Current Research Status on The Production, Storage, And Application of Hydrogen Energy

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Abstract. With the development of society, the demand for energy has significantly increased, and the hydrogen energy industry is an important engine for optimizing energy structure and promoting the transformation of traditional energy. Hydrogen energy is a clean and renewable energy source with abundant sources. The unit mass of hydrogen contains a large amount of energy and can be applied in a wide range of fields. Therefore, analyzing and comparing the hydrogen energy industry chain will contribute to the healthy development of the hydrogen energy industry. This article first investigates the initial stage of development, current situation, and policies of hydrogen energy in China, Japan, and the United States, in order to gain a deeper understanding of the research status and planning of hydrogen energy in different countries. Secondly, the current mature hydrogen production methods (reforming hydrogen, electrolysis hydrogen) and hydrogen storage methods (high-pressure hydrogen storage, solid-state material hydrogen storage, organic liquid hydrogen storage materials) Hydrogen application are analyzed, and their advantages are proposed. Finally, based on research analysis, the future hydrogen energy market is introduced. This research result also provides certain reference value for enterprises that need to transform and enter the hydrogen energy field.

Keywords: Hydrogen energy, Hydrogen production, Hydrogen application.

1. Introduction

With the development of social economy, the increasing demand for energy by humans, especially the excessive dependence on petroleum and other renewable energy sources, not only damages the ecological environment but also generates an excess of carbon oxides that the Earth cannot absorb. The world is facing a serious energy crisis due to the excessive use of non-renewable energy. According to the BP World Energy Statistical Yearbook [1], in 2020, the carbon dioxide emissions from China's use of coal reached 9.894 billion tons, accounting for 30.9% of the global total. In 2021, it increased to 11.9 billion tons, accounting for 33% of the global total. It is expected to reach the peak of carbon emissions globally by 2030, known as "carbon peaking", causing increasingly serious problems such as acid rain and global warming. The development of society requires energy as the foundation, but the shortage of energy supply has become a roadblock on the road to development. Therefore, it is necessary to transform the consumption structure of energy, promote the conversion of new and old energy, search for new energy sources with abundant reserves, and reduce environmental pollution. In recent years, accelerating the development of green energy and low-carbon is the key to achieving high-quality development.

Currently, hydrogen energy, as the most representative renewable energy, can be utilized on a large scale due to its advantages of zero pollution, high energy, and easy access. According to the 2022 Report on the Development of China's Hydrogen Energy and Fuel Cell Industry, China has approximately 56000 tons of renewable hydrogen energy. Among similar energy sources, hydrogen has the highest gravimetric energy density (hydrogen 142.3 MJ/kg, gasoline 47 MJ/kg, coke 32 MJ/kg). Hydrogen energy is the most ideal secondary energy source that can be developed, and it is also the key to achieving high operation of comprehensive energy [2]. Therefore, hydrogen energy has great potential value and can be effectively and reasonably invested in future development. It is very important to optimize the energy structure and promote the transformation and upgrading of traditional industries by developing the hydrogen energy industry as the main focus.

Research has found that the utilization technology of hydrogen energy mainly includes three steps, i.e., hydrogen production, hydrogen storage and transportation, and hydrogen application. Among all the steps, hydrogen storage and transportation are the most difficult and costly. High pressure gaseous transportation, cryogenic liquid storage, and solid-state hydrogen storage materials account for over 50% of the total cost. Therefore, the current storage and transportation technology has not yet met the requirements. Although China has not yet made large-scale investments and developments in hydrogen energy, it is crucial to accelerate China's research and evaluation of the potential value of hydrogen energy in the market, as well as assess its impact on the future market. This can help promote the development of the hydrogen industry in a prepared manner. This article will discuss the research and future plans of hydrogen energy in various countries.

2. Current Status of Hydrogen Energy Research in Various Countries

China started hydrogen energy relatively late compared to advanced countries, but currently, the domestic hydrogen energy industry has preliminarily mastered processes from hydrogen production, storage and transportation, hydrogen refueling stations, fuel cells, and other systems. Small scale demonstration applications of hydrogen fuel cell vehicles have been achieved in some regions [2]. Since 2018, the annual output value of hydrogen energy in China has reached a scale of 20 million tons, and the overall production has shown an increasing trend. Since hydrogen energy was included in the energy category in 2020, the country has advocated for hydrogen energy and its position in the green development energy system has become increasingly prominent. The National Energy Administration has issued relevant policies to guide the development of hydrogen energy. From the analysis of the relevant policies on hydrogen energy issued by the country, it has greatly promoted the high-quality development of China's hydrogen energy industry.

