hydrogen storage technology also began to develop. Storing and releasing hydrogen through chemical reactions, chemical hydrides such as sodium borohydride (NaBH_4) and ammonia borane (NH_3BH_3) demonstrated high hydrogen storage capacity, but their regeneration processes were complex and costly [4].

Entering the 21st century, hydrogen storage technology using nanomaterials has become a research hotspot. Nanomaterials such as carbon nanotubes and graphene, with their high specific surface area and unique physical and chemical properties, are considered to have potential hydrogen storage capabilities. Although the hydrogen storage technology using nanomaterials is still in the laboratory stage, its prospects are broad [5]. Meanwhile, Liquid Organic Hydrogen Carrier (LOHC) technology stores and releases hydrogen through reversible hydrogenation-dehydrogenation reactions, demonstrating high hydrogen storage density and good safety. It has made significant progress in recent years [6]. In recent years, composite hydrogen storage technology has gradually attracted attention. By integrating the advantages of various hydrogen storage methods, such as the combination of high-pressure hydrogen storage and metal hydride hydrogen storage, or liquid hydrogen storage and chemical hydride hydrogen storage, composite hydrogen storage technology aims to enhance hydrogen storage density, safety and economy [7]. The development history of hydrogen storage technology is a process of continuous optimization and innovation. After a long period of development, hydrogen storage technology has formed three main categories: high-pressure hydrogen storage, liquid hydrogen storage and solid-state hydrogen storage. Each technology has its own unique hydrogen storage mechanism, advantages and limitations, and is suitable for different application scenarios. To better understand the characteristics of these

hydrogen storage technologies, the following will respectively discuss their principles, current technical status and applications in detail.

2.2. High-pressure hydrogen storage

High-pressure hydrogen storage is one of the most common and well-developed hydrogen storage methods. It stores hydrogen by compressing it to high pressures, typically in the range of 35-70 MPa for on-board applications in hydrogen-fueled vehicles, and 40-75 MPa in hydrogen refueling stations to enable rapid refueling using pressure differences. This storage technology offers several advantages. Firstly, it has a relatively simple infrastructure requirement. The equipment mainly consists of high-pressure storage vessels, valves, and pipelines. Secondly, the filling and releasing process is fast, which is suitable for applications that require quick hydrogen supply such as vehicles.

There are three main types of high-pressure hydrogen storage vessels. Stationary vessels, like seamless hydrogen storage vessels and multifunctional layered stationary hydrogen storage vessels, are used in hydrogen refueling stations. The former has limitations in volume due to the diameter of seamless thick-walled tubes and is prone to hydrogen embrittlement at high pressures. The latter, developed to overcome these issues, can be made into large-volume vessels with enhanced safety features, such as "only leak, but never burst" characteristics and online safety monitoring capabilities. Vehicular high-pressure hydrogen storage vessels, including Type III with a metallic liner and Type IV with a non-metallic liner, are designed to meet the light-weight and high-density requirements for on-board hydrogen storage. Type IV vessels, made of a seamless, high-density polyethylene liner wrapped with carbon fibers in a resin matrix, offer high gravimetric storage density but face challenges in hydrogen compatibility and durability of the polymeric liner. Type III vessels, with an autofrettage-treated metallic liner, need to balance the thickness of the aluminum liner for light-weight and ensure its fatigue strength under different temperature conditions.

Bulk transportation high-pressure hydrogen storage vessels, such as those in tube trailers, are used to transport hydrogen from production sites to end-users. However, their low hydrogen-carrying capacity and high delivery costs prompt the development of full-winding vessels with large capacities to increase transportation efficiency. Despite its advantages, high-pressure hydrogen storage also has some safety concerns. Hydrogen embrittlement of metals at room temperature can degrade the mechanical properties of storage vessels, increasing the risk of sudden failure. The temperature rise during fast filling can affect the performance of the storage vessel materials and lead to underfilling. Moreover, in case of leakage, hydrogen can form jet fires, and the un-ignited gas may diffuse and cause deflagration or detonation under certain conditions.

