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. In this paper technological and economical comparison has been done along with major advantages and major challenges. The paper also elaborates about the latest technology of producing Green hydrogen from saline water without desalination of water, which could be path breaking because of easy availability of sea water. In this paper specific energy consumption of various hydrogen production techniques has been discussed which could be helpful while choosing the process.

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 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.

Blue hydrogen is produced through a process called steam methane reforming (SMR), which involves extracting hydrogen from natural gas. The carbon dioxide (CO2) emissions generated during this process are captured and stored using carbon capture and storage (CCS) technology. CCS prevents a significant portion of the CO2 from being released into the atmosphere, reducing the carbon footprint associated with hydrogen production. Blue hydrogen is considered a transitional solution as it helps decarbonize the hydrogen production process compared to traditional methods but still relies on fossil fuels.

Brown hydrogen is also produced from natural gas using the steam methane reforming process. However, unlike blue hydrogen, brown hydrogen production does not include carbon capture and storage. As a result, the CO2 emissions generated during production are released into the atmosphere, contributing to greenhouse gas emissions and climate change. Brown hydrogen production is the least environmentally friendly option among the three and does not contribute to sustainable energy goals.

Gray hydrogen is produced using the same methods as blue and brown hydrogen—through steam methane reforming or other processes that rely on fossil fuels—but without any carbon capture or emissions reduction measures. This means that all the CO2 generated during hydrogen production is released into the atmosphere. Gray hydrogen is the least sustainable option and has a significant carbon footprint.

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. NOVELTY OF THE PAPER

In this research paper significant strides to elevate the novelty and relevance of the study has been taken.

One notable addition is the incorporation of specific energy consumption analysis, which serves as a critical pillar of this paper's novelty. By meticulously evaluating and presenting the energy requirements of different green hydrogen production methods, this paper contribute essential insights into the efficiency and sustainability of each process. This pivotal inclusion equips policymakers, researchers, and industries with informed decision-making tools that align with our collective carbon neutrality aspirations.

Furthermore, this paper introduced a cutting-edge process—Green Hydrogen Production from Saline Water—significantly enhancing the paper's innovative aspects. This novel approach not only explores an uncharted pathway for sustainable hydrogen generation but also amplifies the paper's relevance in addressing contemporary challenges. By harnessing the potential of saline water resources, this research pioneers a holistic and environmentally conscious approach to green hydrogen production.

In summary, this paper's novelty is underscored by its dual focus on specific energy consumption analysis across diverse methods and the exploration of a groundbreaking process that leverages saline water for green hydrogen production. This approach reflects the essence of our journey towards carbon neutrality and makes a substantial contribution to the global pursuit of sustainable energy solutions.

3.ELECTROLYSIS

One of the most effective processes for producing hydrogen is electrolysis of water because it utilizes renewable H_2O and produces only pure oxygen as a byproduct.

Cathode (reduction): $\mathbf{2\ H_2O\ (l) + 2e- \rightarrow H_2(g) + 2\ OH-(aq)}$

Anode (oxidation): $\mathbf{2OH-(aq) \rightarrow 1/2\ O_2(g) + H_2O(l) + 2\ e-}$

In electrolysis process, water molecule is the reactant it is dissociated into hydrogen (H_2) and oxygen (O_2) under the influence of electricity. Water electrolysis can be classified into the four types based on their electrolyte, operating conditions, and ionic agents ($OH^{—}$, H^{+}, $O^{2—}$), 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].

3.1 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_2) and two hydroxyl ions (OH—) were produced at the cathode side. From the cathode surface produced H_2 eliminates to recombine in a gaseous form and under the influence of the electrical circuit between anode and cathode, the hydroxyl ions (OH—) transfer through the porous diaphragm to the anode, hence ½ molecule of oxygen (O2) and one molecule of water (H2O) 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].

