

Hydrogen: Production, Applications, and Challenges in Sustainable Energy Systems

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Abstract. Hydrogen has long been recognized for its potential as a clean, versatile energy carrier. In the context of a global push towards sustainable systems and reduced carbon emissions, hydrogen stands out due to its high energy density, flammability, and environmental benefits. Despite these advantages, the production, storage, transport, and utilization of hydrogen present significant technical and economic challenges that must be addressed to realize its full potential. This paper delves into the comprehensive characteristics of hydrogen, focusing on its physical and chemical properties. It examines the various methods employed in hydrogen production, highlighting both traditional and innovative approaches, from steam methane reforming and coal gasification to biomass-derived hydrogen and water splitting, along with their respective advantages and drawbacks. Further, the paper explores key areas of hydrogen application, emphasizing its potential to revolutionize the industrial and energy sectors through hydrogen fuel cells, engines, and industrial feedstock roles. Finally, the paper addresses the current challenges in adopting hydrogen energy on a large scale, particularly the high costs and technological bottlenecks in storage and transportation. Understanding these facets is crucial for advancing hydrogen as a cornerstone of sustainable energy systems.

Keywords: Hydrogen production, fuel cells, sustainable energy, carbon emissions.

1. Introduction

Hydrogen is the most abundant element in the universe and is poised to play an important role in the transition to sustainable energy systems due to its high energy density, flammability, and zero emissions when used as a fuel [1]. This paper provides a comprehensive overview of hydrogen's physical and chemical properties, highlighting its light weight, high flammability, and potent reducing capabilities. It elucidates four primary hydrogen production methods: steam methane reforming (SMR), coal gasification, biomass hydrogen production, also the direct thermal splitting of water, each with distinct advantages and drawbacks in terms of cost, technology maturity, and environmental impact.

The paper also explores the diverse applications of hydrogen, focusing on its use in fuel cells and engines, which have the potential to reduce carbon emissions across various sectors significantly. Hydrogen fuel cells, including proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), and alkaline fuel cells (AFC), offer high efficiency and low pollution, with practical implementations in transportation and power generation. Moreover, hydrogen engines, such as hydrogen internal combustion engines (HICE) and hydrogen gas turbines, present a cleaner alternative to traditional fossil fuels with potential applications in aerospace and industry.

However, the widespread adoption of hydrogen energy faces plenty of challenges, especially in terms of high production costs and the technical difficulties associated with hydrogen storage and transportation. The paper concludes by addressing these hurdles and emphasizes the importance of continued technological advancements and infrastructure development to unlock hydrogen's full potential as a key component of a clean energy future.

2. Hydrogen Characteristics

2.1. Physical Property

Hydrogen is one of the most abundant elements on Earth, widely present in various compounds such as water and organic matter. Hydrogen exists in a gaseous state at a standard temperature of 25 °C and pressure of 1 atm, with a density as low as 0.08988 g/L, making it the lightest of all gases. Hydrogen also has extremely low melting and boiling points, with a melting point of -259.16 °C and a boiling point of -252.87 °C.

2.2. Chemical Property

Hydrogen has high flammability and can be burned in air at extremely low concentrations (about 4% or more) to produce water as the combustion product. Hydrogen has high combustion efficiency and high energy density, making it an ideal clean energy source.

Besides, hydrogen is a strong reducing agent that can undergo reduction reactions with many oxides. For example, in the metallurgical industry, hydrogen can be used to extract metals from ores. This reduction characteristic also enables hydrogen gas to be used in the chemical industry to produce important chemicals such as ammonia and methanol.

Hydrogen can participate in various reactions, such as addition and dehydrogenation, under the action of various catalysts, especially transition metal catalysts [1].

3. Hydrogen Production Method

Nowadays, people pay more and more attention to protecting the environment and are beginning to try to reduce carbon emissions. More and more industries are choosing to use hydrogen, as hydrogen is a green and clean energy with a high energy density. With the increasing demand for low-carbon energy, the production of hydrogen has received widespread attention. In this part, four different hydrogen production methods will be introduced, which are steam methane reforming, Coal gasification, Biomass hydrogen production, and the direct thermal splitting of water.

