

Current Status and Future Prospects of Hydrogen Energy Technology Research in China under Carbon Peaking and Carbon Neutrality Background

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Abstract

Hydrogen energy is an important carrier for building a diversified energy supply system based on clean energy in the future, and its development and utilization have become an essential direction for the new round of world energy technology change. As a member of new energy, hydrogen energy is sustainable and clean, so it has attracted the attention of global energy researchers and is considered as one of the ideal energy sources in the future. This paper introduces the characteristics of hydrogen energy and the current status of its production, and details the problems and challenges that hydrogen energy may face.

Keywords

New Energy; Hydrogen Energy; Hydrogen Energy Utilization Technology.

1. Introduction

Global energy sources mainly include traditional fossil energy sources, such as coal, oil and natural gas, and new clean energy sources including wind, water, solar, ocean and hydrogen[1]. With the progress of human society, the energy problem is also increasing. Traditional fossil fuel is not renewable, and its combustion produces toxic gases and greenhouse gases that seriously pollute the environment. According to the International Energy Agency, global energy demand will increase by nearly 30% by 2040, and natural gas demand will continue to increase until 2030, with continuously soaring low-carbon demand. Under the background of Carbon Peaking and Carbon neutrality, in order to cope with the increasing energy demand and low carbon demand, and accelerate the global transition from fossil economy to low carbon economy, it is urgent to develop new clean and inexpensive energy sources[2].

As a member of new energy sources, hydrogen energy is an efficient and ideal clean energy source[3]. Due to its many advantages such as pollution-free combustion, high energy density, high chemical activity and excellent reproducibility, it has attracted the attention of energy researchers worldwide and is considered as one of the optimal energy sources in the future, and the research on hydrogen energy continues to be hot at home and abroad.

2. Overview of Hydrogen Energy

2.1 What is Hydrogen Energy

It is well known that hydrogen is the most abundant element in nature, accounting for about 75% of the mass of the universe. However, except for the small amount of elemental hydrogen (H₂) contained in air, hydrogen is mainly stored in the form of compounds, mainly in water. Since water is the most widespread substance on earth, it can be said that hydrogen energy is one of the most abundant energy sources that humans can obtain from nature, and it is also one of the most efficient energy sources, so energy researchers believe that hydrogen energy has unparalleled potential research and development value for future society[4].

2.2 Characteristics of Hydrogen Energy

Advantages of hydrogen energy: among all existing elements, hydrogen is the lightest, and among all existing gases, hydrogen has the best thermal conductivity, the highest heating value, excellent combustion performance, high ignition point, and at the same time non-toxic and non-hazardous. In nature, hydrogen is widely present in air and water, so the raw materials for extraction are abundant. In the process of utilization, hydrogen energy can be utilized in various forms and with simple equipment, while in the storage and transportation, it can be stored and transported in the form of gaseous, liquid or solid hydrogen compounds.

Disadvantages of hydrogen energy: there are many problems in the development and utilization of hydrogen energy, such as hydrogen production technology, and storage and transportation technology. The first immediate concern is the development of cheaper hydrogen production technology, which hydrogen researchers are currently working on. Secondly, since hydrogen is the lightest element available, it is important to consider its safety when storing and transporting it. For example, hydrogen is more likely to leak through gaps than liquid and other gaseous fuels, and the choice of transport materials is more prone to hydrogen embrittlement due to manganese steel, nickel steel and other high-strength steels.

3. Hydrogen Energy Production Technology

There are many ways to produce hydrogen, both primary and secondary energy sources can be used to produce hydrogen. At present, hydrogen production routes mainly have four categories: one is electrolysis of water to produce hydrogen, its hydrogen purity can reach 99.7%; Second, reforming fossil energy represented by coal and natural gas to produce hydrogen; Three is coke oven gas, chlor-alkali industry as the representative of industrial by-product purification hydrogen production; Fourth, use renewable energy to produce hydrogen. The comparison of each process is shown in Table 1.

From the overall analysis of Table 1, methanol cracking to hydrogen is an economic way to produce hydrogen, although its production scale is small, raw materials are easily available, investment cost is low, and the purity of hydrogen can be as high as 99.99% after PSA purification, which is perfectly fine as intermittent and supplementary manufacture of hydrogen. In addition, hydrogen production from renewable energy has always been a research and development project of various countries. It can use energy such as wind and light abandonment to reduce the waste of energy. It is the most potential and promising process in hydrogen production industry in the future.