In recent years, the progress of hydrogen energy in Japan has been very rapid. Due to Japan's scarcity of resources, especially fossil fuels and other resources, most of its energy needs to be imported [3]. Therefore, Japan is gradually shifting its main energy supply methods towards hydrogen energy transfer. Japan is one of the world's leading countries in the hydrogen energy industry. Japan's hydrogen energy vehicles have obvious advantages and are far ahead in terms of technology patents. Regarding the field of hydrogen energy, research began in the 1980s and has accumulated and developed over the years. At the same time, the Japanese government has also invested a large amount of funds in the hydrogen energy industry to support the development of hydrogen energy. Since 2001, the Japanese government has introduced strategies such as the Hydrogen and Fuel Cell Strategic Roadmap and the Hydrogen and Fuel Cell Promotion Act. These policies not only plan for Japan to use hydrogen energy as its main energy source in the future, but also provide guarantees for the technology and development of hydrogen energy [3]. Therefore, 70% of hydrogen fuel cell vehicle patents in the world are in the hands of the Japanese.

Since the United States received renewed global attention to carbon emissions in 2019, hydrogen energy and hydrogen fuel electric vehicles have been given more attention by various countries. However, hydrogen energy is not a novelty that has emerged. The United States proposed the concept of a "hydrogen economy" as early as the 20th century, with the goal of proposing clean, economical, and reliable hydrogen energy. In the early 20th century, the National Hydrogen Energy Roadmap was proposed, but due to its innovative concept, the technology and equipment provided at that time were limited and did not match what the market needed. Therefore, the development of the industry is slow. The research on hydrogen energy in the United States has a high upper limit, as it is not only an economic powerhouse but also a talented country, laying the foundation for detailed hydrogen energy research. On October 13, 2023, Biden announced at the White House that the government will provide $7 billion to establish clean hydrogen centers in seven regions of the United States.to accelerate the development of the clean hydrogen market and strengthen energy security in the United States.

3. Production of Hydrogen Gas

3.1. Reforming Method for Hydrogen Production

Methane steam reforming reaction is an important chemical reaction.

Also known as water gas conversion reaction, the chemical equation is:

$$CH_4 + H_2O=CO+ 3H_2 \quad (1)$$

It is one of the main methods for converting natural gas, petroleum and other hydrocarbons into synthetic gas. Among them, syngas is an important chemical raw material that can be used to manufacture chemicals such as synthetic ammonia, synthetic methanol, and synthetic oil [4]. Therefore, steam reforming reaction plays an important role in the chemical industry. This reaction needs to be carried out under high temperature and pressure, usually using a nickel based catalyst. In the reaction, methanol and water vapor react under the action of a catalyst, producing carbon monoxide and hydrogen gas. Moreover, based on the release of a large amount of heat during the steam reforming reaction process, the heat generated by the reaction increases the temperature, making the reaction more thorough and intense, and increasing the reaction rate.

Methanol, also known as hydroxymethance or wood alcohol, is a common and simple saturated monohydric alcohol often used in chemical industry [5]. Methanol reforming is also a commonly used method in hydrogen production. Methanol reforming for hydrogen production mainly includes steam reforming, shift reaction, and methanol steam shift. At the same time, methanol reforming for hydrogen production also has many advantages.

(1) Methanol has a wide range of sources in nature (can be directly or indirectly obtained from organic compounds produced by photosynthesis) and is commonly used in the chemical dye industry due to its low price;

(2) The utilization rate of hydrogen element in methanol is high, and the molecular formula of methanol is CH_3OH with a high hydrogen content ratio and high energy density

(3) The equipment for producing hydrogen from methanol is relatively simple, as methanol is liquid at room temperature and the temperature for methanol reforming is within 300 degrees Celsius for hydrogen reforming.