3.1. SMR

SMR is the most important hydrogen production method in the industry. This is a green technology for obtaining hydrogen from natural gas, which can obtain a large amount of clean and safe hydrogen. It can help reduce pollutant emissions, improve energy efficiency, and effectively reduce energy costs. Therefore, more and more countries are adopting it.

The process principle mainly includes the pre-treatment of natural gas and then converting methane and water vapor into carbon monoxide and hydrogen in the conversion furnace. SMR has a total of three reactions, of which the first two are reformation reactions, and the last one are transformation reactions.

The first two reactions are $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ and $\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2$. The first two reactions are strongly endothermic, and as the reactions progress, the molar flow rate significantly increases. Under high temperatures and low pressure, the conversion rate of methane is very high, almost reaching the equilibrium conversion rate. The third reaction is $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. Unlike the first two reactions, the third transformation reaction is an exothermic reaction, where the amount of material before and after the reaction remains constant. The conversion rate increases with the decrease in temperature, and the reaction conversion rate is independent of pressure. In order to maintain the two endothermic reactions mentioned above, oxygen or air is usually introduced into the reactor for oxidation reaction [2].

Despite its important position in the industry, the reactions mentioned above also have many significant drawbacks, like high internal diffusion resistance, generating environmental pollution and so on. In order to overcome the drawbacks of traditional natural gas steam reforming reactions, many new technologies have emerged, just as the application of selective hydrogen permeation membranes

and selective oxygen permeable membranes. The application of these tools can greatly assist in the forward progression of reactions.

3.2. Coal Gasification

There are two main reactions in coal gasification for hydrogen production.

One reaction is $C + H_2O \rightarrow CO + H_2$. This is the reaction between coal and water vapor under high-temperature conditions, generating carbon monoxide and hydrogen gas, and this reaction is endothermic.

Moreover, the other reaction is $CO + H_2O \rightarrow CO_2 + H_2$. This is the reaction of carbon monoxide and water vapor at higher temperatures, producing carbon dioxide and hydrogen gas and this is an exothermic reaction [3].

These two reactions are the core processes of coal gasification for hydrogen production. Through these two reactions, carbon in coal is converted into gaseous forms of carbon monoxide and hydrogen. These gas mixtures undergo purification, transformation, and purification processes to obtain high-purity hydrogen gas ultimately [4].

Coal gasification has plenty of advantages. For example, the raw material of Coal gasification is coal and water, and these two raw materials have a wide distribution of resources and abundant reserves, with relatively low economic costs. However, this method may generate a large amount of CO_2 , and should pay more attention to the emission of CO_2 .

3.3. Biomass Hydrogen Production

Biomass hydrogen production is the use of biomass, such as plants and agricultural waste, to produce gas under the action of microorganisms or enzymes. Although this method has the advantage of being renewable, the technology is not yet mature, and the cost is high. The current limitation of this method is that efficient and sustainable microorganisms or enzymes that can decompose organic matter to produce hydrogen cannot be found [5].

3.4. The Direct Thermal Splitting of Water

The direct thermal splitting of water needs a temperature exceeding 2000 °C and produces a rapidly recombining mixture of hydrogen and oxygen [6]. This will consume much energy to raise the temperature to 2000 °C. So, it is not a perfect solution to directly raise the temperature to 2000 °C, and solar energy or nuclear energy can help to provide heat [7].

The advantage of this method is that it has no exhaust emissions, but its cost is high because of the raising of the temperature to 2000 °C. Furthermore, if solar energy can be used to provide heat for this method, this will depend heavily on the weather, especially the sunny days. Besides, the usage of nuclear energy is very dangerous [7].