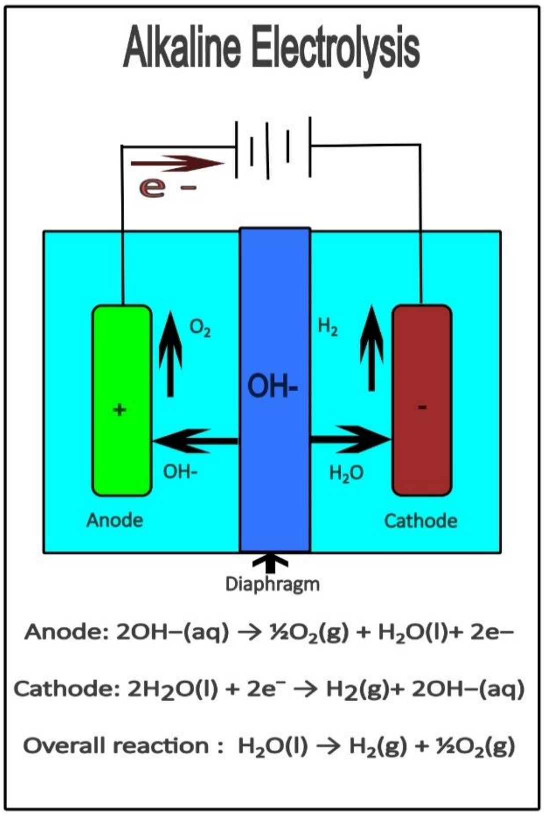

Fig. 1 Schematic illustration of alkaline water electrolysis

3.2 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_2—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 con- ducting 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_2—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]

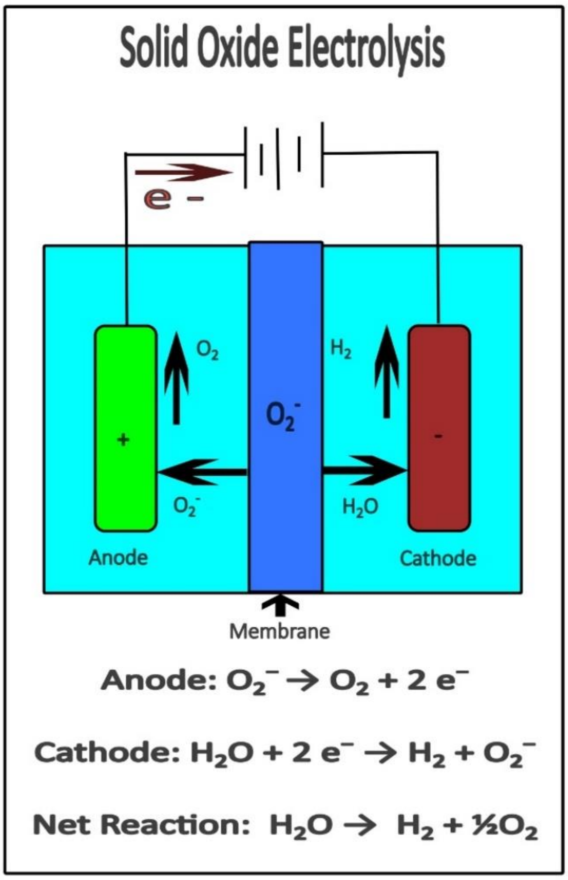

Fig.2 Schematic illustration of Solid Oxide electrolysis.

3.3 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_2, 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].

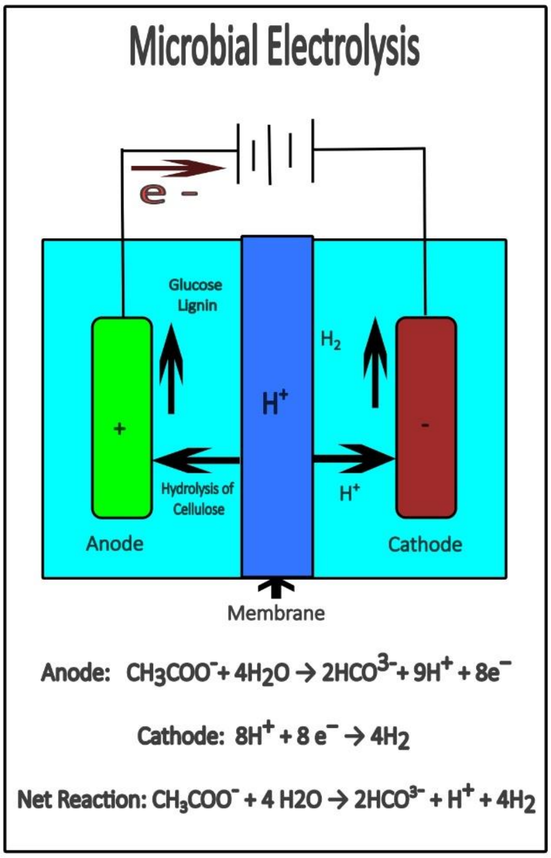

Fig 3.Schematic illustration of Microbial Electrolysis

3.4 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_2), protons (H+), and electrons (e—), 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.

