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Hydrogen Energy Storage and Application Solutions

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Abstract:
The surging global energy demand and the environmental safety issues of fossil fuels have highlighted the importance of hydrogen energy as a clean energy carrier. The contrasts among gaseous, liquid, and solid hydrogen storage techniques are examined in this article along with a systematic analysis of hydrogen energy storage and usage systems,and discuss the advantages, disadvantages and application status of hydrogen fuel cells and engines. Despite having a low bulk density, research indicates that gaseous hydrogen storage technology is mature.Liquid hydrogen storage has a high density but consumes a lot of energy and relies on catalysts. Solid-state hydrogen storage has excellent safety, but its cycle efficiency and cost are limited.In the utilization of hydrogen energy, although fuel cells and engines have zero emissions, they are still constrained by high costs and insufficient infrastructure. This study emphasizes the need to break through material bottlenecks, optimize storage and transportation technologies, and promote the synergy between policies and the industrial chain. In the future, efforts should be focused on the coupling of renewable energy with hydrogen storage, intelligent networks and international cooperation to expedite hydrogen energy's fundamental role in the carbon neutrality process.

Keywords: Energy transition; Hydrogen energy storage; Hydrogen fuel cell; Hydrogen fuel engine.

1. Introduction

The demand for energy has been rising gradually globally as a result of urbanisation, economic growth, and expanding populations. Energy holds a crucial position in global issues and is a key driving force for world economic development.Presently, around 80% of the energy used worldwide comes from fossil fuels including coal, oil, and natural gas [1].Massive emissions of greenhouse gases, mostly carbon dioxide (CO_2), from burning fossil fuels are the primary driver of climate change and global warming.The combustion of fossil fuels also releases pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM), causing air pollution and having a serious impact on human health.In addition, energy security concerns and geopolitical problems have resulted from the unequal distribution of fossil fuel resources [1].Moreover, the existing reserves of fossil fuels are approaching depletion. According to current estimates, oil reserves will be sufficient to support human consumption needs for about 40 years, while natural gas can meet those for 60 years. Fossil fuel shortages and increased pollution levels have brought attention to how urgent the energy transition is [2].

Numerous countries have started investing in clean energy sources including solar, hydrogen, wind, and hydropower, which emit little to no greenhouse gases, in order to solve the escalating environmental and energy security concerns [3]. Hydrogen has become a popular clean energy carrier because of its high energy density, environmental friendliness, and variety of applications. Through its smooth integration with renewable energy and resolution of the related instability issues, hydrogen presents a promising solution to the energy sector's problems and could significantly contribute to the global shift towards a more sustainable and low-carbon future.Essential elements of this transition involve the creation, movement, storage, and utilization of hydrogen.

However, researchers face significant obstacles in safely storing and using hydrogen because of its unique molecular characteristics and high energy density. For this reason, countries around the world have begun to explore safe and efficient hydrogen storage and application technologies. For instance, Japan has made significant efforts to enhance safety and effectiveness of hydrogen storage, transportation, and power generation via research and development of high-efficiency hydrogen-powered cell power generating technology and organic liquid hydrogen storage technology. China is also actively exploring its hydrogen energy development strategy, strengthening policy support for storage and transportation of hydrogen, as well as power applications, to ensure the safe and effective growth of the hydrogen energy sector. Because it offers a dependable and secure way to store hydrogen until it is needed, hydrogen storage technology is essential to the efficient use of hydrogen as an energy carrier [4]. The techniques discussed here fall into one of three categories: gaseous, liquid and solid hydrogen storage [5]. The process of turning hydrogen into usable energy or incorporating it into other uses is known as hydrogen utilization technology. These technologies include grid balancing, hydrogen fuel engines, and hydrogen fuel cells, among others [6].

Therefore, this article aims to review the methods of hydrogen energy storage and the main application fields of hydrogen energy. This study focuses on elaborating on three hydrogen storage methods (gaseous hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage), respectively, and explains their respective advantages and disadvantages. They outline the primary areas of use for hydrogen power at the moment, such as hydrogen combustion and fuel cells. Finally, on this basis, the future development of hydrogen energy is projected.

