Production And Applications of Hydrogen Energy

Yicheng Miao *
Dulwich International High School Programme, Suzhou, Jiangsu 215400, China
* Corresponding Author Email: eason.miao26@stu.dulwich.org

Abstract. Since the Industrial Revolution, climate change has become a major problem for all humans and the whole ecosystem. The concepts of "carbon peak" and "carbon neutrality" have been proposed, which means that it is necessary to start reducing carbon dioxide emissions. It has been shown by studies that hydrogen can be generated via multiple methods, like steam methane reforming and electrolysis. When hydrogen is utilized in automotive fuel cells, tailpipe emissions can be reduced to nearly zero. In industrial applications such as steelmaking, carbon emissions can be significantly cut by substituting traditional carbon-based reducing agents with hydrogen. Furthermore, the variable output of renewable energy sources can be balanced by hydrogen energy storage systems. This research is significant not merely in verifying the feasibility of incorporating hydrogen energy into daily energy consumption, but also in effectively guaranteeing the implementation of “carbon neutral” plans, thus laying the groundwork for future energy development.

Keywords: Hydrogen, New resources, Carbon neutrality.

1. Introduction

The Earth is the common home on which human beings depend for their survival and development. Since the Industrial Revolution, climate change has become a major issue for all humans and the entire ecosystem [1]. The global energy demand, which is surging, is leading to a rapid increase in the total carbon dioxide emissions from the burning of fossil fuels and combustion. There are also growing concerns about climate change. Under the pressure of these two conditions, the development and use of clean and renewable energy is urgent.

However, inefficient, weather-dependent solar and wind power have caused intermittent and stagnant energy transitions. At this time, the preparation and storage technology of hydrogen energy became an important research target [2]. Hydrogen, a clean secondary energy carrier, is a renewable energy source. During the combustion process, no greenhouse gases like carbon dioxide, sulfur dioxide, or harmful substances are produced by hydrogen. This is because when the positive hydrogen ion H and the negative divalent oxygen ion O2- react, only water vapor H2O is generated, with no substances that can pollute the environment. Hydrogen serves as a bridge that connects renewable energy and traditional fossil energy. The vision of future clean energy utilization can be realized by utilizing hydrogen energy and fuel cells [2,3].

The hydrogen energy industry chain consists mainly of hydrogen production, storage, transportation, and application links. It is applicable not only in traditional fields but also in new hydrogen-powered vehicles (such as buses and logistics vehicles) and hydrogen power generation [4]. In recent years, 70 billion cubic meters (roughly 6 million tons) of hydrogen with a purity above 99% has been used annually in China, as reported in [5]. Currently, in China, hydrogen is mainly produced through methods such as coal-based hydrogen production, natural-gas-based hydrogen production, and the use of industrial by-product hydrogen (purifying industrial waste gas rich in hydrogen). Industrial by-product hydrogen is generated as a result of purifying waste from coal and natural gas processes. Currently, in China, hydrogen production, including that of industrial by-product hydrogen, still predominantly depends on fossil fuels [3]. About 90% of the 99% pure hydrogen in China is used for hydrogenation in the production process of industrial smelting products, such as smelting metals and fine chemicals, as protection gas and reduction gas. However, in the daily consumer market, the scale of hydrogen application is still relatively small.

To achieve the Paris Agreement, which will limit the future increase in the average temperature of the planet to around 2 degrees Celsius, Europe will need to generate large amounts of renewable energy and increase the rate of electrification. Ordinary solar and wind power can hardly meet the needs of many users [6]. Under the EU Hydrogen Utilization Plan, it was decided to minimize the energy constraints by adopting PtG (Power-to-Gas) technology, which uses surplus renewable electrolyzed water to convert electricity into hydrogen, which is stored for a long period employing chemical energy. According to the literature, more than 128 PtG projects have been carried out in European countries, including Germany, the Netherlands, and Denmark [7].