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]

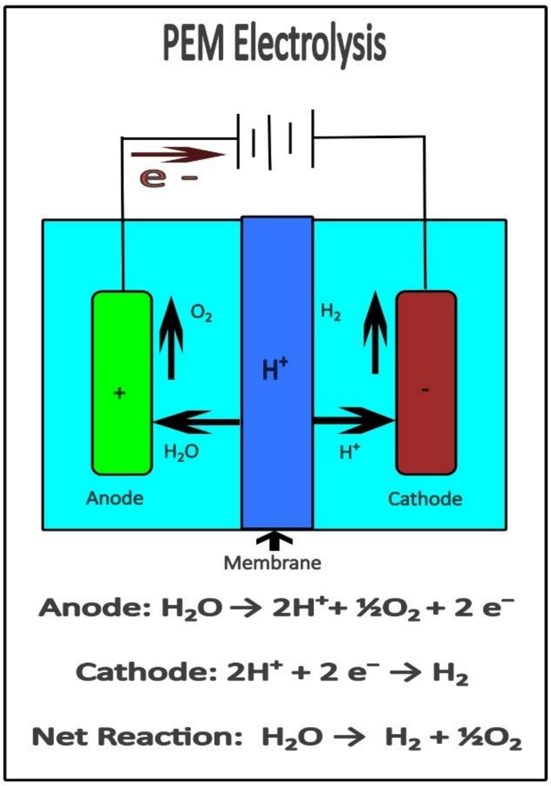

Fig.4. Schematic illustration of PEM water electrolysis.

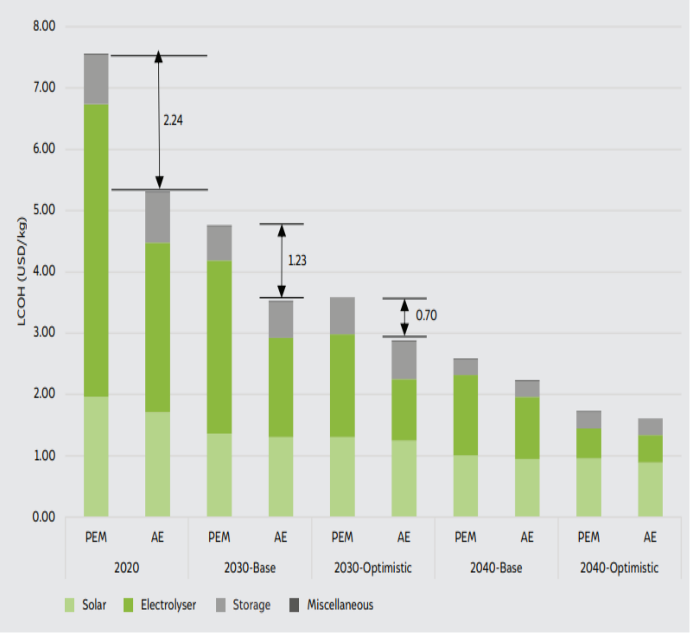

Fig : 5. Hydrogen obtained from the PEM electrolyzer is expensive than alkaline electrolyzer(AE), but the difference is expected to decrease in the future.[17]

As we can see above in figure no 5 that Green Hydrogen obtained from Pem electrolyzer is expensive than Alkaline electrolyzer but 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] and cost is expected to decrease in future.

4. 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_2 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_2 (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].

