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Green Hydrogen Generation: Recent Advances and Challenges

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Abstract. Actually, decarbonization of the global economy presents an important challenge for the worldwide. Expanding renewable energy sources and using green hydrogen to merge renewables in many sectors, such as energy, mobility and industries, present a potential key to meet this challenge. Green hydrogen has the potential to plug the fluctuation of wind and solar energy, to serve as feedstock in many industrial processes, and as fuel for transportation. An overview of the different technologies used to generate green hydrogen is presented in this paper. In addition, this paper summarises the different barriers of the development of green hydrogen.

1. Introduction

Green hydrogen is viewed as a promising and an alternative fuel that can be used to decarbonize many sectors, such as mobility, energy generation, steel and iron, and chemicals. It is also used to store the excess of renewable energy generated during favorable weather conditions, to be re-used during the high demand period. Hydrogen energy and renewable energy are mutually profitable. Green hydrogen is used in the electricity and heat production, and as a raw material for industrial operations. It is able to run heavy machinery, metal treatment, and vehicles for petroleum refinement. Besides, green hydrogen can create new numerous job opportunities in the field of generation, transportation, and storage of hydrogen.

Actually, there is no universal definition of green hydrogen. [1, 2] defined green hydrogen as the hydrogen generated from renewable energy resources with or without explicit mention to air pollution. According to [3], green hydrogen is generated by any low carbon emission energy sources with unquantified emission intensity. Also, [4] defined green hydrogen as hydrogen produced by any energy sources with low carbon and environmental impact. The common process used to generate green hydrogen is the electrolysis of water. Electricity is used in the electrolysis process to split water into hydrogen and oxygen. The feedstocks used in the electrolysis are water, sea water (brine), biomass, and hydrogen sulfide. The electricity and the heat used in electrolysis can be extracted from renewable energy resources, nuclear energy, or from recovered energy.

Currently, green hydrogen accounts just 0.1% of the global hydrogen generation [5]. Global demand for green hydrogen is projected to increase to attain 530 million tons by 2050, replacing 10.4 billions barrels of oil equivalent. In addition, green hydrogen market is projected to raise at a high rate and creates 300,000 employment in the fields of renewable energy and hydrogen generation [6].

Despite the benefits of green hydrogen related to the reduction of greenhouse gas emissions, bringing energy transition and ensuring a sustainable future, its efficiency is low and its generation

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cost is high. According the IEA, the cost of generating 1 kg of green hydrogen varies between USD$3 to $7.50, while this cost is between 0.90 to $3.20 for hydrogen generated by steam methane reforming [6].

2. Technologies used to generate green hydrogen

Many technologies are developed and many research studies are conducting to split the water and generate green hydrogen in an efficient way and with low cost. Splitting water can be operated by:

2.1. Electrolytic cell

Direct current/electricity is passed through two electrodes immersed in water to split the water molecules and generate hydrogen at the cathode and oxygen at the anode. Currently, many kinds of electrolysis could be used in this method. Some of these method use a liquid electrolyte like the aqueous solution of potassium hydroxide (KOH) due to its high conductivity and are known as the alkaline electrolyser (unipolar and bipolar). Another method uses an electrolyte as a solid ion conducting membrane and is known as proton exchange membrane electrolyser (PEM). Compared to alkaline electrolyser, PEM could supply lower gas exchange, higher proton conductivity, lower membrane thickness and it can perform under high pressure [7, 8]. Sea water can be used as an aqueous electrolyte in the electrolysis process since it is more abundant than pure water. It does not require a pretreatment and purification, resulting in cutting their associated cost. In sea water electrolysis, hydrogen evolution reaction is composed at the cathode and chlorine evolution is composed at the anode. The drawbacks of the use of sea water are the corrosion of the equipment and the generation of chlorine as by product.

2.2. Photoelectrode device

Photoelectrode device is viewed as a promising option for green hydrogen generation to overcome the thermodynamic barrier in the water electrolysis. A semiconductor electrode is used to separate hydrogen and oxygen from water by using the photo-absorption method that creates electron-hole pairs at the semiconductor areas. A separation of the pairs into electrons and holes occurred thanks to the surface band bending on n-types semiconductor. The holes and electrons minimize and oxidize water to generate hydrogen and oxygen, successfully. Nanotechnology is used in the green hydrogen generation by creating a novel sunlight-photosensitive-nanostructured electrode. This electrode subjects to photocatalyst to be able to split water molecules intro hydrogen and oxygen under the sun’s light. The benefit of nanostructure derives from its ability to boost the operational surface area of the electrode, thus augment the performance of electrode for green hydrogen generation.

2.3. Solar cells

Water splitting is performed by the photovoltage of connected solar cells. Many joined crystalline cells (like Si and CIGS) are probable due to the solar to hydrogen performance and solar-operated durability for hydrogen generation [9]. The benefit of CIGS is the capability to modulate the ban gap energy to efficaciously soak up the solar spectrum. Perovskite solar cells can be used also to drive water splitting. Two perovskite cells connected in series, compared to at least three to four Si or CIGS cells, can achieve open circuit voltages at 0.9 V, which is adequate for an effective water splitting [10, 11]. According to [12, 13] , the cost of hydrogen generated by the PV-electrolysis is more than $5/kg and the efficiency is less than 5%. [14] conducted a study to improve the performance and the hydrogen generation of an hybrid system of electrolysis and PV to generate hydrogen. Results showed that the performance and hydrogen generation could be improved by thermal integration. Besides, Concentrator photovoltaic (CPV) can be used to run an electrolysis. The solar to hydrogen efficiency (STH) of CPV-electrolyser reaches the highest of 28% using alkaline system, to now [15].