Step 1: Steam reforming usually uses metals such as nickel, palladium, and rhodium as catalysts at high temperatures and pressures to react methanol and water vapor to produce carbon monoxide and hydrogen gas. Step 2: The transformation reaction generates carbon dioxide and hydrogen gas from carbon monoxide and water vapor under the action of a catalyst. This step is the crucial step in generating hydrogen gas. Step 3 methanol steam transformation: the remaining methanol reacts with water vapor under the action of a catalyst to produce carbon dioxide and hydrogen gas. This step is to fully utilize the remaining hydrogen atoms in methanol and increase the production of hydrogen in the total product.

The above reforming produces hydrogen gas, and due to the presence of organic compounds such as methane and methanol as reactants, the byproducts of the reaction are carbon dioxide and carbon monoxide. It should be noted that carbon oxides are harmful pollutants to the atmosphere, and secondly, carbon monoxide can cause harm to the human body. Therefore, reforming hydrogen production is not the optimal choice.

3.2. Water Electrolysis

Hydrogen production by electrolysis of water is actually based on an electrolysis cell, which consists of four parts, cathode, anode, electrolyte, and external power supply. Electrolysis is the process of using electric current to decompose water into new substances (oxygen and hydrogen) [6]. When electrolyzing water, pure water is a typical weak electrolyte with no other impurities, low ionization degree, and low conductivity. Therefore, it is often necessary to add other electrolytes to increase the ionization ability of the solution, in order to successfully electrolyze water to obtain the required hydrogen gas and by-product oxygen. Electrolytic production usually selects substances

such as sulfuric acid, sodium hydroxide, potassium hydroxide, etc. The total reaction equation is as follows:

$$\text{total reaction: } 2H_2O \rightleftharpoons 2H_2+O_2 \quad (2)$$

The total reaction can be divided into a reduction reaction (or hydrogen evolution reaction) occurring at the cathode and an oxidation reaction (or oxygen evolution reaction) occurring at the anode. Due to the increase in electrolysis and ionization energy, the solution can be divided into acidic, alkaline, and neutral [7]. Although their final product is the same, the reaction process and intermediate products are different [8].

The reaction equation in acidic electrolytes is as follows:

$$\text{cathodic reaction: } 4H^+ + 4e^- \rightleftharpoons 2H_2 \quad (3)$$

$$\text{anodic reaction: } 4H^+ + 2O^{2-} - 4e^- \rightleftharpoons 2H_2O \quad (4)$$

The following reactions occur in alkaline or neutral electrolytes:

$$\text{cathodic reaction: } 2H_2O + 4e^- \rightleftharpoons 2H_2 + 4OH^- \quad (5)$$

$$\text{anodic reaction: } 4OH^- \rightleftharpoons 2H_2 + O_2 + 4e^- \quad (6)$$

The generated gas can be filtered through a specific device to obtain hydrogen gas.

Electrolytic water production of hydrogen is a sustainable energy production method with environmental and sustainable characteristics. Using electricity to generate hydrogen gas, theoretically every two water molecules decompose into one oxygen molecule and two hydrogen molecules. It can be seen that the theoretical conversion efficiency is 100%, but in practice, the conversion efficiency of electrolytic water is often lower than 100% due to various factors. In general, as electrolysis proceeds, water is gradually consumed and the concentration of electrolytes in the solution increases. Affects the ionization degree of water. Therefore, the conversion rate of energy needs to be considered. According to current data, the total electricity consumption for producing one kilogram of hydrogen is 50-55 kWh, which is 180000 KJ to 198000 KJ in energy units. The energy contained in one kilogram of hydrogen is 143000KJ, and the overall energy conversion efficiency is 72% to 79%. The conversion rate is relatively high. At the same time, electrolysis of water for hydrogen production does not produce any pollutants, making it a clean and environmentally friendly hydrogen production method that is in line with the current development background. Moreover, the flexibility of the reaction is high and can be adjusted according to actual requirements, achieving complete control over the occurrence and cessation of the reaction.