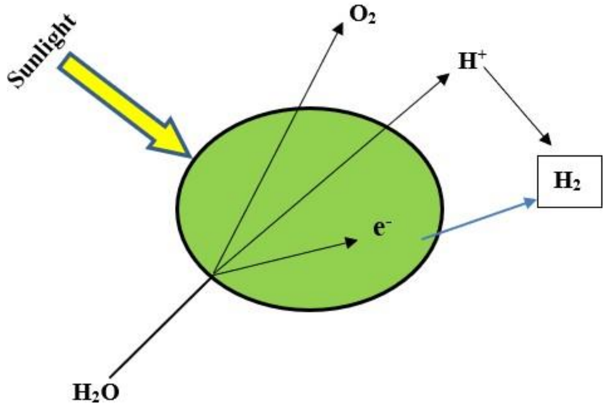

Fig 6. Impeded photosynthesis under sulfur deprivation causing net oxygen consumption by cell respiration in anaerobic indirect photolysis.

5.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. Thebenefits of TWSCs include

1. Separation between O_2-H_2 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]

5.1 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_3O_4/Fe, SnO_2/SnO, CeO_2/Ce_2O_3, Mn_2O_3/MnO, Co_3O_4/CoO, CdO/Cd, and GeO_2/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].

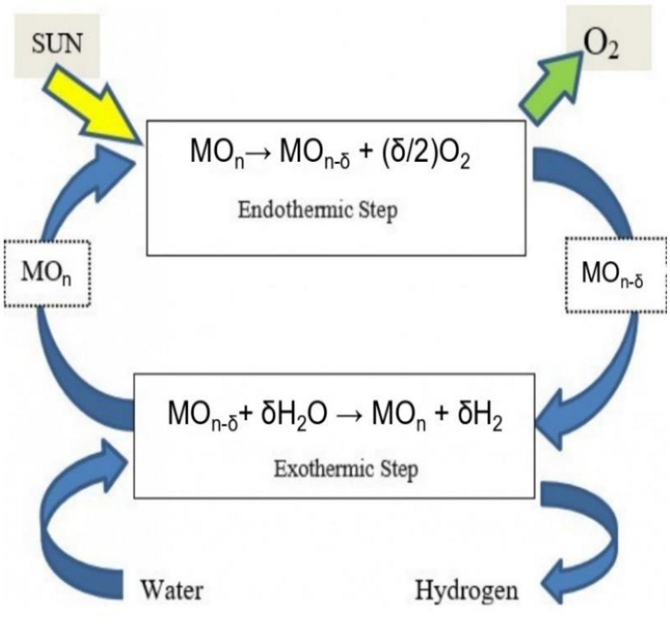

Figure 7: Two step thermochemical cycle

5.2 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 is given in figure 8 [45], The most well-known three-step TWSC is the sulfur-iodine (S-I) Thermochemical Water-Splitting Cycles from General Electric. Two endothermic phases and a middle exothermic step make up the process. The intermediate step is exothermic, the other two endothermic

$H_2SO_4 \rightarrow SO_2 + H_2O + ½O_2$; $T > 800^0C$ (1)
$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$; $T < 120^0C$ (2)
$2HI \rightarrow I2 + H2$; $T > 300^0C$ (3)

The first and last steps are endothermic, while the middle stage is exothermic. Recommended temperatures of 100°C for the exothermic process (2), 400–500°C for the endothermic reaction (3), and 850–900°C for the endothermic reaction (1) [45]. Although even lower temperatures have been suggested, the cycle's efficiency improves as the reaction's temperature rises.

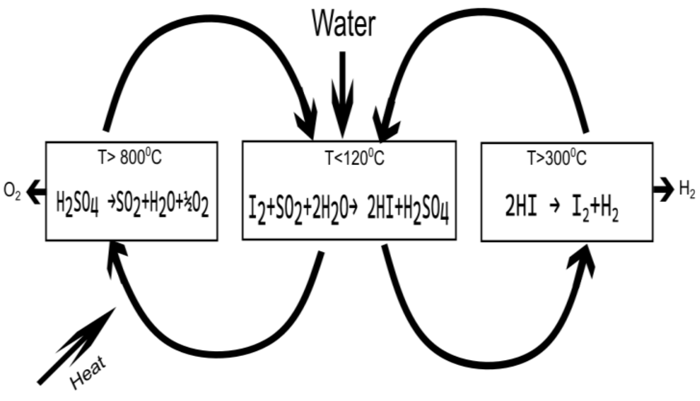

Fig. 8 Three step Thermochemical cycle

6.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 tomodulate and change the light absorption. Depending on thespecific 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-richelectrons 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.8 Then, at the catalytic sites, electrocatalysts split water while concurrently producing gaseous H_2 and O_2. 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):

