



## Moving Towards Carbon Neutrality: a Comprehensive Assessment of Various Process of Green Hydrogen Production

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# MOVING TOWARDS CARBON NEUTRALITY: A COMPREHENSIVE ASSESSMENT OF VARIOUS PROCESS OF GREEN HYDROGEN PRODUCTION

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**Abstract— Climate change is a terrible threat to all living things on Earth which is caused by the excessive use of fossil fuels and this is constantly prompting us to seek for various clean energy resources.** Among many available clean energy resources Green hydrogen looks promising to achieve Goals of decarbonization. This study provides a summary of current green hydrogen production technologies from a technological, economic, and policy viewpoint. It also discusses potential green hydrogen production technologies and their viability. The higher cost of green hydrogen in comparison to its other competitors is the only deciding factor that limit its true potential. The paper also elaborates on the regulatory frameworks that could support further cost reduction and the general commercialization of electrolyser technologies.

**Keywords—component, formatting, style, styling, insert** (key words)

## I. INTRODUCTION

Fossil fuels have served to society's requirements and industry for more than a century [1]. Today there are Numerous reasons to encourage a reduction in the use of fossil fuels [2]. High energy consumption brought on by the expanding global population increased the use of fossil fuels and drove up prices [3]. In order to lessen the effects of climate change, it is imperative to concentrate on green sources [4]. By 2050, it is anticipated that 12% of all energy consumed will come from hydrogen base systems [5]. Since it is anticipated that two-thirds of the total hydrogen will be produced from renewable energy sources and one-third from natural gas combined with CCS, this rise highlights the importance of low-carbon hydrogen. Global specialists agree that green hydrogen will be crucial in achieving the goals set forth in the Paris Agreement [5].

Hydrogen energy is regarded as the most promising energy source of the twenty-first century. because it can be created using reliable, sustainable renewable energy sources, Hydrogen-based sustainable development can be defined as a source of energy capable of meeting the various needs of the industrial, transportation, household, and energy-conservation sectors. While this is happening, the majority of the raw materials are used to make hydrogen and they originate from the chemical reformation of existing energy sources. According to sources used to produce Hydrogen it

can be divided into Further Brown, Gray, Blue, and Green Hydrogen. Hydrogen produced by water electrolysis does not release carbon dioxide into the atmosphere, in contrast to hydrogen produced from solid fuels and thus It is called Green Hydrogen.

Currently Green Hydrogen is costly than Blue and Gray Hydrogen, but production costs will decline over time as a result of constantly declining costs for producing renewable energy, economies of scale, lessons learned from current projects, and technological advancements. Green hydrogen will consequently become more affordable. According to a Study Green Hydrogen will be cheaper than Blue Hydrogen till 2030 and cheaper than Gray Hydrogen till 2050.

This paper will list different methods for producing green hydrogen and analyze them from the points of view of carbon emissions and economics.

## 2. ELECTROLYSIS

One of the most effective processes for producing hydrogen is electrolysis of water because it utilizes renewable H<sub>2</sub>O and produces only pure oxygen as a byproduct.

Cathode (reduction):  $2 \text{H}_2\text{O} (\text{l}) + 2\text{e}^- \rightarrow \text{H}_2(\text{g}) + 2 \text{OH}^-(\text{aq})$   
Anode (oxidation):  $2\text{OH}^-(\text{aq}) \rightarrow 1/2 \text{O}_2(\text{g}) + \text{H}_2\text{O}(\text{l}) + 2 \text{e}^-$

In electrolysis process, water molecule is the reactant it is dissociated into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>) under the influence of electricity. Water electrolysis can be classified in to the four types based on their electrolyte, operating conditions, and ionic agents (OH<sup>-</sup>, H<sup>+</sup>, O<sup>2-</sup>), however operating principles are both the cases same.

The four kinds of electrolysis methods are (i) Alkaline water electrolysis (AWE) [7–9], (ii) Solid oxide electrolysis (SOE) [10,11] (iii) Microbial electrolysis cells (MEC) [14,15]. (iv) PEM water electrolysis [12,13].