2. Use of the Text

2.1. Hydrogen Production by Electrolysis with Water

Globally, over 96% of the raw materials for hydrogen production are sourced from fossil fuels, while the remaining hydrogen is produced through water electrolysis. Traditional approaches to hydrogen production encompass hydrogen production via fossil energy reforming and industrial by-product hydrogen production. In contrast, new hydrogen production technologies are classified into water electrolysis hydrogen production, solar hydrogen production, and biomass hydrogen production. "Green hydrogen" is a key term in the water electrolysis hydrogen production process. Water electrolysis hydrogen production can be categorized into three types. The following elaborates on these three methods.

2.1.1 Alkaline water electrolysis

Currently, Alkaline Water Electrolysis (AWE) stands as the most prevalent hydrogen production technology, as noted in [8]. In this technology, water is electrolyzed within an alkaline electrolyte environment. Its fundamental principle involves using direct current to dissociate water into hydrogen and oxygen. As depicted in Figure 1, an electrolytic cell necessitates a power supply, electrolyte, cathode, anode, and diaphragm. The electrolyte typically consists of a 20% - 30% concentration of KOH solution or a 26% concentration of NaOH solution. Under the influence of direct current, at the cathode, water molecules decompose into hydrogen ions and hydroxide ions. Subsequently, the hydrogen ions acquire electrons to form hydrogen atoms, which then combine to form hydrogen molecules. Meanwhile, under the effect of an electric field, hydroxide ions pass through the diaphragm and react with the anode to generate oxygen [9]. As presented in Table 1, AWE hydrogen production represents the most well-developed hydrogen production technology. It is highly regarded in the commercial market because of its low cost and straightforward operation. However, its drawback lies in the fact that most AWE systems have only a 60% conversion efficiency and high energy consumption, and the electrolytes are prone to be affected [10].

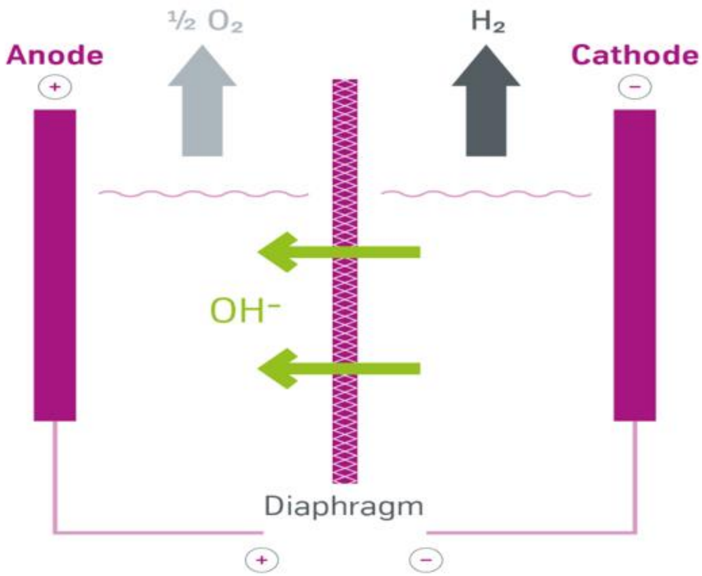

Fig. 1 The diagram of AWE

Table 1. Analysis of Water Electrolysis-Based Technologies of Hydrogen Production [2]

	AWE	PEMWE	SOE
electrolyte	KOH solution	H_2SO_4 solution	Zirconia
Current density (A/cm2)	0.2-0.7	1.0-2.2	1.0-2.0
Battery voltage(V)	1.8-2.4	1.8-2.2	1.3-1.4
Temperature (°C)	< 90	< 80	500 - 800
Energy consumption (KWH/m3)	~5	~4.5	< 3.5
Hydrogen purity (%)	99.5-99.9	>99.99	>99.9
Stack efficiency (%)	50-60	45-71	85-90
Durability	100,000 hours	20,000-80,000 hours	< 10,000 hours
Development progress	mature	commercialized	developing
Capital cost	$500-1000 / KW	$700-1400 / KW	>$2000 / KW
Advantages	·Low cost ·Wide range of material ·High durability ·Skilled techniques	·High density of the current ·High gas purity ·High voltage efficiency	·High efficiency ·No corrosive electrolyte
Disadvantages	·Low current density ·Corrosive electrolyte	·Higher cost ·High quality of raw water	·Large device ·Low durability

2.1.2 Proton membrane electrolysis of water to produce hydrogen

The industrialization of alkaline electrolytic water commenced in the 1920s. As time elapsed, this technology grew more mature and was gradually commercialized. Nevertheless, it harbors numerous drawbacks. For instance, the equipment is bulky, and its operation at a lower current result in the shortcoming of low-purity hydrogen, making it challenging to meet subsequent industrial demands. This situation has spurred technicians to develop new hydrogen production technologies. Proton membrane electrolysis water hydrogen production (PEMWE) technology has emerged as one of the most promising approaches owing to its advantages of high efficiency, rapid response, and zero emissions.