Table 1. Comparison of hydrogen production methods

The hydrogen production methods	advantage	disadvantage
Steam methane reforming (SMR)	Mature technology and low-cost	High carbon dioxide emissions
Coal gasification	Rich resources	Complex processes and serious pollution problems
Biomass hydrogen production	Renewable	Immature technology with high costs
The direct thermal splitting of water	Pollution-free	High cost, relying on power sources

4. Hydrogen Application

There are many ways to use hydrogen energy. Whether in the industrial or energy sector, hydrogen energy is highly used. Hydrogen can be used as an industrial raw material; hydrogen can also be used as fuel for hydrogen fuel cells and hydrogen engines. Hydrogen has a significant potential to

revolutionize both the industrial and energy sectors. As technology advances and the infrastructure for hydrogen production and distribution expands, hydrogen is poised to play a critical role in reducing carbon emissions.

Hydrogen is widely regarded as an important component of the future clean energy system because of its high energy density, easy storage, and zero emission characteristics. With the increasing demand for environmental protection and energy security, hydrogen has received increasing attention worldwide.

4.1. Hydrogen Fuel Cells

Hydrogen reacts with oxygen electrochemically in the fuel cell to generate electricity directly, with high efficiency and low pollution. A hydrogen Fuel Cell (HFC) is a device that directly converts the chemical energy of hydrogen into electrical energy, mainly composed of an anode, cathode, and electrolyte membrane.

4.1.1. Reaction principle of hydrogen fuel cells

The basic principle is to decompose hydrogen molecules (H_2) into protons (H^+) and electrons (e^-) through electrochemical reactions under the action of anode catalysts. Protons migrate to the cathode through the electrolyte membrane, while electrons generate current through an external circuit, ultimately reacting with oxygen (O_2) at the cathode to generate water (H_2O), releasing energy.

The basic reaction formula is as follows: Anodic reaction: $2H_2 \rightarrow 4H^+ + 4e^-$; Cathodic reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$; Overall response: $2H_2 + O_2 \rightarrow 2H_2O$. This process not only provides stable electrical energy output but also produces only water, achieving zero emissions.

4.1.2. Types of hydrogen fuel cells

According to electrolyte materials and operating temperature, fuel cells are mainly divided into the following types:

(1). Proton exchange membrane fuel cell (PEMFC): It is widely used in transportation and portable power sources. Its operating temperature is relatively low (about $80^\circ C$), it starts quickly and has high efficiency.

(2). Solid oxide fuel cells (SOFCs): These are suitable for distributed power generation and applications, with high operating temperatures ($600^\circ C$ - $1000^\circ C$), high efficiency, and compatibility with multiple fuels.

(3). Phosphoric Acid Fuel Cell (PAFC): Mainly used for commercial and backup power sources, with an operating temperature of about $200^\circ C$ and mature and reliable technology.

(4). Alkaline Fuel Cell (AFC): It has applications in the aerospace field and has good operational performance but is sensitive to CO_2 [8].

4.1.3. Examples of hydrogen fuel cell applications

Hydrogen fuel cell vehicles such as Toyota Mirai and Honda Clarity have been commercialized. The short refueling time and long range of hydrogen make it competitive in specific long-distance transportation.

4.2. Hydrogen Engines

Hydrogen can be directly used as a fuel for internal combustion engines and only discharges water, making it an ideal clean fuel. The working principle of the hydrogen engine is similar to traditional internal combustion, but it converts gasoline or diesel fuel into hydrogen, which can be mainly divided into hydrogen internal combustion engines (HICE) and hydrogen gas turbines (HGT).

4.2.1. Working principle of hydrogen engine

The working principle of a hydrogen engine involves four key processes. First, during the air intake process, hydrogen is mixed with air and drawn into the cylinder. Due to hydrogen's high diffusion coefficient, it mixes efficiently with air, resulting in a well-prepared fuel mixture that aids complete

combustion. Second, in the compression process, the piston moves upwards, compressing the hydrogen-air mixture to a high-pressure and high-temperature state, readying it for ignition and combustion. Third, in the combustion process, the spark plug ignites the highly compressed mixture under high pressure and temperature, releasing heat energy that pushes the piston downwards, thereby completing the work cycle. Lastly, the exhaust process expels the combustion products, primarily water vapor and possibly small amounts of nitrogen oxides (if any), through the exhaust system [9].