2.3. Liquid hydrogen storage

Liquid hydrogen storage involves cooling hydrogen to extremely low temperatures (around -253°C) to convert it into a liquid state, which significantly increases its density compared to gaseous hydrogen at normal conditions, enabling more hydrogen to be stored in a given volume.

One of the major advantages of liquid hydrogen storage is its high energy-density per unit volume. This makes it suitable for applications where space is limited, such as in some aerospace and long-range vehicle projects. In the aerospace industry, liquid hydrogen is often used as a fuel for rockets due to its high-energy content and low molecular weight.

However, liquid hydrogen storage also has several challenges. The process of liquefying hydrogen is energy-intensive. It consumes about 30-40% of the Lower Heating Value (LHV) of hydrogen, which increases the overall cost of hydrogen storage. Additionally, maintaining the low temperature required for liquid hydrogen storage demands advanced insulation technologies. Vacuum-insulated vessels are commonly used to minimize heat transfer from the surroundings, but these vessels are complex and expensive to manufacture.

Safety is also a crucial aspect. Liquid hydrogen is cryogenic, and any contact with the skin or eyes can cause severe cold burns. Moreover, when liquid hydrogen leaks, it quickly vaporizes into gaseous hydrogen, which has a low density and can disperse rapidly. If the vaporized hydrogen accumulates in an enclosed space, it can form a flammable mixture with air, posing a risk of explosion. Another limitation is related to the infrastructure. The storage and handling of liquid hydrogen require specialized equipment and facilities. For example, hydrogen refueling stations for liquid hydrogen need to have cryogenic storage tanks, pumps, and transfer lines that can operate at extremely low temperatures. The lack of a well-developed infrastructure is currently a major barrier to the widespread adoption of liquid hydrogen storage, especially for large-scale applications. Despite these challenges, research is ongoing to improve the efficiency of hydrogen liquefaction processes, develop better insulation materials, and enhance safety measures. New technologies are being explored to reduce the cost of liquefaction and improve the overall performance of liquid hydrogen storage systems.

2.4. Solid-state hydrogen storage

Solid-state hydrogen storage encompasses a range of methods that store hydrogen in solid materials through physical or chemical interactions. These materials can be metal hydrides, carbon-based materials, or other complex compounds.

Metal hydrides are one of the most studied solid-state hydrogen storage materials. They store hydrogen by forming metal-hydrogen bonds. When hydrogen is introduced to the metal hydride, it reacts and is absorbed into the lattice structure of the metal. This process is reversible, and upon heating or reducing the pressure, hydrogen can be released. Metal hydrides offer high hydrogen storage capacities in some cases, and they can store hydrogen in a relatively compact and safe manner. For example, some metal hydrides can store hydrogen at relatively low pressures compared to high-pressure gaseous storage, which reduces the risk of hydrogen leakage and explosion.

Carbon-based materials, such as activated carbon and carbon nanotubes, also show potential for hydrogen storage. They store hydrogen through physical adsorption. The large surface area of these carbon-based materials allows hydrogen molecules to adhere to their surfaces. Although the hydrogen storage capacity of carbon-based materials is generally lower than that of some metal hydrides, they have advantages such as fast charging and discharging rates and good cycling stability.

Solid-state hydrogen storage has several safety benefits. Since hydrogen is bound or adsorbed in the solid matrix, the risk of sudden hydrogen release and leakage-related hazards is reduced compared to gaseous or liquid hydrogen storage. In addition, solid-state storage systems can be designed to be more compact, which is beneficial for applications with limited space, like in portable power devices or small-scale hydrogen-powered vehicles.

However, solid-state hydrogen storage also faces some challenges. The cost of many solid-state hydrogen storage materials, especially metal hydrides, is relatively high, which limits their large-scale commercialization. Some metal hydrides also have slow hydrogen absorption and desorption kinetics, which means it takes a long time to charge and discharge the stored hydrogen. Moreover, the performance of these materials can be affected by factors such as temperature and pressure, and finding materials that can operate under a wide range of conditions remains a challenge.