In PEMWE technology, a proton exchange membrane (PEM) is utilized to substitute the liquid electrolytes in traditional alkaline water electrolysis for hydrogen production. An electrolytic cell's main components consist of a cathode, an anode, and a membrane electrode. Here, the membrane electrode is constituted by two gas diffusion layers and a proton exchange membrane with an anode and cathode catalytic layer sprayed on it [9]. The porous diffusion layer, a porous material positioned between the membrane and the bipolar plate on both sides of the electrode, serves two crucial functions. Firstly, it facilitates the electrical conduction between the electrode and the bipolar plate, and secondly, it ensures the efficient transfer of liquid water and gaseous substances between the electrode and the flow channel [11]. The MEA is composed of a proton exchange membrane, with a cathode catalyst and an anode catalyst respectively attached to its two sides. Regarding materials, Ti is used as the material for the anode, and the cathode can be fabricated from graphite and stainless steel.

In the working process, water flows into the side of the anode. Under the action of the anode catalyst, it is decomposed into oxygen, protons and electrons, and the generated oxygen is discharged through the gas diffusion layer and flow field plate of the anode. At the same time, as protons move towards the cathode through the exchange membrane, electrons are conducted to the cathode via the circuit. This movement is a crucial part of the water electrolysis hydrogen production process. In the context of water electrolysis, which is one of the new hydrogen production technologies, this electron-proton flow mechanism is fundamental to the generation of hydrogen. For instance, in proton exchange membrane water electrolysis hydrogen production technology, this process occurs within the electrolytic cell where the membrane plays a key role in facilitating the selective movement of protons, while the circuit enables the conduction of electrons, ultimately leading to the formation of hydrogen at the cathode. For the cathode, the electrons from the circuit and the protons from the exchange film undergo a reduction reaction under the action of the cathode catalyst to produce hydrogen, which is discharged through the gas diffusion layer of the cathode and the flow field plate. The following is a technical comparison of PEM. PEM has the highest hydrogen purity and current density of the three technologies to help improve the efficiency of hydrogen preparation. At the same time, it requires the lowest temperature conditions. However, the cost is very high. The water quality in the electrolyzer also affects the reaction efficiency and hydrogen output.

2.1.3 Steam solid oxide electrolysis (SOE)

High-temperature electrolysis can operate in temperatures of 500-900 °C [9]. Due to the conditions of high temperature, the conversion efficiency can reach 90%, but high temperature has increased the requirements for materials. Although it is still in the experimental stage, it is a promising technology. Steam can be electrolyzed to H2 and O2 by electricity and heat at high temperatures about 700-1000°C [12]. Steam solid oxide electrolysis (SOE) is a famous hydrogen production technology. Another hydrogen production technology that is under development offers high efficiency. Non-precious metals are the catalysts most commonly used in this technology. Electrode materials are generally made of nickel-based ceramics. It can produce hydrogen electrochemically, usually consisting of a 1.3V anode for producing oxygen, a hydrogen-producing cathode and an oxygen-conducting electrolyte [13, 14]. In solid oxide in an electrolytic cell, the cathode will undergo a hydrogen evolution reaction (HER), and the anode will undergo an oxygen evolution reaction (OER), resulting in the formation of hydrogen and oxygen [15]. According to Table 1, although the fuel cell stack efficiency of SOE is higher than the other two methods, without the use of alkaline water required by AWE to increase the probability of corrosion, the durability of SOE is less than 10,000 hours, which is not durable enough, and this preparation technology also requires large-scale equipment support.