The technical status of hydrogen engines indicates ongoing advancements in enhancing fuel mixing efficiency, optimizing combustion to reduce emissions, and increasing the durability and performance of engine components exposed to hydrogen combustion by-products.

4.2.2. Application fields of hydrogen engines

(1). Aerospace: Hydrogen gas turbines have the same potential for application in the fields of aviation and aerospace. The high density and clean characteristics of hydrogen are suitable as fuel for aircraft and spacecraft, which helps to reduce aviation emissions and achieve sustainable development.

(2). Industry and power generation: Hydrogen engines can be used for industrial power and distributed power generation systems, providing a stable and efficient energy supply, especially in industrial equipment that requires high reliability and long lifespan.

4.3. Raw Material

In the petroleum refining process, hydrogen gas is used for processes such as hydrodesulfurization, hydrocracking, and hydrofining, which helps to improve fuel quality and reduce sulfur content. Taking the production of ammonia as an example, hydrogen is an indispensable material in it.

5. The Current Challenges of Hydrogen Energy

5.1. High Production Cost

At present, hydrogen production mainly relies on the natural gas reforming process, and the use of electrolytic water to produce green hydrogen is expensive, mainly due to the cost of electrolytic equipment and the higher price of renewable electricity.

5.2. Storage and Transportation Technology Bottlenecks

The low density and high volatility of hydrogen, the storage of hydrogen at extremely low temperatures, and the high-pressure storage tanks required to compress hydrogen present technical and safety challenges [10,11].

6. Conclusion

This comprehensive review of hydrogen as a clean, versatile energy carrier has highlighted several critical insights crucial for understanding its potential and the challenges in its adoption. The primary findings reveal hydrogen's exceptional energy density, high flammability, and environmental benefits, making it an ideal candidate for sustainable energy systems. The detailed analysis of physical and chemical properties underpins the versatile applications of hydrogen, ranging from fuel cells and engines to industrial feedstocks.

The paper emphasized the current methods of hydrogen production, such as steam methane reforming, coal gasification, biomass-derived hydrogen, and direct thermal splitting of water. Each method exhibits unique advantages and drawbacks in terms of cost, maturity, and environmental impact. For instance, while steam methane reforming is economically feasible, it produces significant carbon emissions, contrasting with the cleaner, albeit costlier, alternatives like biomass hydrogen production and direct thermal splitting of water.

The research's implications extend to the industrial and energy sectors, where hydrogen fuel cells and engines could drastically reduce carbon emissions. Practical implementations, such as hydrogen

fuel cell vehicles and hydrogen gas turbines, showcase that hydrogen can be used in transportation and power generation. As these technologies advance, hydrogen's role as a clean energy carrier becomes increasingly viable.

However, several limitations were identified. High production costs and significant technical bottlenecks in storage and transportation pose ongoing challenges. The dense, volatile nature of hydrogen requires advanced storage solutions and safety measures, which are currently under development but remain less mature compared to other energy carriers.

Looking forward, continued research and technological advancements are imperative. Future studies should focus on reducing production costs, improving storage technologies, and developing robust infrastructure for hydrogen distribution. Innovations in electrolytic methods, particularly using renewable energy sources, could make hydrogen production more economically sustainable. Additionally, policy support and investment in hydrogen infrastructure are necessary to overcome the existing barriers.

In conclusion, while hydrogen promises a revolutionary impact on sustainable energy systems, realizing its full potential will require concerted efforts across research, technology development, and policy frameworks. Effectively addressing these challenges could position hydrogen as a cornerstone of a clean energy future, significantly contributing to global carbon emission reduction and promoting environmental sustainability.

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