Current hydrogen production methods and their economic and environmental analysis

Ruiting Fan *

College of Design and Engineering, National University of Singapore, Singapore

* Corresponding Author Email: E1352664@u.nus.edu

Abstract. As global temperatures continue to rise due to the extensive use of fossil energy sources, concerns about the environment continue to deepen. Accelerating the energy transition is a major trend, and countries are continuously increasing the proportion of clean energy in the energy supply. Hydrogen energy is one of the most promising clean energy sources and a hot research topic in various countries. Hydrogen production is a key step in the use of hydrogen energy, this paper focuses on the current mainstream hydrogen production methods including electrolysis of water, solar decomposition of water, biomass hydrogen production, nuclear technology, steam methane reforming, coal gasification, methane pyrolysis, etc. And the economic and environmental benefits of each method. According to studies, the mainstream method of producing hydrogen today involves burning fossil fuels, and more recent methods—like the electrolysis of water—need a lot more testing and development before they can be used extensively. The implementation of CCS or CCUS technology can considerably lower the carbon emissions of the hydrogen production process when it comes to hydrogen produced from fossil fuels, but doing so will result in higher energy costs and hydrogen production costs. This paper is expected to support future research directions and help governmental decision-making in the energy transition.

Keywords: hydrogen production; carbon emission; hydrogen.

1. Introduction

The energy transition is becoming increasingly urgent due to public concern over global warming and climate change. As of the end of 2020, there were 2799 gigawatts of renewable energy capacity available globally [1]. With a capacity of 1211 gigawatts, hydropower accounted for 43% of this capacity [1]. The remaining capacity was made up equally of solar and wind energy, with 714 gigawatts (26%) and 733 gigawatts (26%) respectively [1]. The remaining 5% of energy production was sourced from other renewable energy methods [1]. An ever-growing number of nations across the globe are embracing a paradigm shift towards renewable and sustainable energy sources as viable alternatives to traditional fossil fuels. For example, the US wants to enhance hydrogen production via biomass gasification, whereas Japan has declared plans to manufacture hydrogen using entirely renewable electricity [2].

Among the many new energy sources, hydrogen energy is one of the most promising ones and is expected to become the most dominant energy source in the future. However, at present, the production, transportation and storage of hydrogen are still facing many problems, and there are still a lot of difficulties to be overcome before the wide-scale use of hydrogen energy, including the establishment of policies and regulations, safety issues during hydrogen production, transportation and storage such as hydrogen embrittlement, development of advanced hydrogen storage materials, and large infrastructure expenditures. In terms of hydrogen production, the most widely used industrial application is still the traditional way of hydrogen production, and there are still many technical barriers to be solved in the production of green hydrogen. This paper is devoted to summarizing and introducing each type of hydrogen production method and analyzing and evaluating the economic and environmental benefits of each method, with a view to providing references and ideas for future research and governmental decision-making.

2. Green hydrogen production technology

2.1. Electrolysis of water

2.1.1. Alkaline water electrolysis (AEW)

AWE is one of the most sophisticated ways to produce hydrogen today, with decades of application experience [3]. KOH is used as an electrolyte solution to decompose water into hydrogen and oxygen in the presence of direct current electricity [4]. AWE has the advantages of mature technology, easy operation, low cost and long service life, but it also suffers from the defects of large size of the device, long time needed for starting and shutting down the electrolyzer, and alkali liquid in the gas produced.

2.1.2. Proton exchange membrane water electrolysis (PME)

PME has been developing rapidly in recent years, and has begun to be applied on a large scale in Europe and the United States. Companies such as Purdon and Siemens have also released megawatt-class PEN electrolytic water system products. PME can be operated at high current densities and has a fast reaction rate, small size and high purity of the gas produced. With the popularization and application of PME, its cost will continue to decrease in the future.

2.1.3. Solid Oxide Water Electrolysis (SOE)

SOE is a hydrogen production technology in which water is electrolyzed to produce hydrogen at the cathode and oxygen at the anode by adding direct current to the electrodes on both sides of the device at temperatures between 700 and 900 degrees Celsius. SOE has a good development prospect, but compared with AWE and PME, SOE technology is not mature enough, and many problems need to be solved before it can be put into large-scale application.

2.2. Solar decomposition of water

Solar decomposition of water to produce hydrogen methods mainly include photocatalytic hydrogen, photoelectrochemical method of hydrogen.