Research in solid-state hydrogen storage is focused on developing new materials with higher storage capacities, faster kinetics, and lower costs. Scientists are also working on improving the understanding of the hydrogen-material interaction mechanisms to optimize the performance of solid-state hydrogen storage systems and make them more competitive in the hydrogen energy market.

This part introduces the historical evolution of hydrogen storage technologies, outlining the basic principles and application backgrounds of high-pressure hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage. Despite the distinct characteristics of the three technologies and their demonstrated certain advantages in different application scenarios, their practical feasibility is still limited by key factors such as energy density, safety, and economic cost. Hence, in the following discussion section, this paper will commence from these core indicators to comparatively analyze the strengths and weaknesses of different hydrogen storage approaches, thereby offering a theoretical basis for the efficient storage and application of hydrogen energy.

3. Discussion

3.1. Energy density comparison

Hydrogen is a clean and efficient energy source with a very high energy density. The energy density of hydrogen refers to the energy contained in a unit volume or mass of hydrogen. The energy density of hydrogen is mainly divided into two types: volumetric energy density and mass energy density. Volumetric energy density refers to the energy contained in a unit volume of hydrogen, while mass energy density refers to the energy contained in a unit mass of hydrogen. Due to the low density of hydrogen, how to increase its volumetric energy density while ensuring storage safety has always been an important direction for technological research and development.

From the perspectives of volumetric energy density and mass energy density, the mass energy density of hydrogen storage at high pressure is relatively high, but the volumetric energy density is relatively low.

Compressed Hydrogen Storage (CHS) is one of the most mature and widely applied hydrogen storage methods at present. It mainly stores hydrogen gas in high-strength storage tanks under pressures up to 35 MPa (350 bar) or even 70 MPa (700 bar). The advantage of this method lies in its high mass energy density, which can reach 120 MJ/kg, approaching the level of liquid hydrogen storage. However, due to the low density of hydrogen gas, even under ultra-high pressures, its volumetric energy density is still relatively low, typically about 4-6 MJ/L [8].

Although the equipment for high-pressure hydrogen storage is relatively mature, its limitation in terms of volumetric energy density makes it have certain disadvantages in scenarios with space constraints. For instance, in long-distance transportation or hydrogen storage stations, larger hydrogen storage containers are needed to meet energy demands. Moreover, high-pressure hydrogen storage tanks are usually made of carbon fiber composite materials to withstand extreme pressure, which increases

production costs. Additionally, the high diffusivity of hydrogen gas requires special sealing designs for high-pressure tanks to reduce the risk of leakage.

Nevertheless, on account of its rapid refueling capacity and relatively low energy consumption loss, high-pressure hydrogen storage remains the mainstream hydrogen storage scheme for fuel cell vehicles. Even though electric vehicle manufacturers such as Tesla are inclined towards lithium-ion batteries, automakers like Toyota and Honda still insist on developing high-pressure hydrogen storage fuel cell vehicles. For instance, the Toyota Mirai adopts a 70 MPa high-pressure hydrogen storage technology [9].

Liquid hydrogen storage has the highest volumetric energy density, yet it entails high energy consumption (30-40% of the hydrogen energy is consumed during the liquefaction process).

Solid-state hydrogen storage has a moderate volumetric energy density, but is limited by materials, resulting in a relatively low mass energy density. Liquid hydrogen storage significantly increases the volumetric energy density of hydrogen by cooling it to -253°C (20 K) to liquefy it, reaching 8-10 MJ/L, far exceeding high-pressure hydrogen storage [10]. Its mass energy density is approximately 120 MJ/kg, comparable to high-pressure hydrogen storage, but due to the higher density of liquid hydrogen, it can store more energy per unit volume.