4. Brief Introduction and Comparison of DifferenH hydrogen Storage Methods

4.1. High Pressure Hydrogen Storage

High pressure hydrogen storage technology is a technical method of compressing and pressurizing hydrogen gas, and storing it in a high-pressure form [9]. Hydrogen gas is stored and transported in gas transport bottles under high pressure (15.2-70.9 megapascals), and the release of hydrogen gas can be controlled by adjusting the pressure reducing valve. Convenient and reliable, it is the most practical and common hydrogen storage method. Hydrogen energy storage technology is gradually receiving attention in the hydrogen energy industry chain. Reasonable storage of the produced hydrogen can effectively solve the safety and efficiency issues throughout the entire process. As one of the basic thermodynamic parameters, high pressure actually compresses the distance between hydrogen molecules, which is often accompanied by the overlap of electron clouds in the molecules, which may change the physical, chemical and other properties of the substance [8]. It is also possible to generate and form phase transitions into structures that have not yet been recognized. Therefore, physical behavior detection is required during the pressurization process.

The basic structure of high-pressure hydrogen storage containers is as follows.

The hydrogen storage pressure vessel mainly consists of a high-pressure hydrogen storage vessel with a metal lining, and the outermost layer of fiber protection layer, among other parts [9]. And four basic pressurized hydrogen storage containers.

The first type is a metal hydrogen storage container, mainly made of steel structure, so it is the heaviest and often very difficult to transport. Mainly used for fixed purposes in industry. The first type of container can store approximately 1% of the world's hydrogen gas, with a pressure of 200-300 bar.

The second type is lighter than the first type because composite materials are added to the circumferential structure. However, due to the high weight of the first two models, the hydrogen storage density is low, which is often not suitable for vehicle applications.

The third type uses metal Al as the inner lining and is wrapped with certain composite materials, which not only reduces weight but also acts as a barrier for hydrogen permeation, while eliminating brittleness and providing over 5% mechanical resistance. Type III is often proven to be reliable in the pressure range of 450-700 bar.

The main difference between the fourth and third types is the use of high-density polyethylene plastic as the lining, usually composed of carbon/glass fiber reinforced epoxy resin matrix composite materials. Therefore, the fourth type of container is the lightest pressure vessel and is often the ideal choice for vehicle applications, capable of withstanding pressures up to 1000 bar.

4.2. Solid State Hydrogen Storage Material Storage

According to figure 1, solid state hydrogen storage mainly utilizes the physical and chemical adsorption of hydrogen by metal materials (reacting with hydrogen to generate new substances), and stores hydrogen elements in solid materials. During use, reverse reactions are carried out to decompose and obtain the required hydrogen gas. Compared with other hydrogen storage methods, solid-state hydrogen storage has advantages such as less leakage, high density, high safety, and long storage time. It is currently the most widely used and has a high future limit as a means of hydrogen storage.

Hydrogen storage materials are mostly composed of metallic elements such as Mg, V, Ca, Ti, Co, Ni, etc, or a mixture of multiple elements, such as AB5 series (lanthanum nickel alloy $LaNi_5$), AB2 series (zirconium manganese alloy $ZrMn_2$), A2B series (magnesium nickel alloy Mg_2Ni), AB series (titanium iron alloy TiFe) [10]. Essentially, the metal that can store hydrogen atoms depends on the properties of the metal itself. There are often large enough gaps on the surface, and the more space there is to store hydrogen atoms, the better the hydrogen storage material [11].

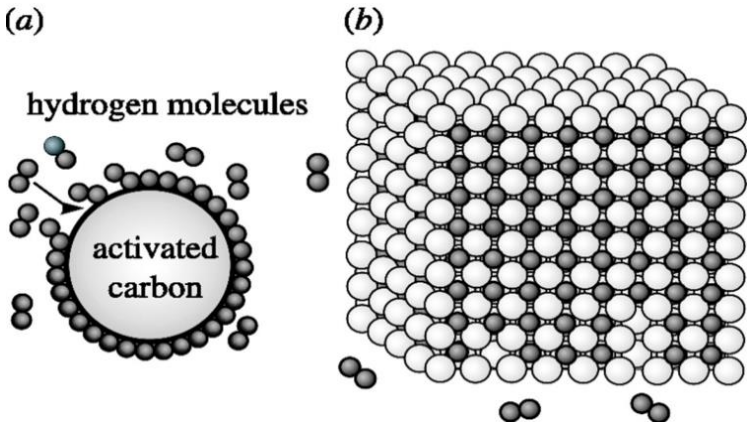


Fig. 1 Hydrogen adsorption. (a). Physical adsorption of hydrogen molecules. Hydrogen element dose not participate in the reaction and is adsorbed on activated carbon. (b). Chemical adsorption of hydrogen element. Hydrogen breaks chemical bonds to form hydrogen atoms and occupies voids in metals or alloys [12]