2.2.1. Photocatalytic decomposition

The basic principle is that a semiconductor absorbs sunlight to make an electron jump from the ground state to the excited state and generates sufficiently energetic conduction-band electrons and valence-band holes to meet the thermodynamic requirements for water decomposition [5]. The United States Department of Energy's assessment of the industrial use of photocatalytic water-to-hydrogen decomposition states that, although the maximum STH conversion efficiency of this process is currently only around 1%, the process should have a STH conversion efficiency of at least 10%. Though there is still a long way to go before it can be commercialized, one of the most promising technologies for resolving environmental and energy-related issues as well as achieving effective solar energy conversion and storage is photocatalytic breakdown of water to create hydrogen.

2.2.2. Photoelectrochemical water splitting

The PEC water separation technology boasts several compelling advantages: it exhibits a notably high efficiency in converting solar energy into chemical energy, facilitating a clean and renewable energy conversion process. Furthermore, the collection of products is straightforward and safe, minimizing operational hazards. Lastly, its high technical reliability ensures consistent performance and longevity, making it a dependable solution for sustainable energy generation [6]. Among several solar hydrogen technologies, PEC can ensure long-term durability of more than ten years, resulting in stable and viable solar hydrogen production. The primary challenge facing PEC water separation technology lies in identifying more cost-effective materials for photoelectrodes, crucial for enhancing economic viability and widespread adoption.

2.3. Biomass hydrogen production

2.3.1. Thermochemical processes

The key thermochemical processes for producing hydrogen from biomass include steam reforming, pyrolysis, and gasification. The process of gasification involves heating biomass, steam, and oxygen to temperatures exceeding 700 °C in a controlled environment in order to create CO, hydrogen, and CO_2 [7]. Heating biomass to create methane, hydrogen, etc. is known as pyrolysis. The most developed technique at the moment is pyrolysis, which has several commercial uses [8]. One technique that has been extensively studied over many years is steam reforming, which has the potential to produce hydrogen from biomass pyrolysis oil and its byproducts in an effective manner.

2.3.2. Biological processes

The intricate biological process of biomass hydrogen synthesis harnesses biochemical reactions, notably fermentation and digestion, within specialized organisms to generate biohydrogen. Microorganisms, through their growth and metabolic machinery, orchestrate the transformation of biomass components into hydrogen gas. Among these processes, dark fermentation emerges as a formidable light-independent technology, showcasing immense potential in deriving biohydrogen from biomass resources abundant in organic matter. This technology stands out from photo-fermentation due to its energy efficiency; specifically, it necessitates lesser energy input, making it a more economically viable option [9]. In addition, anaerobic digestion technology produces gases, including methane and hydrogen, by utilizing the anaerobic decomposition of organic materials such as food waste. This cost-effective approach not only reduces the environmental burden associated with food waste disposal, but also contributes to decentralized hydrogen production, enhances energy security and promotes a circular economy.

2.4. Nuclear technology for hydrogen production

Nuclear energy can be harnessed to produce hydrogen via various techniques. Specifically, radiolysis process utilizes the high-energy particles released in a nuclear reaction to break the chemical bonds within the water molecules, effectively converting them into hydrogen, thus utilizing the powerful energy released in the nuclear reaction to produce clean energy. Electrolysis, on the other hand, relies on the electrical energy generated by nuclear power plants. While conventional technology uses this electrical energy directly to break down water through electrochemical reactions, new electrolysis technology combines the electricity and high-temperature steam for higher efficiency and productivity. This hybrid approach utilizes the high temperatures generated by the nuclear energy system to preheat the steam, reducing the whole energy demand. A more effective and economical method of producing hydrogen is by hybrid thermochemical water decomposition, which makes use of the high temperatures that nuclear energy systems can achieve. In contrast to these hybrid methods, pure thermochemical water decomposition relies exclusively on high-temperature heat [10].

2.5. Hydrogen production from seawater

Since the late 1900s, a great deal of research has been done on seawater electrolysis since it is the most plentiful water resource on Earth. Finding effective and affordable catalysts for seawater electrolysis and the corrosion of electrode materials by saltwater continue to be scientific challenges. Three categories may be used to classify the electrocatalysts used: base metals and their alloys, noble metals, and hybrid electrocatalysts. Seawater electrolysis severely corrodes Type I and Type II electrocatalysts despite their great catalytic activity. Furthermore, it is very difficult to use noble metals industrially because of their scarcity and high cost. As a result, the creation of hybrid electrocatalysts is a hot area of study that is producing improved outcomes right now [11].