Table 1. Comparison of different hydrogen production processes

Hydrogen production methods	Main technologies	Principle	Upsides	Downsides
Electrolytic water Hydrogen production	Electrolytic water	Hydrogen and oxygen are produced by electrolysis of water	Simple process, flexible production, green	High cost and high power consumption
Fossil energy reforming to hydrogen	Water and gas	Converting coal into syngas by gasification technology, and then purifying the water gas by conversion and separation treatment	Mature and efficient process, stable production on a large scale, low cost of hydrogen production	Long process flow, relatively complex operation, high investment
	Natural gas steam reforming	At a certain temperature and in the presence of a catalyst, the exchange reaction between methane and water vapor occurs	Mature process, reliable plant operation, strong economy, green and environmental protection	Large investment in industrial equipment, easy carbon deactivation of catalysts
Hydrogen production from industrial by-product purification	Coke oven gas	Pressure Swing Adsorption (PSA) purification	Low input, high output, energy saving and consumption reduction	Mostly used in the steel industry for its own recycling, limited external supply of hydrogen
	Chlor-alkali industry	Dissolve saturated NaCl solution by spotting	Low purification difficulty, low impurity content, high utilization rate	Small scale, low ion membrane localization rate, chlor-alkali imbalance, high energy consumption
	Methanol cracking	Methanol and water under certain temperature, pressure and catalyst undergo cracking transformation reaction to produce hydrogen gas	Flexible scale, low investment cost, low carbon emission, sufficient and easy access to raw materials	Production scale is limited
	Propane Dehydrogenation (PDH)	Propylene and hydrogen are produced from propane at high temperatures and by the action of a catalyst	High purity of hydrogen, less difficulty in purification	Catalysts are more expensive
Renewable Energy to Hydrogen	Biomass gasification to hydrogen	The biomass raw material (straw) is pressed and shaped in the gasifier.	Biomass is abundant and an important renewable energy source	-
	Microbial hydrogen production	Enzyme-catalyzed reaction using microorganisms at room temperature and pressure to produce hydrogen		
	Solar Hydrogen Production	Adding catalyst to water, using solar energy		

3.1 Electrolysis of H₂O to Produce Hydrogen

Hydrogen production from electrolytic water is the most widely used technology for converting renewable energy into hydrogen. The process of hydrogen production is a reverse process of hydrogen and oxygen combustion to produce water, the process is relatively simple and does not produce pollution, but the energy for decomposing water needs to be provided from outside and the consumption is large, which still adds a burden to the traditional thermal power generation, so from the economic point of view, this kind of hydrogen production technology can not achieve large-scale production.

3.2 Conventional Fossil Fuel Hydrogen Production Technology

Hydrogen production from traditional fossil fuels such as coal, oil and natural gas is the most primitive and the most utilized hydrogen production technology. This method of hydrogen production has become more widely utilized, especially since the development of natural gas extraction technology has reached a certain stage where large-scale extraction is possible.

1) Hydrogen production from coal

The main methods of producing hydrogen-containing gas from coal are coal coking (also known as high-temperature dry distillation) and coal gasification. Coking is the production of coke from coal at 900~1000°C under the condition of air isolation, and the by-product is coke oven gas. Coke oven gas can be used as city gas and as a raw material for hydrogen production. Gasification is the conversion of coal into gaseous products by reaction with a gasification agent at high temperature and atmospheric pressure or under pressure. The purpose of gasification is to produce chemical raw materials or city gas.

2) Hydrogen Production from Natural Gas or Light Oil

This method is used to produce hydrogen by reacting with water vapor in the presence of a catalyst.

3) Hydrogen Production by Partial Oxidation of Heavy Oil as Raw Material

Heavy oil feedstock includes atmospheric pressure, reduced pressure residual oil and fuel oil after deep petroleum processing. The reaction of heavy oil with water vapor and oxygen can produce hydrogen-containing gas products, which are valued for their low raw material cost.

Coal, oil and natural gas are the most important methods to produce hydrogen, which is mainly used as chemical raw material and some hydrogen-containing gas products are also used as gas fuel to supply city gas. However, the reserves of traditional fossil energy are extremely limited, and there are many fields that need it, so this method of hydrogen production definitely adds to the pressure of traditional fossil energy consumption, not to mention that the process of preparation can cause serious pollution to the environment. Therefore, this method of hydrogen production cannot be relied on for a long time, and other hydrogen production technologies should be developed as soon as possible.

3.3 Biological Hydrogen Production Technology

Biomass is rich in resources and is an important renewable energy source. Biological hydrogen production technology has good environment and safety, and in this process, it needs to use chemical or physical methods to convert biomass into hydrogen, and the biomass that can be used is relatively wide, such as most plants, industrial and agricultural wastes, and domestic wastes, etc. Therefore, this kind of hydrogen production technology is the ideal way to make reasonable use of waste and reduce environmental pollution, which is completely free from traditional fossil energy and achieve sustainable use of resources, which will be one of the hot spots for hydrogen energy researchers to focus on developing and researching for a long time in the future.