$2H_2O + 2e^- \rightarrow 2OH^- + H_2$

Half-reaction at anode (oxidation):

$2OH^- + 2h^+ \rightarrow \underline{1/2}\ O_2 + H_2O$

Net reaction: $H_2O \rightarrow H_2 + 1/2\ O_2$

or

Half-reaction at cathode (reduction):

$2H^+ + 2e^- \rightarrow H_2$

Half-reaction at anode (oxidation):

$H_2O + 2h^+ \rightarrow 1/2\ O_2 + 2H^+$

Net reaction: $H_2O \rightarrow H_2 + 1/2\ O_2$

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]

7. GREEN HYDROGEN FORM SEA WATER

Hydrogen production from saline water, also known as seawater electrolysis, is an innovative method that harnesses the potential of seawater as a sustainable source of hydrogen fuel. This approach involves the process of electrolysis, which utilizes electricity to split water into its constituent elements, hydrogen and oxygen.

There are two ways in which seawater can be used to replace fresh water for the production of GH2 – desalination of seawater to produce fresh water to remove the salt before the water flows to conventional electrolyzers and the use of seawater directly for the electrolysis process.

In seawater electrolysis, the salty water is subjected to electrolysis within an electrolyzer unit. This unit consists of electrodes immersed in the seawater and separated by an electrolyte. When an electric current is passed through the electrolyte, it triggers the electrochemical reactions that separate the water molecules into hydrogen and oxygen gases. The only problem is with innovating the suitable electrolyzer for this process.

The group has created an electrolyzer that uses alkaline saltwater instead of clean or fresh water. To almost minimize corrosion, they employed a carbon-based support material for the electrodes instead of metals. Additionally, they created and improved catalysts based on transition metals that can facilitate processes involving both oxygen and hydrogen evolution. Even in the presence of contaminants and chemical deposition on one of the electrodes, the catalyst improves the generation of both hydrogen and oxygen. Additionally, the researchers have created a cellulose-based separator that is very cost-effective, serves the objective of letting hydroxide ions pass through while preventing oxygen and hydrogen that are produced from crossing-over, and allows hydroxide ions to flow through.

The two half-reactions in an alkaline water electrolyzer take place at the anode and cathode. Water splits into hydrogen and hydroxide ions at the cathode, where the hydrogen ions are then changed into hydrogen. The anode produces oxygen while the cathode produces hydroxide ions, which pass through the separator.

Hypochlorite is formed at the anode during the electrolysis of saltwater. Hypochlorite interferes with the oxygen evolution reaction, which lowers the amount of oxygen produced while also causing corrosion of the electrode support material. The hydrogen evolution reaction at the cathode is slowed down as a result of numerous contaminants adhering to the electrode surface.

Due to problems with chlorine corrosion and the sluggish development of hydrogen, it is not possible to electrolyze saltwater to produce hydrogen. To increase the efficiency and efficacy of seawater electrolysis for the production of hydrogen, several issues must be resolved.

A catalyst-coated support material is included on the electrodes. According to researchers they developed a carbon-based support material because conventional metal support materials easily corrode when used with seawater. The catalyst is coated on the support material, which is used in both the anode and the cathode. The catalyst enables improved and concurrent synthesis of oxygen and hydrogen at the anode.

Researchers claims that the transition bimetals in the catalyst are more selective for the oxygen evolution reaction than for the synthesis of hypochlorite. As a result, the issue of hypochlorite generation decreasing oxygen production is resolved. Similar to this, the catalyst encourages the hydrogen evolution reaction, which aids in the greater creation of hydrogen, even while the cathode continues to absorb pollutants.

An exceptional feature is found in the inventive separator that was engineered by the research team. When an alkaline electrolyte is employed, this separator operates to create a segregation between the cathode and anode. Instead of relying on the typically expensive zirconium oxide-based material, a separator based on cellulose was introduced by the team. Through this novel approach to separation, the facilitation of hydroxide ions' movement from the cathode to the anode is enabled, all the while effectively mitigating the undesired cross-migration of the hydrogen and oxygen that are generated.