2.2. Hydrogen Production Technology with New Resources

Water electrolysis is among the most prevalent commercial hydrogen production techniques. However, this method invariably consumes a substantial amount of electricity, which directly contributes to high costs and pollution. Nevertheless, hydrogen can also be produced through new energy approaches. The following will introduce a hydrogen production technology based on a specific new energy source.

According to the literature, in Canada, hydrogen production via hydropower is the preeminent hydrogen production method [16]. Canada is endowed with abundant hydropower resources. Hydropower constitutes the most crucial source of electricity in Canada, accounting for 55.1% of the nation's total power generation. Notably, in British Columbia, Manitoba, Newfoundland and Labrador, Quebec, and the Yukon, over 90% of electricity is generated from hydropower [16].

There are two primary methods for generating hydrogen using hydropower. The first approach, as investigated in Venezuela, posits that a certain proportion of hydroelectric power is utilized to produce hydrogen via electrolytic cells [17]. Fundamentally, it is water electrolysis, yet the electricity generated by Venezuela's hydropower eliminates the cost of additional power for hydrogen generation. Another way to gauge the hydrogen production potential is by capitalizing on the increased water inflow at run-off hydropower stations during the rainy season and the consequent fluctuations in electricity demand and production. The actual efficiency of the turbine and hydropower plant is computed using a physical formula. In the context of hydropower-based hydrogen production, the second method is more efficient than the first. This is because it enables real-time calculation and evaluation of efficiency, minimizing resource wastage as much as possible.

2.3. Hydrogen Production Technology with New Resources

2.3.1 Hydrogen–fueled vehicles

In 2006, the world's first hydrogen fuel cell light rail train was unveiled by the East Japan Railway Company (JR East). This train is equipped with two 65kW hydrogen fuel cells and 340kW batteries, capable of reaching a top speed of 100km/h. Compared to internal combustion engines, it can save approximately 50% of the energy [18]. This represents the development of hydrogen-powered vehicles in Japan. In 2019, it was mentioned that the vehicle had a range of 300km and a top speed of 110km/h, and the latest train is still under development. Currently, hydrogen energy can only be applied to railway transportation because of its high cost and limited-service life.

When hydrogen is used as fuel, its combustion product is solely water. Pollutants such as carbon monoxide, carbon dioxide, and nitrogen oxides are not produced. Thus, it can significantly reduce air pollution, contribute to alleviating the greenhouse effect, and enhance air quality. The energy density of hydrogen is far higher than that of traditional fossil fuels. Specifically, the energy released by the complete combustion of hydrogen per unit mass is approximately three times that of gasoline. This implies that, under the condition of the same fuel mass, hydrogen-powered vehicles can theoretically cover longer distances and possess more advantages in terms of endurance.

Hydrogenation stations and other supporting infrastructure are seriously insufficient, the construction of hydrogenation stations not only the initial investment is large, but also faces many challenges such as technical, and safety norms, which lead to hydrogen transportation in the use of hydrogenation inconvenience, limiting its scope of promotion. Core technologies such as hydrogen fuel cells need further breakthroughs, such as the durability and stability of fuel cells still need to be improved to reduce the risk of failure during use and extend the service life.

2.3.2 Metallurgical industry

In the iron and steel industry, hydrogen has two main applications. Firstly, in blast furnace ironmaking, hydrogen injection is employed to reduce the content of iron oxides (the impurities adhering to the iron surface). Secondly, hydrogen has the potential to be used as a fuel for various heating operations, for instance, during the creation of ferrocement, in the course of pelletizing procedures, and when heating ladle furnaces [19]. When hydrogen-rich gases are added to the blast furnace, the density and viscosity of the mixture are decreased. These reductions directly result in lower pressure and more rapid heat transfer between the gas mixture and the material being heated. Consequently, the utilization efficiency of heat can be enhanced through hydrogenation.

It is now essential to clarify that hydrogen metallurgy already presents several advantages. Firstly, the reduction product of hydrogen metallurgy is H_2O. By using hydrogen, the dependence on coal and coke is reduced, which in turn leads to a decrease in the emission of the greenhouse gas CO_2. Additionally, owing to the high calorific value, low density, strong permeability, and fast reduction rate of H_2, H_2 is a superior reducing agent compared to CO. Moreover, the raw materials for producing H_2 are abundant, ensuring that the large-scale supply demand can always be met.