2. Storage of Hydrogen Energy

One viable medium- and long-term energy storage approach is hydrogen storage. Compared to traditional fuels, it has a significantly lower volume density of energy (1/3000 of petroleum), despite having an elevated bulk density of energy.Its volume energy density is 0.01 MJ/L and its mass energy density is 120 MJ/kg. Therefore, raising the overall energy density of hydrogen is a crucial need for creating hydrogen storage [7]. The solution to this problem is expected to lead to substantial progress in hydrogen technology. In addition, hydrogen storage systems must take into account the cost, safety and operation in practical applications [8].

2.1 Storage of Hydrogen in Gas

The two primary types of gaseous storage are underground and compressed hydrogen holdings. Compressed hydrogen storage involves storing hydrogen under high pressure in a gaseous form. Large storage containers made to resist high pressure or high-pressure gas cylinders are used to store compressed hydrogen. The term "underground hydrogen storage" describes the storing of hydrogen in subterranean geological formations, such as aquifers, salt caverns, or layers of depleted oil and gas [9].

2.1.1 Compressed hydrogen storage

Compressed hydrogen allows for the storage of larger amounts of hydrogen in a smaller container, which is a direct and efficient way. Address the issue of its inadequate density of energy per volume. At present, high-pressure gaseous hydrogen storage technology is relatively mature and is the most commonly used hydrogen storage technology in China. Compressing hydrogen under high pressure into a high-pressure-resistant vessel is known as high-pressure gas hydrogen holding. The hydrogen is kept in gaseous form in the high-pressure container, and the hydrogen content stored is directly proportional to the pressure inside the storage tank. Gas tanks are usually used as containers, which are simple and easy to operate. Their advantages include low storage energy consumption, low cost (when the pressure is not too high), and the release of hydrogen can be regulated through a pressure-reducing valve [10]. However, this method has significant limitations. One notable limitation is that its storage capacity may not be sufficient to meet the seasonal energy storage

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demands. In addition, the pressurization process of hydrogen storage tanks is costly, and as the pressure increases, the safety of hydrogen storage will also be greatly reduced, with potential safety hazards such as leakage and explosion [2].

China now stores and transports hydrogen mostly using 35 MPa carbon fiber composite steel cylinders, whereas nations such as Japan primarily utilize 70 MPa hydrogen storage tanks. The density of hydrogen in 35 MPa hydrogen storage tanks is approximately 23 kg/m³, and the density of hydrogen in 70 MPa hydrogen storage tanks is about 38 kg/m³ [10]. In the future, high-pressure gaseous hydrogen storage still needs to develop in the directions of lightweight, high pressure, low cost and stable quality. We should continue to explore new materials for hydrogen tanks have the potential to increase the economics and safety of hydrogen storage while fulfilling the requirements of higher pressure storage of hydrogen.

2.1.2 Underground Hydrogen Storage

In recent years, research on underground hydrogen storage has aroused widespread interest from all aspects to achieve safe and successful operation. Underground hydrogen storage is the cheapest way to store large amounts of gaseous hydrogen. The placement of underground hydrogen warehouses has to be carefully determined, taking into consideration both geological features and budgetary constraints [11].

Aquifers are porous and permeable media, with their pores filled with fresh water or salt water. Aquifers are a feasible option for underground hydrogen storage because they can be found all over the world [12].

Two primary aquifer types are appropriate for storing hydrogen [11]. One type is the confined aquifer, which is naturally surrounded and enclosed by the upper and lower geological layers. By serving as natural barriers, these geological strata effectively stop gas movement and guarantee the safe storage of hydrogen.

Another kind is the unconfined aquifer, which allows groundwater to come into direct contact with the surface because it lacks an impermeable sealing layer at the top. The effectiveness of hydrogen storage may be decreased in unconfined aquifers due to the absence of a natural sealing layer, which might allow hydrogen to rise through groundwater and escape into the atmosphere. Aquifers offer greater flexibility when choosing storage sites. Because of this adaptability, it is more cost-effective to connect hydrogen manufacturing sites, transportation infrastructure, and final use facilities [5].

The best options for storing hydrogen underground are depleted oil and natural gas strata because of their distinct geological structure, high reservoir quality, and the presence of infrastructure that was initially both on the surface and beneath [9].