1) Biomass gasification to hydrogen

Biomass raw materials such as firewood, sawdust, wheat straw, rice straw, etc. are pressed into shape and then gasified or cracked in a gasifier (or cracker) to produce hydrogen-containing fuel gas.

2) Microbial hydrogen production

Certain algae in rivers, lakes and seas, such as *Chlorella* and nitrogen-fixing cyanobacteria, can use sunlight as energy and water as raw material, and are able to emit hydrogen gas continuously. Similarly, using various industrial and domestic organic wastewater and agricultural waste as raw materials, microbial hydrogen production can be carried out, and the technology is attracting attention.

3.4 Solar Thermochemical Cycle Hydrogen Production Technology

Solar thermochemical cycle hydrogen production technology uses solar concentrators to gather solar energy in order to generate high temperatures that drive thermochemical reactions. From the whole life cycle process, the processing of the thermochemical reactor and the final waste abandonment as well as the use of metals and metal oxides can cause some environmental pollution. In addition, since the reactions are carried out at high temperatures, the recombination of hydrogen and oxygen has the risk of causing explosions in the reactor.

3.5 Other Hydrogen Production Technologies

In addition to thermochemical methods, hydrogen production by photocatalytic reaction of solar semiconductors is also a widely studied technology for hydrogen production. TiO₂ and transition metal oxides, layered metal compounds such as K₄Nb₆O₁₇ and Sr₂Ta₂O₇, and catalytic materials that can use visible light such as CdS and Cu-ZnS have been found to be able to catalyze the decomposition of water under certain light conditions to produce hydrogen. However, because many semiconductors undergo photolysis while photocatalytic hydrogen production, and the current photocatalytic hydrogen production efficiency is too low, there is still a need for further research before large-scale hydrogen production.

Nuclear energy to hydrogen technology is also a process that essentially uses the thermochemical cycle of decomposing water, i.e., the thermal energy of a high-temperature reactor or nuclear reactor is used to decompose water to produce hydrogen.

4. Hydrogen Energy Storage Energy Technology

According to the physical and chemical principles involved in hydrogen storage technology, hydrogen storage can be divided into physical hydrogen storage and chemical hydrogen storage.

4.1 Physical Hydrogen Storage

- 1) High-pressure gaseous hydrogen storage: not a preferred option in the long run.
- 2) Low temperature liquid hydrogen storage: Europe, America and Japan are more mature, and about 1/3 of the global hydrogen refueling stations use liquid hydrogen storage technology to supply hydrogen; domestically, liquid hydrogen is only used in the aerospace field due to the limitation of core technology and high cost.
- 3) Low-temperature and high-pressure hydrogen storage: Compared with high-pressure gaseous hydrogen storage, hydrogen storage density is increased and energy consumption is reduced compared with liquid hydrogen storage. However, this technology is still in the research and development stage, and many problems have yet to be solved.
- 4) Hydrogen storage in porous materials: such as carbon nanomaterials and metal-organic frameworks, which have large specific surface area and can adsorb hydrogen through van der Waals forces, but the adsorption performance and hydrogen storage capacity at room temperature and pressure need to be improved.

4.2 Chemical Hydrogen Storage

It mainly includes metal hydride hydrogen storage and organic liquid hydrogen storage.

- 1) Metal hydride hydrogen storage: some specific metals and metal compounds can react with hydrogen at certain temperature and pressure to produce metal hydrides, which can be re-released by heating, such as magnesium-based alloys, titanium-based alloys, rare earth-based metals, etc. This

method has high safety and can maintain high purity of hydrogen. However, the hydrogen absorption and release performance and recycling performance need to be improved.

2) Organic liquid hydrogen storage: In recent years, unsaturated hydrocarbon organic solutions are seen as promising hydrogen carriers. Hydrogen is stored by hydrogenation reaction and released by dehydrogenation reaction, with high hydrogen storage density, and hydrogen can be transported with the existing liquid fuel transportation infrastructure. It is still in the development stage, the reaction catalyst needs to be further optimized, and the hydrogen after dehydrogenation needs to be further purified.