### 2.1 Alkaline water electrolysis (AWE)

In the beginning of the alkaline water electrolysis process, two molecules of alkaline solution (KOH/NaOH) were reduced to one hydrogen molecule (H<sub>2</sub>) and two hydroxyl ions (OH<sup>-</sup>) were produced at the cathode side. From the cathode surface produced H<sub>2</sub> eliminates to recombine in a gaseous form and under the influence of the electrical circuit

between anode and cathode, the hydroxyl ions (OH<sup>-</sup>) transfer through the porous diaphragm to the anode, hence ½ molecule of oxygen (O<sub>2</sub>) and one molecule of water (H<sub>2</sub>O) is discharged. [16]

At the electrode's surface, oxygen is recombined and then escapes as hydrogen, according to the process depicted in Fig. 1 Alkaline electrolysis uses an aqueous solution (KOH/NaOH) as the electrolyte, with a concentration of 20% to 30%, and works at lower temperatures, such as 30 to 80 °C [7,18–19]. In the electrolysis of alkaline water,

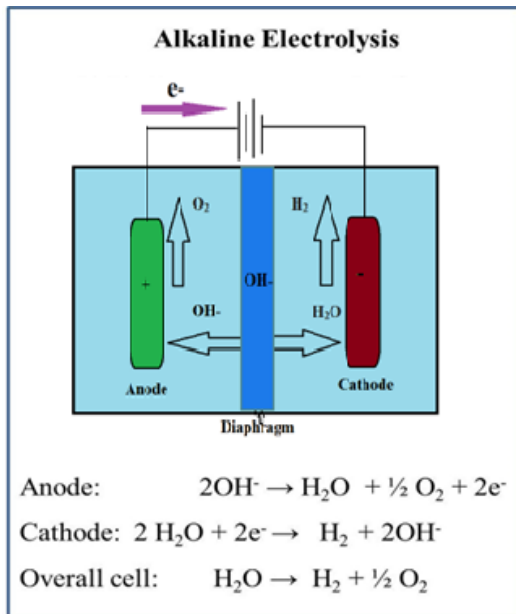


Fig. 1 Schematic illustration of alkaline water electrolysis

## 2.2 Solid oxide electrolysis (SOE) :

Due to the electrical energy's conversion to chemical energy and the process's increased efficiency in creating ultra-pure hydrogen, solid oxide electrolysis has received a great deal of attention [21, 22]. Steam is produced from water during solid oxide electrolysis, which works at high pressures and temperatures (500–850 °C). Conventionally, the solid oxide electrolysis process employs O<sub>2</sub><sup>-</sup> conductors, the majority of which are made of nickel/yttria stabilized zirconia [60], as shown in Fig 2. In recent years some of the ceramic proton conducting materials have been developed and studied in solid oxide fuel cells.

However, ceramic proton conducting materials are receiving more focus for the SOE electrolysis process because they exhibit high efficiency and superior ionic conductivity to O<sub>2</sub><sup>-</sup> conductors at an operating temperature of 500–700 °C [13]. The primary benefit of solid oxide electrolysis (SOE) technology over low temperature electrolysis is its higher operating temperature. However, there are some issues with the SOE's lack of stability and degradation that must be resolved before it can be commercialized on a large basis. [11,24–26]

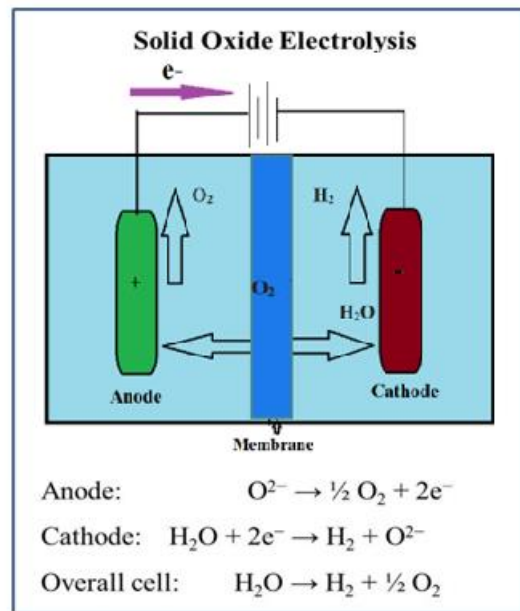


Fig.2 Schematic illustration of Solid Oxide electrolysis.