Additionally, the residual gas in depleted deposits of natural gas and oil might be a promising option for storing hydrogen.However, two significant variables contributing to hydrogen loss are the absorption of hydrogen in either oil or water and the potential chemical interaction of hydrogen with leftover oil [12]. Because the lower cushion gas may be accommodated by the pre-existing reservoir gas and because integrity tests are not necessary for cap efficiency, depleted oil and gas storage systems are better than aquifer storage.

The salt around the salt cavern is highly impermeable and almost leak-proof. The only way for gas to escape is likely through the leaking well or the induced cracks. Nevertheless, the leakage rate may be less than 1% [12].

The greatest advantage of hydrogen storage in underground salt caverns is the simplicity of the technology, the fast charging and discharging of hydrogen, and the provision of a higher level of safety. The drawback is that the volume density of hydrogen does not increase proportionally with pressure, and the microorganisms in sulfate-reducing bacteria can produce H_2S, which is a by-product of salt caverns [7]. Because fluid passage via the pores faces considerable resistance, porous media (depleted natural gas and oil strata and aquifer) are far more appropriate for fundamental demands on load than salt caverns. A salt cavern can support several cycles; however, this way of storing is limited in terms of the number of cycles it can do annually and its modest gas injection rate [9].

2.2 Storage of Hydrogen in Liquid

Hydrogen is cooled and stored at very low temperatures or in organic liquids as part of liquid storage [1]. Compared with gas storage, liquid storage provides a higher density of energy.

2.2.1 Low-temperature Storage of Liquid Hydrogen

Hydrogen is first liquefied at a very low temperature (20K) before being stored in cryogenic insulated containers as part of cryogenic liquid hydrogen storage. The greatest advantage of this method is that hydrogen in liquid form has a volume energy content that is many times greater than compressed storage [13]. Liquid hydrogen has a density of 70.78 kg/m³, which is over 850 times that of hydrogen under normal circumstances. Energy conservation during the liquefaction process and insulating cryogenic storage vessels to minimize hydrogen evaporation are the two main issues of cryogenic liquid hydrogen storage. It can lose as much as 40% of its energy content during the lengthy and energy-intensive process of hydrogen liquefaction. On the other hand, compressed storing hydrogen results in a waste of energy of about 10%. Therefore, small to enormous scale transportation and storage are the most prevalent uses for this preservation technique [4]. Although the storage temperature is relatively low, only 20K, evaporation loss is the main problem. Storage tanks with extremely thick walls are required to be properly insulated and to have extra protective layers in order to safeguard liquid hydrogen [14].

2.2.2 Organic Liquid Hydrogen Storage

Compounds called Liquid Organic Hydrogen Carriers (LOHC) are employed to store hydrogen. During the exothermic hydrogenation process, the raw hydrogen and organic hydrogen stored as liquid mix in the reaction vessel. The solution is then heated to a particular temperature while catalyst is active in order to generate the appropriate unsaturated hydride [8]. Through chemical processes, LOHC may reversibly interact with hydrogen molecules, allowing it to store hydrogen in regulated environments [11]. LOHC is compatible with current storage technology and has a cubic hydrogen holding capacity of about 50 g/L. It is safe and practical, making the application of organic liquid hydrogen storing techniques in liquid form storing systems increasingly important [7]. However, this concept has not yet been widely accepted, mainly due to reasons such as the insufficient stability of dehydrogenation catalysts and the technical constraints on the energy needed for hydrogen release [8].

2.3 Storage of Hydrogen in Solid-state

Hydrogen is stored in solid materials using solid-state methods of preservation, including chemical adsorption and physical adsorption, similar to adsorption on porous materials like carbon or metal hydrides. Compared to gaseous or liquid storage, this method can store hydrogen at lower temperatures and pressures, thereby boosting energy density and lowering the need for infrastructure [15].

2.3.1 Hydrogen Storage in Metal Hydrides

The usage of metal hydride substances to store hydrogen is referred to as metal hydride hydrogen storage (such as $NaAlH_4$, $LaNi_5H_6$, MgH_2) to store and release hydrogen. The reaction of transitional metals or composites with hydrogen under pressure and at a specific temperature, adsorbs the hydrogen as metal hydrides, which are then heated to liberate hydrogen [10].