4.3. Organic Liquid Hydrogen Storage

Organic liquid hydrogen storage materials include two types, traditional organic liquid hydrogen storage materials and new organic liquid hydrogen storage materials. The principle of the traditional type is that chemicals such as benzene, toluene, and naphthalene react with hydrogen to change their substitution number and bonding mode, and change their chemical properties to store hydrogen. When hydrogen is needed, it is removed through high-temperature chemical reactions, but currently there are still side reactions such as cracking in high-temperature chemical reactions. The utilization rate of hydrogen element is low, accompanied by the generation of impurities.

5. Hydrogen Energy Application

When hydrogen energy technology is mature and mastered, it can achieve civilian hydrogen energy. It can be divided into two categories. The first is the hydrogen internal combustion engine that directly burns hydrogen to generate energy, and the other is the hydrogen fuel cell, which is relatively mature in technology and has high efficiency as its main advantage and is currently the mainstream. If hydrogen fuel cells are used to power new energy vehicles, it reduces the consumption of kerosene, reduces carbon dioxide emissions, and generates more energy compared to other energy sources. It can also be applied to civilian drones. Compared to conventional lithium-ion batteries, hydrogen energy improves the current problems of short endurance and insufficient power of drones, bringing a better experience.

In recent years, China's military field has achieved rapid development. In the modern high-tech military environment, many advanced military equipment is gradually being put into use. This includes communication equipment, special vehicles, and advanced weapons. Hydrogen energy technology also has great potential for development in the military field. With the development of military combat capabilities and reconnaissance and anti-reconnaissance technologies, there is an urgent need for new supply methods. Hydrogen fuel cells also have advantages such as low infrared signal, good stealth performance, high endurance, and low noise, and are highly favored in the military region. As hydrogen fuel cells excel in endurance, the flight records of electric drones are mostly created by hydrogen fuel cell drones, which not only have strong compliance but also can achieve rapid replenishment. At present, the military regions stationed in the cold regions of the plateau mainly rely on diesel generators for power supply. Although diesel power generation technology is relatively mature, in extreme environments, there are often factors such as high energy consumption, long start-up time, high transmission losses, low power supply efficiency, and instability due to low temperatures. Taking all factors into consideration, hydrogen generators can greatly alleviate the aforementioned drawbacks. In summary, with the increasing requirements of military power systems, military fuel cells have been widely used as a new type of power supply device in the military field due to their outstanding advantages of high efficiency, cleanliness, economy, and safety.

6. Conclusion

The paper investigates and studies the starting point, current situation, and future development of different countries, and finds that most countries are vigorously developing hydrogen energy, emphasizing the importance of hydrogen energy in future energy systems. Furthermore, the paper provides a detailed explanation of the production, storage, transportation, and application of hydrogen energy. The ultimate goal of hydrogen production is to achieve blue hydrogen that does not produce greenhouse gases during the process, which not only has no pollution but also improves the utilization rate of hydrogen elements. Secondly, the storage of hydrogen energy should be long and safe. When using hydrogen, it is necessary to choose a hydrogen storage method with fewer side reactions and a controllable reaction rate and improve the yield of hydrogen element. In the future, the production, storage, and application of hydrogen energy can achieve efficiency and safety, and can be supplied

to different groups in different regions for use. When hydrogen is widely used in future daily life, it is within reach. However, due to the low density of hydrogen, the transportation and storage of hydrogen are difficult and require a large amount of equipment. At the same time, hydrogen is a flammable and leak prone gas, which can easily cause safety accidents during storage and transportation. It is a major risk in industries and other fields, so frequent testing and maintenance are also required, which further increases costs. Although hydrogen energy has many advantages, its potential drawbacks will limit the development of hydrogen energy and the future hydrogen energy market. It is necessary to continuously improve and develop corresponding technologies while developing hydrogen energy, constantly explore new methods, and solve the safety issues of hydrogen energy, in order to prevent accidents before combustion.

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