2.4. Storage Technique

In the pursuit of effective hydrogen storage solutions, key material properties have been the focus of researchers to ensure their applicability in hydrogen storage [19]. High hydrogen storage capacity remains crucial. Metal hydrides, like magnesium hydrides, and chemical hydrides, such as borane ammonia, possess significant storage capabilities. However, metal hydrides demand high temperatures for dehydrogenation, and in practical applications, chemical hydrides often lack reversibility. Physical adsorbent materials, for example, metal-organic frameworks and carbon nanotubes, feature a large surface area and the potential for low-temperature storage. Nevertheless, low temperatures are needed to attain an efficient density during storage, necessitating a balance between high capacity and practical operation.

The hydrogen absorption and desorption dynamics are also a major concern. Researchers are dedicated to enhancing the rates to enable rapid and efficient hydrogen storage cycles, which involves the exploration of materials and composites on a nanoscale. Thermal and chemical stability are vital for maintaining durability and performance over numerous cycles. Safety and cost-effectiveness play a decisive role in the actual implementation of materials that are non-toxic, non-explosive, and economically feasible.

The efficiency of hydrogen storage in materials is intricately linked to their physical and chemical properties, particularly thermodynamic and kinetic characteristics. At present, the primary technical obstacle to establishing a sustainable hydrogen economy lies in the development of efficient hydrogen storage systems. When assessing hydrogen storage methods and materials, aspects such as high-pressure tank design, hydrogen density, refueling speed, energy efficiency, and cost must be taken into account. To transport hydrogen, enhancing the density of energy plays a vital role in this case. Approaches such as liquefaction, the formation of metal hydrides, and the utilization of liquid organic carriers have been put forward [20].

2.4.1 Compressed hydrogen

Compression technology offers a straightforward means for hydrogen storage. However, because of the low density when H2 is compressed (around 42.2 kg per cubic meter at a pressure of 69.0 MPa), the method has shown a bad efficiency on both volume and weight. For H_2 fuel cell electric vehicles to achieve a higher volumetric energy density, extremely high pressures of up to 70.0 MPa are required, and thus, tanks capable of withstanding such pressure must be utilized. At present, these high-pressure tanks are crucial for attaining a driving range comparable to that of conventional fuel-powered vehicles. The storage of hydrogen in high-pressure tanks (up to 700 bar) is a well-established technology [21]. Innovations in this area are primarily concentrated on two aspects: (1) The development of lightweight composite materials for tank bodies is carried out to enhance weight efficiency and safety; (2) Advanced safety systems are implemented to monitor and regulate pressure and temperature, aiming to reduce the risks of leaks and explosions.

2.4.2 Liquid hydrogen

Liquid H2 is an alternative for efficient storage. This is because it has high density and great purity (70.8kg/m3). The density is almost 800 times compared with the hydrogen under standard temperature and pressure without compression. However, a major disadvantage is that needs a very low temperature (- 253°C), which leads to a large amount of energy wasted. Due to the need for cooling, liquid H2 is not a good method for long-term storage and transportation.

3. Conclusion

Hydrogen is an important factor in the future of clean and sustainable energy, and its production and application are also the focus of this paper. In the preparation of hydrogen, most of the methods of electrolysis of water are already proficient and commercially available. It is even more astonishing that new energy sources are applicable for hydrogen production. These results can be optimized to increase hydrogen production. In terms of application, in the early 21st century, hydrogen has been studied as a fuel vehicle, which also shows great potential. The emergence of hydrogen vehicles will help reduce the emission of related polluting gases. A more efficient and environmentally friendly mode of transport is expected to be achieved in the future. This research is significant because it provides a comprehensive understanding of the hydrogen energy transition, allowing industries and planners who want to use hydrogen to make informed choices. However, this energy source also has limitations, such as the "green hydrogen" mentioned above, the production cost of this energy source is high, which becomes an obstacle in application. Looking forward to the future, various hydrogen production methods are summarized, and limited resources are effectively used to further develop more efficient and low-cost production technologies.

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