## 2.3 Microbial electrolysis :

Electrical energy is transformed into chemical energy in microbial electrolytic cells (MECs). MECs used organic materials to produce hydrogen under the effect of an electric current. In the process of microbial electrolysis, microorganisms first oxidize the substrate on the anode side before producing CO<sub>2</sub>, protons, and electrons.)

The protons travel to the cathode via a proton conducting membrane (electrolyte), and the electrons move from the external circuit to the cathode side, where they join to form hydrogen. The MEC concept is depicted in Fig.3 . The MEC process generates some electrochemical potential during oxidation on the anode side, but this electrochemical potential is insufficient to provide the minimum voltage needed for the hydrogen evolution reaction on the cathode side, so additional voltage was necessary. (0.2 V–1.0 V) Although this MEC technology is still in development, there are still a number of issues that must be resolved before it can be commercialized, including the rate at which hydrogen is produced, high internal resistance, electrode materials, and complex design [15].

## 2.4 PEM water electrolysis :

Grubb idealized the first PEM water electrolysis in the early 1950s, and General Electric Co. developed it in 1966 to address the limitations of alkaline water electrolysis [27–29,30,31]. In PEM water electrolysis, hydrogen and oxygen are electrochemically separated from water at their corresponding electrodes, such as the cathode and anode. Pumping water to the anode, where it splits into oxygen (O<sub>2</sub>), protons (H<sup>+</sup>), and electrons (e<sup>-</sup>), initiates PEM water electrolysis. The proton carrying membrane transports these protons to the cathode side.[16].The external power circuit, which supplies the reaction's propelling force (cell voltage),

is where the electrons leave the anode. The subsequent mechanism, as depicted in Fig. 4 occurs at the cathode side to produce hydrogen from the recombination of protons and electrons.

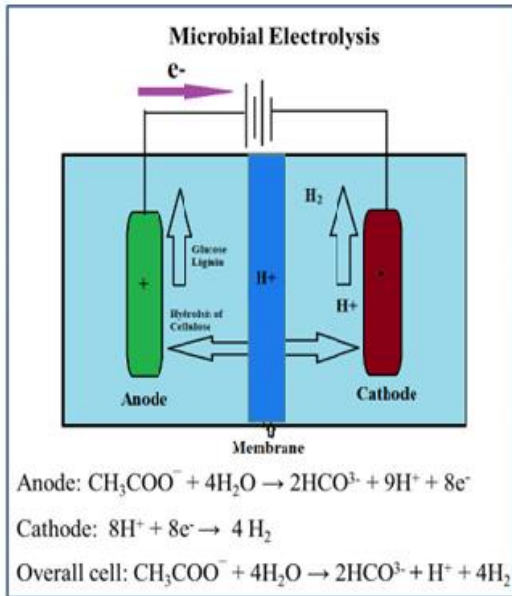


Fig 3. Schematic illustration of Microbial Electrolysis.

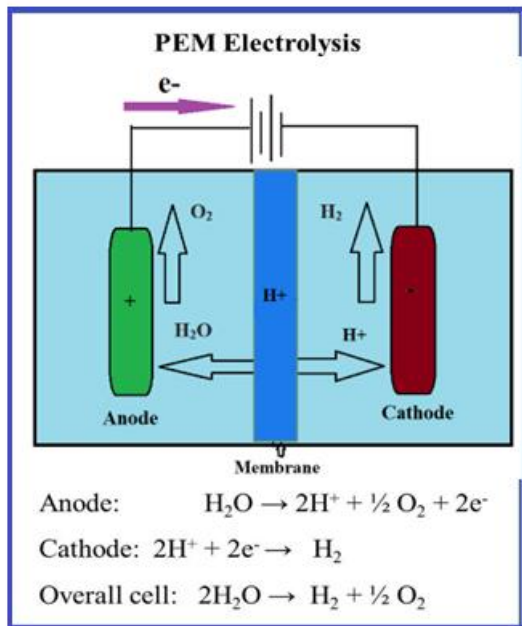


Fig.4. Schematic illustration of PEM water electrolysis.