High volume capacity for hydrogen preservation, ease of use, secure transport, and excellent economics are the benefits of metallic hydride hydrogen preservation technology. Metal hydrides (MgH_2 at 6.5 H atoms/cm^3) have a greater retention of hydrogen capacity compared to hydrogen in its liquid form (4.2 H atoms/cm^3) [13]. A relatively safe and possibly efficient solution for high-density hydrogen preservation is metal hydrides. Compared with compressed hydrogen storage, they can eliminate the energy needed for compressing or liquefied. Research, development and demonstration of metallic hydride hydrogen retention technologies are still ongoing, with relatively few applications. The main remaining challenges it faces include reducing material costs, enhancing the ability of metallic hydrides to preserve hydrogen, improving their recyclability, and controlling the formation of unwanted gases during desorption [4].

2.3.2 Hydrogen Storage in Cavities Carbon-based Materials

Hydrogen storage in cavities materials is the method of preserving hydrogen in solid adsorbents through physical adsorption, such as porous carbon-based materials, MOFs, zeolites, metal nitrides, etc [13].

Through a variety of techniques, include carbonization, activation, and hydrothermal treatment, porous materials based on carbon may be produced from a variety of carbon-rich predecessors, comprising carbon dioxide, fossil fuels, and polymer compounds, both sustainable and non-renewable [15]. Materials made of perforated carbon have a large pore size and a particular area on the surface, which can physically adsorb hydrogen in the porous matrix, facilitating hydrogen storage. Compared with the chemical adsorption of materials such as metal hydrides, physically adsorbed hydrogen has quicker both adsorption and desorption rates and is simpler to release hydrogen [5]. In addition, the advantage of using porous carbon-based materials is that they can withstand high pressure without affecting their structure and pore characteristics. The hydrogen absorption capacity of porous carbon is very small and varies linearly with pressure at room temperature. However, near the boiling point of nitrogen (77 K), the total surface area of the material with holes and its capacity to hold hydrogen have a linear relationship that is unaffected by the characteristics of the carbon substance. The capacity of porous carbon-based compounds to store hydrogen can be enhanced through numerous methods, including division, ionization, radiation, transition- metal doping, and conditions of culture (climate, stress, and hydrogen charge duration) [6].

2.4 Comparison of Three Hydrogen Storage Methods

To sum up, it is possible to summarize and draw conclusions about the benefits and drawbacks of the three different methods of storing hydrogen: gaseous, liquid, and solid. Table 1 lists the benefits and drawbacks of the three hydrogen preservation techniques.

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Table 1. Comparison of the benefits and drawbacks of three hydrogen preservation technologies

Hydrogen preservation technology	Benefits	Drawbacks
Gaseous storage	The method is relatively mature, with fast hydrogen charging and discharging speeds, and low cost and energy consumption.	The hydrogen storage density per unit volume is low.
Liquid storage	It is somewhat safe and has an excellent hydrogen preservation capacity per volume.	Hydrogen liquefaction consumes a lot of energy and requires strict operating conditions.
Solid-state storage	It has an outstanding hydrogen preservation capacity per volume, low energy consumption and good safety.	The technology is not mature and the efficiency of hydrogen charging and discharging is low.

3. Utilization of Hydrogen Energy

3.1 Hydrogen Fuel Cell

Hydrogen fuel cells are integrated electrochemical devices that are widely used to generate electrical energy from chemical energy by use of REDOX processes. Typically, an electrolyte membrane layer, a cathode, and an anode make up a hydrogen fuel cell [16]. There are five most common fuel cells. Among them, the proton exchange membrane fuel cell has a low working temperature and quick start-up, making it appropriate for the transport industry. Solid oxide fuel cell is all-solid-state and has a high conversion of energy rate. The energy producing gadget is both efficient and clean, typically used in large-scale centralized power supply, distributed power generation, and other fixed power stations [10].