2.4. Thermoelectric (TE) devices

The efficient use of sunlight by solar cells are effective only in the zone of visible light and ultraviolet. Since the infrared light occupied around half of the sunlight, an integration of thermoelectric device with infrared-active materials could enhance the conversion of infrared light into electricity needed in water splitting. The energy provided by infrared light is in the form of heat, TE is used to convert the heat into electricity [16]. Infrared-active materials are materials with high photothermal conversion efficiency are used to enlarge the imbibition of the infrared lights by thermoelectric device and promote the performance of TE device [17]. In turn, it leads to improve the efficiency of the electrolyser. On the other hand, TE device could be used with Photo-electrochemical reaction (PEC). The sunlight is used to separate water by using specialized semiconductors knows as photo-electrochemical materials in PEC reaction. The use of TEC with PEC leads to maximize the solar energy harvest and enhance the performance of electrolysis process [18].

2.5. Heat with pyroelectric materials

Pyroelectricity is the capability of some materials to create an electric potential when exposed to a change of temperature. A temperature oscillations in a pyroelectric device can be supplied naturally, by transient low-grade waste heat, by thermos-electric effect, and by a combination of wind with sunlight. The operational principle of this technology is based on the change of polarization of a pyroelectric material, that is highly polarized, with the change of temperature. The polarization decreases as the temperature increases and leads to release charge on its surface. Whereas, the polarization increases when the temperature decreases and reverse the current flow since charge is attracted to the high polarized surface [19]. Thus, an electric potential is established and can perform the electrolysis process.

3. Barriers of green hydrogen generation

The generation of green hydrogen faces many economic and technical barriers. A summary of these barriers is presented below.

- Cost of water: Water electrolysis requires huge quantity of water to generate hydrogen, around 18 tons of water are required to generate only one ton of hydrogen [5]. This amount can be more due to losses during the operation and the transportation. Also, the used water should be purified before using it in the electrolyser. The purification processes are expensive, especially if they are fast, accounting around $2,400 per ton of hydrogen. In addition to the purification and the water cost, there is the transportation cost of water to be supplied into the electrolyser.
- Cost of infrastructures: the high flammability and the low volumetric density of hydrogen cause an increase of the operational cost of the hydrogen due to the need of dedicated pipelines and carriers. Moreover, the existing green hydrogen facilities are needed to be enlarged to meet the rise of market demand. So, designs optimisation and end-to-end green hydrogen, that are expensive and complex are required, resulting in increasing of the capital cost of hydrogen generation. Besides, a huge quantity of renewable energy will be required to meet the growth of the hydrogen market
- Limitation of suitable place: Since green hydrogen should be run using renewable energy, electrolyser facilities should be installed near renewable energy resources (wind or solar farm). That means that there is a limitation of the suitable locations to install electrolyser. Besides, the hydrogen plant should be in proximity of a site where water is abundant or near water treatment plant. Devoted pipelines for transportation with all the associated times and cost will be required in the hydrogen plants if there are installed far from the renewable energy resources and water.
- Energy losses: A significant quantity of energy is lost during the generation, converting and transportation of green hydrogen. In the electrolysis process, around 30-35% of the utilised energy is lost [20]. Besides, 13-25% is lost in the converting process of hydrogen to facilitate its transportation and storage. In addition, energy inputs, around 10-12% of the hydrogen' own energy, are needed to transport the generated hydrogen [20]. Also, additional energy loss, around 40-50%, is recorded in the process of using hydrogen in fuel cells [20].
- Lack of skilled workers: As hydrogen market is projected to increase in the coming years, more job opportunities are excepting to be created. Whilst, there is a lack of specialized workforce needed to boost the growth of hydrogen market, resulting in impeding its progress.

- Carbon capture and storage: using CCS with the hydrogen generation declines CO_2 emissions. However, the cost of equipment and infrastructure used to separate CO_2, transport it and store it is expensive and rises the generation cost of green hydrogen. Besides, the transportation and the storage of CO_2 could be parlous. In addition, the stored CO_2 is used in enhanced oil recovery to liberate unattainable oil, that can emit more CO_2 emissions when burned.

4. Conclusions

Green hydrogen is viewed as a key pillar in the global decarbonization of transportation, chemical and industrial sectors. Many technologies are developed to generate green hydrogen, such as photoelectrode, solar cell, pyroelectric materials, thermoelectric devices, and electrolytic. Though its advantages in decarbonization many sectors, green hydrogen faces many economic and technical impediments associated with the huge amount of required water and its pretreatment and purification, and energy losses during generation, transportation and storing of hydrogen. Also, restriction of adequate sites to install hydrogen plant due to the use of the water and renewable sources and lack of experienced workers. Dropping the cost of renewable energy and the capital cost of electrolysis are the main drivers to decrease the cost of green hydrogen production. In addition to the reduction of the capital cost of electrolyser, an improve of its efficiency and increase of its lifetime present an important part in the way to generate a competitive and an affordable green hydrogen. The generation cost of green hydrogen should be decreased to \$2/kg to ensure a transition to green hydrogen. Thus, it would be easily utilized in many areas like steel and fertilizer generation, and power generation. Besides, green hydrogen can be used to generate green ammonia, that can act as a clean replacement of fossil fuel in thermal power plants

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