Due to their innate capacity to instantly ramp up and down, PEM electrolyzers are discovered to be better suited for integration with variable renewable energy sources (solar and wind). Although PEM electrolyzers are more expensive and less effective than alkaline electrolyzers, a study shows that costs will gradually decline from 2020 to the following two decades.[17]

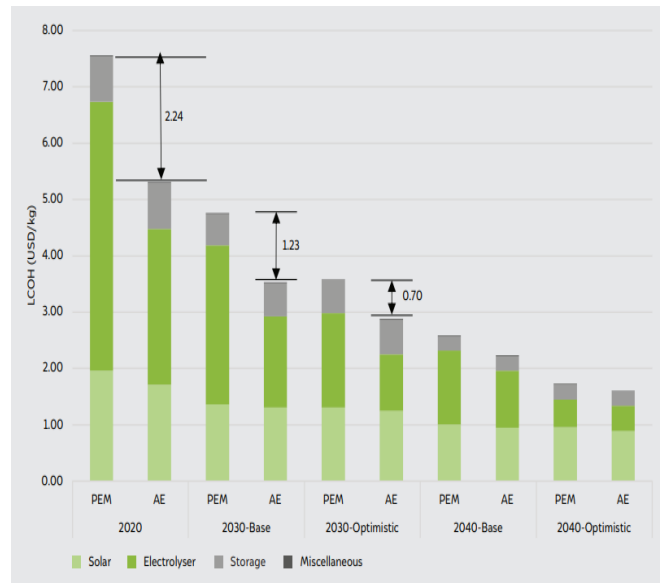


Fig : 5. Hydrogen obtained from the PEM electrolyser is expensive than alkaline electrolyser(AE), but the difference is expected to decrease in the future.[17]

In a study it is found that using optimal electrolyzer capacity production cost range of green Hydrogen vary from USD 5.39/kg to USD 3.23/kg.[6]

### 3.Direct photolysis :

It takes advantage of the cyanobacteria's and algae's capacity to photosynthesize, converting water into oxygen and hydrogen. As shown in Fig.6, algae have developed the ability to release protons and electrons when splitting water with solar energy. Direct light absorption results in the production of hydrogen, and electrons are then transferred to two distinct enzymes, hydrogenases and nitrogenases [33]. Photosynthetic microbes use the hydrogenase enzyme to convert H to H<sub>2</sub> when oxygen is lacking (anaerobic conditions) or when too much energy has been stored [34,35]. According to a study [36], chloroplast hydrogenase recombines the electrons and protons liberated during the water-splitting reactions to create high-purity H<sub>2</sub> (up to 98%).

Hydrogen production is consequently constrained because photosynthetic microbes produce oxygen rather than hydrogen [32,37]. Researchers have studied how to manipulate microorganisms so that the majority of solar energy is transferred to the production of hydrogen and the minimum amount is transferred to cell maintenance to prevent oxygen buildup. Similar research is being done to isolate the hydrogen and oxygen evolutions, find less oxygen-sensitive microorganisms, and change the photosynthesis respiration ratio [38]. Sulfate dosing can reduce oxygen generation, but it can also reduce hydrogen production, according to studies [34,35].

Direct photolysis has the benefit of a plentiful and affordable feedwater source.

To make the procedure workable, significant obstacles needed to be overcome. In order to capture enough solar energy, large cultivation regions are required. Continually

producing hydrogen under aerobic circumstances is an obstacle as well [38].