The products of hydrogen fuel cells only contain electricity, water and heat. The current generated by a single hydrogen fuel cell is of low voltage, so multiple individual hydrogen fuel cells need to be stacked to match the required power. Moreover, in a hydrogen fuel cell system, direct current (DC) must be transformed to alternating current (AC) using an inverter [9]. Advantages of hydrogen fuel cells lie in the fact that their reactants are supplied externally and the constituent materials are not consumed. Therefore, as long as fuel and oxidants are available, hydrogen fuel cells can operate continuously. Moreover, they have high thermodynamic efficiency and pollution-free products. However, factors such as high prices, lack of hydrogen infrastructure, and immature technology have hindered the large-scale commercialization of fuel cells [16]. Increasing power density and effectively using platinum or other substitutes in electrodes can both help reduce the cost of fuel cells. In addition, establishing an economically effective and convenient hydrogen supply is a necessary condition for fuel cells to be competitive or economically feasible.

3.2 Hydrogen Fuel Engine

Hydrogen has excellent combustion properties. It has a high calorific value, good combustion stability, complete combustion, and a very high flammability ratio of hydrogen in air (4%-75% by volume). Hydrogen fuel contains no carbon components, so it does not produce carbon-based emissions such as carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM) after combustion, and the combustion is clean. These characteristics make it applicable in internal combustion engines, and the working principle of hydrogen fuel engines is the same as that of conventional spark-ignition combustion engines. A hydrogen fuel engine consists of four processes: intake, compression, power generation and exhaust. Hydrogen fuel mixes with air and burns in the combustion chamber to generate high-temperature and high-pressure steam. The gas produced by combustion drives the piston to move, completing the transformation of chemical power to mechanical power. The advantage of hydrogen fuel engines is that they can adjust the power output by the concentration of the combination of gasoline and air ratio, without the need for a throttle valve, and there is no loss of flow in the fuel pump. In addition, the octane number of hydrogen is as high as 130, and its self-ignition temperature is very high. During the compression process of the engine cylinder, it has a strong ability to resist premature combustion. Therefore, it is possible to adopt a greater ratio of compression, which is the ratio of the cylinder's highest volume to its lowest volume while piston is at both ends of the stroke.

All of these can enhance the overall efficiency of the engine [15]. According to Ford, a hydrogen fuel engine with a compression ratio of 14.5:1 can achieve a maximum efficiency of 52%.

Although hydrogen fuel engines have excellent performance, several technical challenges must be addressed to achieve large-scale application. Firstly, the volumetric energy density of hydrogen is rather low, and since it is a gaseous fuel under standard temperature and pressure conditions, it is inevitable that compressed hydrogen systems need to be added, which leads to the need for external input energy to match the demand [16]. In terms of engine operation, due to the fuel properties of hydrogen that are different from those of conventional fuels, for instance, hydrogen only requires an ignition energy that is one order of magnitude smaller than that of gasoline. This means that the residual heat or thermal residual gas in the combustion chamber can trigger abnormal combustion of hydrogen. Therefore, the hydrogen injection and combustion strategies must be carefully adjusted, with a focus on the design of the combustion chamber, fuel injection parameters, and the application of cold spark plugs [16].

4. Conclusion

This article systematically reviews the storage technologies and application fields of hydrogen energy, echoing the urgency of global energy transition and the crucial role of hydrogen energy as a clean energy carrier. Research shows that the core challenge of hydrogen energy storage technology lies in balancing energy density, safety and economy. The gaseous hydrogen storage method is mature and cheap, but its volumetric energy density is insufficient. Although liquid hydrogen storage (at low temperatures and with organic carriers) can significantly increase hydrogen storage density, it has difficulties with catalyst stability and excessive energy usage. Storage of hydrogen in solid states (like metal hydrides and porous materials)has outstanding potential in terms of safety and energy density, but cycle efficiency and material cost remain bottlenecks. In terms of hydrogen energy utilization, fuel cells and hydrogen fuel engines have demonstrated advantages of zero emissions and high energy efficiency. However, their large-scale application is constrained by insufficient infrastructure, high technical costs, and the complexity of system integration.

Hydrogen energy, as a bridge connecting renewable energy and end applications, its development is not only related to energy security and climate goals, but also a core driving force for reshaping the global energy landscape. Future research should focus on developing new composite materials to enhance the cycling stability of solid-state hydrogen storage. Explore hydrogen liquefaction processes coupled with renewable energy to reduce energy consumption; Build an intelligent hydrogen energy network and integrate the production, storage, transportation and utilization links.

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