3. Conventional hydrogen production technologies

3.1. Steam Methane Reforming (SMR) and Steam Methane Reforming with Carbon Capture and Sequestration (SMR-CCS)

As the mostly used method, SMR plants usually get yield between 80 and 90 percent; larger and more efficient units provide higher yields [12]. In addition, the catalysts used in SMR reactors typically have a lifetime of 5-10 years and can be regenerated or replaced at regular intervals. Since steam methane reforming uses fossil fuels, the process is bound to produce greenhouse gas emissions. As a result, researchers are now combining steam methane reforming with carbon capture technology to develop SMR-CCS technology to reduce carbon emissions from steam methane reforming to hydrogen. Four commercial SMR-CCS systems are currently operational worldwide, and an additional 15 are anticipated to go online by 2028, according to the Global CCS Institute [13]. Since SMR currently produces the largest amount of hydrogen, retrofitting the plant with a CCS unit is a very effective means of reducing carbon emissions.

3.2. Coal gasification

Fixed and fluidized bed gasifiers are the two primary types of gasification processes with relatively high effectiveness. Certain research comparing the two types of gasifiers have revealed that the fluidized bed produces a greater proportion of hydrogen gas [14]. At present, China is the country that uses the most coal in the world, and the coal-to-hydrogen technology has a broad development prospect in China, and is applied more in large-scale enterprises. The technical conditions of coal-to-hydrogen process are very mature and the economic cost is relatively low.

3.3. Methane pyrolysis

Methane pyrolysis technology offers a cost-effective method of hydrogen production with minimal or virtually no emissions [15]. Methane pyrolysis technology has been developed in many directions, including catalytic pyrolysis, plasma pyrolysis, moving carbon bed pyrolysis, microwave pyrolysis, molten metal pyrolysis, molten salt pyrolysis, etc. However, methane pyrolysis technology is still in its nascent stages of development, and reactor design, catalysts, etc. are still far from reaching maturity, and there are many hurdles to be overcome before this technology can be commercialized, with significant room for advancement and refinement.

4. Economic and environmental analysis

4.1. Economic analysis

The current price range for green hydrogen production is approximately between USD 2.28 and USD 7.39 per kilogram of hydrogen generated [16]. Majid K. Abbas et al. estimated the cost of converting solar energy to hydrogen utilizing photovoltaic energy systems in four major Iraqi cities at $3.79 per kilogram [17]. According to Ali Kakavand et al, the cost of hydrogen produced by proton exchange membrane electrolysis in Iran is 2.94-3.32 USD/kgH_2 [18]. The cost of hydrogen production by thermo-chemical water decomposition is 3.92 USD/kgH_2 according to Adetunji Onigbajumo et al [19]. As for biomass hydrogen production, previous research indicates that producing bio-H_2 is relatively expensive [20]. The cost of SMR is 0.67-USD 1.31/kgH_2, and when using CCS technology, the cost is USD 0.99-USD 1.83/kgH_2 produced [21]. McFarland, E et al. expect the price of hydrogen from methane pyrolysis to be about $2/kg hydrogen, depending on the cost of natural gas [22].

4.2. Carbon emission analysis

In general, hydrogen produced using fossil fuels emits more carbon dioxide than hydrogen produced using renewable energy sources. The hydrocarbon-based systems that use fossil fuels to

create H2 have greenhouse gas emissions that vary from 17 to 38 kg CO2/kg H2 [23]. Less than 2 kg CO2/kg H2 is released when green hydrogen is created using renewable energy [23]. The most advanced technology for producing hydrogen to minimize greenhouse gas emissions is water electrolysis; however, the processes used to produce hydrogen by this method are currently inefficient and water-intensive, and it is important to take the environmental effects of this large water consumption into account.

5. Conclusion

Hydrogen energy is one of the most effective means of addressing greenhouse gas emissions. This paper analyzes the hydrogen production technologies that are currently in use and compares hydrogen production based on renewable energy sources with hydrogen production based on fossil fuels in terms of economic and carbon emissions. At present, the use of fossil fuels to produce hydrogen is still the mainstream technology, water electrolysis, a new type of technology will take a long time to research and explore in order to reach the level of industrialization and application. Conventional hydrogen production using fossil fuels has high elevated energy performance and cost-effectiveness, but also brings more carbon emissions. Hydrogen production from electrolyzed water produces few greenhouse gases, but due to the immaturity of the current technology, on the one hand, it consumes a lot of energy, and on the other hand, the materials used are very expensive, which increases the cost and makes some of the technologies inefficient in the production of hydrogen. The introduction of CCS or CCUS technology can significantly reduce the carbon emissions of the hydrogen production process, but this increases energy consumption and raises the cost. Hydrogen production based on water electrolysis will be widely developed in the future, but the environmental problems caused by the large amount of water consumption need to be taken into account in practical applications. How to solve the problem of water supply in water-scarce areas like Africa is also one of the difficulties faced by water electrolysis for hydrogen production.

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