The main advantage of liquid hydrogen storage lies in its suitability for large-scale storage and transportation. For instance, in the aerospace industry, NASA has long used liquid hydrogen as rocket fuel to maximize energy storage and reduce launch weight. Some hydrogen energy infrastructure projects also prefer liquid hydrogen storage to optimize storage space. However, its main disadvantage is the high energy consumption of the liquefaction process, which typically consumes 30-40% of the hydrogen's own energy. The requirement for a low-temperature environment necessitates complex insulation designs to minimize boil-off losses, further increasing the technical difficulty and economic cost of storage and transportation.

Therefore, liquid hydrogen storage is typically suitable for the intermediate links of the hydrogen energy supply chain, such as large-scale hydrogen transportation and storage. Currently, some countries are actively promoting liquid hydrogen storage technology to build long-distance hydrogen energy transportation networks. For example, the Hydrogen Energy Supply Chain Technology Research Association (HySTRA) in Japan is advancing a hydrogen production project from brown coal, aiming to import hydrogen from Australia through liquid hydrogen storage technology to meet domestic hydrogen energy demands [11].

3.2. Safety considerations

For high-pressure hydrogen storage, there is a risk of explosion of high-pressure tanks, which is influenced by variations in temperature and pressure, and hydrogen leakage is difficult to detect. Although modern hydrogen storage tanks adopt advanced composite materials and multiple safety mechanisms, such as pressure relief valves and pressure relief channels, to decrease the probability of accidental explosions, once subject to severe external impacts, like traffic accidents or fires, high-pressure hydrogen storage tanks still may rupture, resulting in rapid hydrogen release and triggering fires. Additionally, hydrogen has a relatively low autoignition temperature and an extremely wide flammability range, which makes leaked hydrogen highly prone to combustion or explosion in the air.

Furthermore, the detection of hydrogen leakage is rather challenging. Hydrogen is the lightest gas and possesses extremely strong diffusivity. Once leaked, it will rapidly diffuse in the air, forming flammable gas clouds. As hydrogen is colorless and odorless, traditional gas detectors are difficult to detect it, thereby requiring specialized hydrogen sensors. Moreover, during the charging and discharging processes of high-pressure hydrogen storage tanks, local high or low temperature phenomena may occur, influencing the material properties and increasing the risk of leakage.

Liquid hydrogen storage is a method to increase volumetric energy density by cooling hydrogen to -253°C to turn it into a liquid state. However, this ultra-low temperature environment brings additional safety challenges.

Low-temperature operation poses a risk of frostbite. Liquid hydrogen can easily cause contact frostbite, and operators must wear specialized protective gear to prevent direct contact with the extremely cold hydrogen or storage equipment. Additionally, the low-temperature environment can affect the mechanical properties of metal materials, making them brittle and increasing the risk of structural damage to the equipment.

Liquid hydrogen storage also faces the problem of boil-off loss. During storage and transportation, liquid hydrogen will inevitably evaporate gradually due to heat conduction. Although storage containers typically use efficient vacuum insulation technology to reduce heat transfer, this issue cannot be completely eliminated. For example, during long-term storage, boil-off loss may cause pressure build-up, requiring regular gas venting to prevent excessive internal pressure in the storage container. Excessive hydrogen venting not only wastes resources but also may create an explosive atmosphere in confined spaces.

In contrast, solid-state hydrogen storage is considered one of the safest hydrogen storage methods. This technology mainly utilizes metal hydrides, nanomaterials, or adsorbent materials to store hydrogen at relatively low pressures (typically 1-10 MPa). Due to its stable storage form, hydrogen does not easily leak, avoiding problems such as high-pressure hydrogen tank explosions or liquid hydrogen boil-off loss.

The low-pressure operation of solid-state hydrogen storage significantly reduces the risk of physical explosions. Most metal hydrides can store hydrogen under relatively mild conditions, and the hydrogen release process is relatively controllable. For

example, magnesium-based hydrides (MgH_2) can release hydrogen at 300-400°C [12], while titanium-iron hydrides (TiFeH_2) can operate at lower temperatures. Since it does not involve high-pressure environments, the safety of solid-state hydrogen storage systems is much higher than that of high-pressure hydrogen tanks.