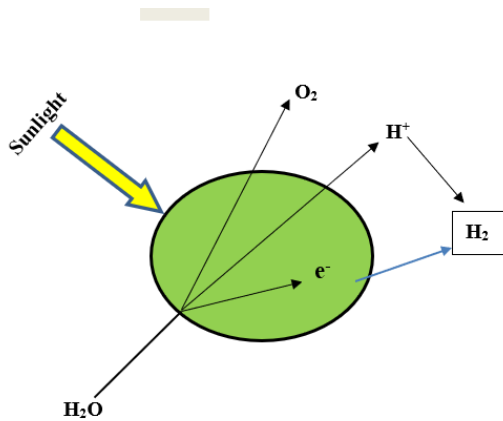


Fig 6. Impeded photosynthesis under sulfur deprivation causing net oxygen consumption by cell respiration in anaerobic indirect photolysis.

**4. Thermochemical Method :** The idea behind thermochemical water splitting is to use intermediary reactions to separate water molecules into hydrogen and oxygen. The catalysts are not required for these reactions. The benefits of TWSCs include

1. Separation between O<sub>2</sub>-H<sub>2</sub> is not required.
2. 500-1800 °C is the operational temperature range.
3. No need of Electricity

There are two types of thermochemical cycles: pure thermochemical cycles, which are powered solely by thermal energy, and hybrid thermochemical cycles, which are powered by thermal energy along with one other source of energy, such as electric or photonic energy. In hybrid TWSCs, water, electricity, and heat (from concentrated solar power or nuclear reactors) are provided as inputs, and hydrogen is produced as an output in a single process [39]. Single step thermochemical cycles need very high temperatures, so two or more step cycles with lower temperature requirements (2000 °C) have been suggested. [40]

**4.1 Two-step thermochemical cycles:** Two-step thermochemical cycles create valence metal oxide after undergoing high temperature reduction in the first step. 1700–3000 K should be the working temperature range. The two-step thermochemical cycle is depicted in Figure 7 and involves the reduction of the metal oxide in an endothermic step and the introduction of water to conduct out oxidation in an exothermic step to produce hydrogen. Numerous two-step thermochemical cycles, including ZnO/Zn, Fe<sub>3</sub>O<sub>4</sub>/Fe, SnO<sub>2</sub>/SnO, CeO<sub>2</sub>/Ce<sub>2</sub>O<sub>3</sub>, Mn<sub>2</sub>O<sub>3</sub>/MnO, Co<sub>3</sub>O<sub>4</sub>/CoO, CdO/Cd, and GeO<sub>2</sub>/GeO, are built on redox pairs of volatile and non-volatile metal oxides[41], [42]. There is evidence to support the thermodynamic advantage of zinc-based TWSCs [43]. Due to difficulties such as slow kinetic reactions, back reactions, and oxygen separation from zinc, the ZnO/Zn have only been tried on a small scale thus far [44].

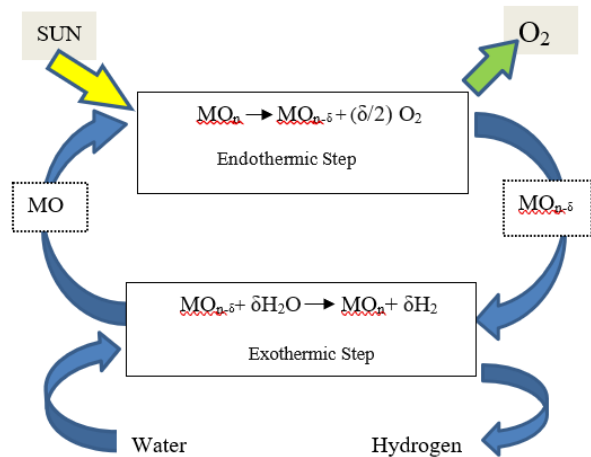


Figure 7: Two step thermochemical cycle

**4.2 Three step thermochemical cycles:** In a three-step cycle with just two steps, the reduction reaction is swapped out for the second phase. The cycle's total temperature is lowered as a result. The three-step thermochemical cycle's chemical processes are expressed as follows in [45]:

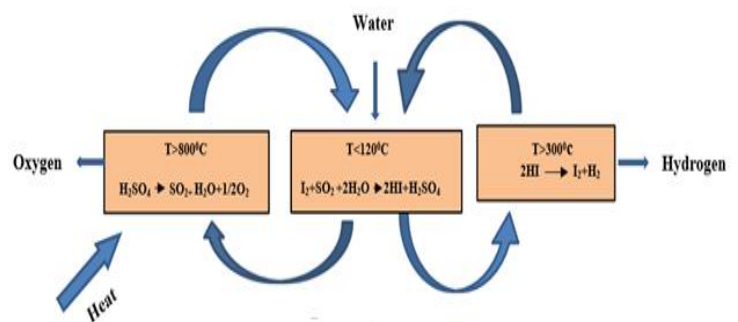
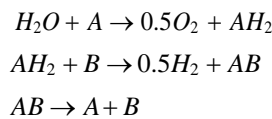


Fig. 8 Three step Thermochemical cycle

### 5. Photoelectrochemical

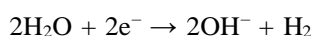
Water-splitting photoelectrochemical (PEC) cells combine PEC processes to generate hydrogen and oxygen from sunlight and water. They are integrated solar fuel generators that incorporate multiple functional materials. In a typical device the semiconductor materials harvest the incident sunlight, and any substances or parts in the optical path



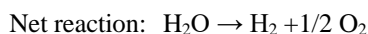
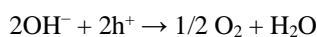
between the sun and the semiconductors have the potential to modulate and change the light absorption. Depending on the specific design of the system, the light illumination may come from either side of the cell or from both sides. "Photocathode and dark anode," "photoanode and dark cathode," and "photocathode and photoanode" are the three standard categories.

The overall voltage produced by the photo absorbers in each of the three groups must be greater than the voltage needed to cause the water-splitting reaction. Energy-rich electrons and holes are produced by absorbed photons in the semiconductor material and are moved to the electrocatalysts by means of bulk and interfacial charge transfer processes.<sup>8</sup> Then, at the catalytic sites, electrocatalysts split water while concurrently producing gaseous H<sub>2</sub> and O<sub>2</sub>. The following equations show the potential two half reactions and the associated net reaction that are engaged in the entire process:[46]

Half-reaction at cathode (reduction):

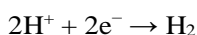


Half-reaction at anode (oxidation):

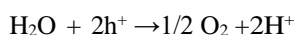


or

Half-reaction at cathode (reduction):



Half-reaction at anode (oxidation):



Unlike solar thermochemical water splitting, in which two full redox reactions take place, photoelectrochemical water-splitting uses two half reactions, e.g., hydrogen evolution reaction and oxygen evolution reaction.[46]

## Technological And Economical Comparison

Hydrogen Production Method	Feed	Energy Source	Major Advantages	Major Challenges	Efficiency(%)	LCOH (\$/kg)
Electrolysis	Water	Electricity	No emissions - Integration with renewable energy	Large electricity consumption - Difficulties in storage and transport	60-80	3-4
Photolysis	Water	Photonic	Abundant feed - No emissions - Conversion of solar energy to hydrogen	Low efficiency - Difficult to scale-up - Requires for sunlight	0.06	8-10
Photoelectrochemical	Water	Electricity + photonic	-Abundant feed -Less power required compared to photolysis	Low efficiency - Requires for sunlight	2-20	2-4
Thermochemical	Water	Thermal	Abundant feed - Large-scale hydrogen production - Utilization of waste heat	Requires heat-resistant materials - Thermal losses	20-45	4-6

Table 1. Overview of Green hydrogen production methods, including the feed, energy source and major advantages and challenges. [47]

## 7. Conclusion

In many nations around the world, the growth of the hydrogen economy is usually seen as an essential step toward complete decarbonization. The use of "green" hydrogen is crucial to this process, but it is presently much more expensive than other forms of H<sub>2</sub> with a larger carbon footprint. So, in addition to lowering the price of renewable energy, which is the primary cost factor for "green" hydrogen, another decrease in the price of electrolyzers themselves, which is the second-most crucial component, is required. It is probable that a combination of technological advancement and policy support mechanisms will be used to accomplish this.

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