Table 2. Comparison of different storage methods for hydrogen

Hydrogen storage method	Main Technologies	Principle	Hydrogen storage materials	Hydrogen storage density per unit mass	Advantages	Disadvantages
Gaseous hydrogen storage	High pressure gaseous hydrogen storage	Compression of hydrogen gas under high pressure	High pressure resistant materials	1.0% - 5.7%	Low cost; low energy consumption; fast hydrogen charging and discharging; simple vessel structure	Small storage capacity; hydrogen density is strongly influenced by pressure; material limits pressure; transportation is hazardous
Liquid hydrogen storage	Organic liquid hydrogen storage	Reversible reaction with hydrogen gas by means of hydrocarbon hydrogen storage agent	Cyclohexane; methylcyclohexane; decahydronaphthalene, etc.	5.0% - 7.2%	High density and efficiency of hydrogen storage; safe storage and transportation of hydrogen carriers	Higher reaction temperature; lower dehydrogenation efficiency; high catalyst cost and easy to be poisoned by intermediate products
	Low temperature liquid hydrogen storage	Liquefaction of hydrogen when it is cooled to -253°C	Special materials that resist ultra-low temperatures and maintain low temperatures	4.7%-10%	High hydrogen storage density; large hydrogen storage capacity; simple storage and transportation	High cost of liquefaction; high energy losses (about half the calorific value of hydrogen storage), evaporation losses; dangerous transportation
Solid Hydrogen Storage	Hydrogen storage by physical adsorption	Hydrogen storage using physical or chemical changes between hydrogen and hydrogen storage materials to transform into solid solutions or hydrides	Metal-organic frameworks; nanostructured carbon materials	1.0% - 4.5%	High hydrogen storage density; suitable charging and discharging speed, good reversibility, high safety; low cost of hydrogen storage materials, good cycle life	Low weight hydrogen storage efficiency; light weight hydrogen storage material with high hydrogen release temperature and poor cycling performance
	Chemical hydride hydrogen storage		Metal hydrides; complex hydrides; organic hydrides			

Hydrogen storage technology is the bottleneck of hydrogen energy application, which mainly lies in the need to improve the density of hydrogen storage, reduce the cost of hydrogen storage and improve the speed of hydrogen charging and discharging. The storage of hydrogen has a direct impact on the application of hydrogen energy. At present, there are three main ways to store hydrogen: gaseous, liquid and solid. Among them, high-pressure gaseous hydrogen storage technology is more mature and is the most common and frequently used hydrogen storage method; liquid organic hydrogen storage stands out among many other hydrogen storage methods due to its high hydrogen storage capacity, good safety and good cycling performance, and is the focus of global research and development at this stage; solid hydrogen storage method has become a new generation of hydrogen storage technology due to its high safety and high hydrogen storage density. The comparison of different storage methods of hydrogen is shown in Table 2.

5. Hydrogen Energy Utilization Technology

Hydrogen energy can be used in a variety of ways, including direct combustion and fuel cell. As the most ideal fuel of fuel cell is hydrogen, the hot utilization technology of hydrogen energy mainly focuses on fuel cell. The so-called fuel cell is to convert the chemical energy of fuel storage into electric energy through the electrochemical reaction of fuel and oxidant. Through this advanced energy conversion method of fuel cell, hydrogen energy can truly become the efficient and clean energy power of human society. Hydrogen can also be directly used as fuel by hydrogen internal combustion engine that can store hydrogen. This is a new type of internal combustion engine that can convert the chemical energy stored in hydrogen into mechanical energy through combustion process, which can then be used as automobile fuel or even power generation.

6. Summary and Outlook

Through the production of hydrogen from new energy power such as solar energy and the combination of hydrogen and fuel cells to generate electricity, the hydrogen industry ecosystem can be formed, which is helpful to ensure China's energy security and accelerate the construction of a clean and low-carbon hydrogen energy supply system, which is of great significance to China's sustainable development strategy.

Hydrogen energy storage can be used as a new idea of energy storage system to solve the problem of insufficient absorption capacity of renewable energy and new energy grid connection. Hydrogen combined fuel cell power generation is a key technical link in the full life cycle application of hydrogen energy. Hydrogen power generation can produce a variety of products with direct economic benefits (such as pure oxygen), achieve the purpose of greatly reducing carbon dioxide emissions, and has good economic and environmental benefits.

The application of hydrogen energy is promising, but there are some challenges that need to be solved. Hydrogen is highly diffusible, flammable and explosive, and contact with metal can easily lead to hydrogen embrittlement and bad storage, so proper solution of hydrogen energy storage and transportation is the key to safe and efficient use of hydrogen energy. In addition, the cost of hydrogen production by electrolysis of water is high. Based on the above problems, the following recommendations are made.

- 1) In the future, we should focus on the four links of hydrogen energy production, storage, transportation and use, and focus on building and improving the hydrogen energy system, increasing the interaction between hydrogen energy and the power grid, and promoting the energy transformation in China.
- 2) Clearly define the positioning of hydrogen energy development and give perfect policy support to the hydrogen energy industry.
- 3) Vigorously develop electrolytic water hydrogen production technology, use abandoned wind, abandoned light and abandoned water resources to produce "green hydrogen", and solve the economic problems of electrolytic water hydrogen production and energy waste.

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