Solid-state hydrogen storage systems do not require extreme low temperatures, thus avoiding the problems of low-temperature frostbite and material embrittlement. However, this technology also faces some limitations. For instance, the hydrogen storage and release rates are relatively slow, which may affect the immediate energy supply requirements of hydrogen fuel cells. Additionally, some hydrogen storage materials (such as magnesium-based hydrides) require higher temperatures to release hydrogen, which may lead to additional energy consumption in practical applications.

3.3. Economic feasibility

Economic feasibility of high-pressure hydrogen storage. High-pressure hydrogen storage technology has been extensively utilized in the domain of automotive hydrogen fuel cells. The significant economic challenges this technology confronts are predominantly manifested in two aspects: the costs of compression and tank fabrication. To augment the hydrogen content per unit volume, the process of compressing hydrogen in high-pressure storage commonly employs multistage compressors. The costs of high-pressure gas cylinders and compressors constitute approximately 40-60% of the total cost [13]. To enhance the volumetric energy density of hydrogen, it is typically necessary to lower the pressure; however, this leads to a marginal diminishing trend in the improvement of storage density and a substantial escalation in cost. For example, upgrading from a pressure of 35 MPa to 70 MPa can increase the capacity of the storage system, but it concurrently incurs a significant increase in cost. Additionally, the acquisition and maintenance costs of compression equipment are relatively elevated, and especially in long-term operation, equipment wear and energy efficiency attenuation further drive up the operational cost.

Furthermore, the material cost of storage tanks holds a crucial position in the economic feasibility of high-pressure hydrogen storage. Currently, the most widely applied are carbon fiber composite storage tanks due to their outstanding compressive performance and relatively light weight. Nevertheless, carbon fiber composites are expensive. According to research findings from the U.S. Department of Energy (DOE), the cost of carbon fiber composites accounts for over 60% of the cost of hydrogen storage tanks. Moreover, to guarantee safety and durability, complex multi-layer coating and reinforcement treatments are requisite, which further elevate the manufacturing cost.

From an economic perspective, high-pressure hydrogen storage holds certain advantages when applied in mobile scenarios, such as hydrogen fuel cell vehicles, as its high mass energy density can offer a prolonged ability within a confined space. Nevertheless, due to the high cost of tank materials and high energy consumption, the application of this technology in stationary energy storage systems is restricted.

Economic feasibility of liquid hydrogen storage. Liquefaction cost is one of the core challenges to the economic viability of liquid hydrogen storage. Liquefaction equipment, including refrigerators and cryogenic pumps, incurs high capital costs and daily maintenance expenses. Additionally, the investment in hydrogen liquefaction facilities is substantial; for instance, the initial construction cost of a large-scale liquefaction plant can reach hundreds of millions of dollars.

The materials for cryogenic storage tanks are expensive and have high maintenance costs. To ensure the long-term storage of liquid hydrogen at ultra-low temperatures, the tank bodies typically adopt a high-vacuum multi-layer insulation structure. Materials such as stainless steel and aluminum alloys are chosen, which are not only costly but also require special processing to enhance their low-temperature resistance [14, 15]. Moreover, liquid hydrogen storage tanks suffer from boil-off losses, where hydrogen evaporation during storage and transportation leads to economic losses, especially during long-distance transportation.

Although liquid hydrogen storage has certain economic rationality in long-distance transportation, its high energy consumption and the cost of maintaining ultra-low temperatures make it economically unfeasible in distributed energy storage systems. Therefore, the application of liquid hydrogen storage is more concentrated in hydrogen distribution hubs and large-scale industrial hydrogen energy facilities.

Economic feasibility of solid-state hydrogen storage. The economic performance of solid-state hydrogen storage technology is primarily restricted by material costs and process complexity. Metal hydride materials are costly, particularly magnesium-based and titanium-based hydrides, as the extraction and purification of rare metals involved lead to high raw material costs. For example, alloys like LaNi_5 and TiFe demand high-purity metallurgical processes during their preparation, which are complex and energy-consuming [13].

The production cost of solid-state hydrogen storage technology is also relatively high, mainly due to the intricate preparation processes of hydrogen storage materials and the expensive equipment investment. For instance, to enhance the hydrogen storage capacity and cycling stability of the materials, nano-sizing treatment or alloying is often necessary, which involves processes such as high-temperature and high-pressure sintering and vacuum melting. These procedures are cumbersome and have high equipment requirements [16].

The hydrogen charging and discharging rates of solid-state hydrogen storage are relatively slow. Although it has advantages in safety, this characteristic restricts its application in scenarios requiring rapid hydrogen refueling and large hydrogen flow rates.

Therefore, solid-state hydrogen storage technology is more suitable for small portable devices or household energy storage systems rather than large-scale industrial hydrogen storage facilities.

4. Conclusion

In the current energy transition process with clean energy at its core, hydrogen energy is widely recognized as a crucial component of the future energy system. Nevertheless, hydrogen, as a low-density gas, the efficient, safe, and economical storage method remains a key technical bottleneck for the large-scale application of hydrogen energy. This research focuses on three major hydrogen storage technologies - high-pressure hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage, and systematically compares their performances in terms of energy density, safety, and economy, aiming to offer theoretical support and technical references for the development of the hydrogen energy industry.

The study indicates that the high-pressure hydrogen storage technology holds an advantage in mass energy density and is relatively mature, having been widely utilized in fields such as hydrogen fuel vehicles. However, the manufacturing cost of storage tanks is relatively high, and there exist certain risks of leakage and explosion under high-temperature and high-pressure circumstances. Liquid hydrogen storage demonstrates the most outstanding performance in volume energy density and is suitable for long-distance and large-scale hydrogen transportation and storage. Nevertheless, its preparation process consumes an enormous amount of energy (the liquefaction process consumes 30-40% of the hydrogen energy), and the operation and maintenance costs of the low-temperature storage system are extremely high. Solid-state hydrogen storage has emerged as a research hotspot due to its superior safety performance, particularly suitable for miniaturized and portable application scenarios, such as unmanned aerial vehicles or portable power generation devices. However, the current mainstream hydrogen storage materials, such as metal hydrides, still encounter issues like low hydrogen storage and release rates, high reaction temperatures, and expensive raw materials, which restrict their large-scale promotion.

Comprehensively considering various indicators, the three hydrogen storage methods each have their strengths and weaknesses and are applicable to different application scenarios. The future hydrogen storage system is likely not to rely on a single technology but rather to develop through the synergy of multiple hydrogen storage methods, achieving differentiated layouts based on different usage requirements. To facilitate the realization of this direction, future research should concentrate on the development of new hydrogen storage materials, the structural optimization of hydrogen storage systems, the enhancement of liquid hydrogen preparation efficiency, and the reduction of hydrogen storage equipment manufacturing costs. Additionally, it is necessary to strengthen policy support and industrial collaboration to accelerate the commercialization pace of hydrogen storage technologies.

Although each hydrogen storage technology still confronts its own technical bottlenecks and economic challenges at present, with breakthroughs in materials science and the advancement of large-scale applications, hydrogen storage technology will embrace a more efficient, safe, and sustainable development prospect. This research is conducive to providing systematic decision-making references for policymakers, technology developers, and industrial investors. Under the overarching trend of energy decarbonization, continuously promoting the evolution of hydrogen storage technology holds significant importance for constructing a clean, efficient, and sustainable hydrogen energy society.

This research also has certain limitations. Due to the lack of experimental conditions and first-hand data, this paper could only rely on secondary sources for analysis, and some parts may be slightly theoretical. If given more time and resources, this paper would combine simulation software for modeling analysis or design a more complete application scenario evaluation framework to enhance the practical value of the research.

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