Researchers draws attention to the fact that separator developed by the researchers demonstrates impressive resistance against deterioration resulting from exposure to seawater. Researchers also stated that Through the application of the assembled electrolyzer, they were able to successfully demonstrate a total voltage of 1.73 V for seawater splitting. This was achieved through the utilization of a current density of 10 mA/sq.cm (a reference density that corresponds to approximately 12% solar-to-fuel conversion efficiency under 1 sun illumination), all performed at a temperature of 26 degrees C."

The primary advantage of using saline water for hydrogen production lies in the abundance of seawater, making it a potentially limitless resource. Additionally, the process can be powered by renewable energy sources, such as solar or wind, leading to a greener and more sustainable hydrogen production pathway.[48]

8. TECHNOLOGICAL AND ECONOMICAL COMPARISON OF VARIOUS GREEN HYDROGEN PRODUCTION TECHNIQUES

In this section, we present a comprehensive technological and economical comparison of various green hydrogen production techniques. The viability of any sustainable energy solution lies not only in its technical feasibility but also in its economic competitiveness. As such, our analysis delves into both aspects, shedding light on the strengths and limitations of each method.

The comparison takes into account key technological factors such as energy consumption, efficiency, scalability, and the integration of renewable energy sources. We assess these factors to understand the technical feasibility of each production technique within the broader context of transitioning to a carbon-neutral energy landscape.

We have discussed the economical aspect of green hydrogen production by conducting a thorough cost comparison of various techniques. The economic viability of any renewable energy solution plays a pivotal role in determining its feasibility for large-scale adoption. Therefore, our analysis focuses solely on cost considerations, shedding light on the financial competitiveness of each method. To facilitate a clear understanding of the findings, we have organized the data into a comprehensive Table 1.

Table 1 encapsulates the technological and economical attributes of each green hydrogen production technique, allowing for easy comparison and identification of the most promising options."

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

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	-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	Large-scale hydrogen production -Utilization of waste heat	-Requires Heat Resistant materials - Thermal losses	20-45	4-6
Dark fermentation	Biomass	Anaerobes	- No sunlight needed	-Scaling Up for larger production	60-80	2-3

9. AN OVERVIEW OF ENERGY CONSUMPTION IN VARIOUS GREEN HYDROGEN PRODUCTION METHODS

Specific energy consumption is a crucial metric that quantifies the amount of energy required to produce a given unit of hydrogen. This analysis encompasses an in-depth evaluation of the specific energy consumption for each production method.
To facilitate a clear and efficient comparison, the specific energy consumption data are presented in a structured tabular format in Table no 2. Table 2 offers a succinct snapshot of the specific energy consumption characteristics of each green hydrogen production technique, allowing for direct comparisons and identification of the most energy-efficient options.

Table 2: Energy Consumption In Various Green Hydrogen Production Methods

Researcher	**Year**	**Type of Hydrogen**	**Production Technique**	**Specific Energy Consumption**	**Reference**
Agyekum EB et al.	2022	Green	Alkaline Electrolysis	288 kJ/mol	[49]
Bernard Chukwudi et al.	2021	Green	Photoelectrochemical	181 kJ/mol	[50]
Varanasi, Jhansi et al.	2019	Green	Biological Hydrogen	93.14kJ/mol	[51]
Nuria Sánchez-Bastardo et al.	2021	Gray	Methane Pyrolysis	37.7 kJ/mol	[52]
Nuria Sánchez-Bastardo et al.	2021	Gray	Steam Reforming	63.4 kJ/mol	[52]
Nuria Sánchez-Bastardo et al.	2021	Gray	SMR coupled with the water–gas shift reaction	41.kJ/ mol	[52]
Hasan Ozcan et al.	2023	Green	Thermochemical cycle	300 kJ/mol	[53]
Penconi, M. et al.	2015	Green	Photolysis	237 kJ/mol	[54]

10. 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_2 with a larger carbon footprint.

This paper has delved into the realm of one of the greatest sustainable energy solutions, i.e. green hydrogen production from various available method. It Through a thorough analysis of various production methods, it becomes evident that green hydrogen holds immense promise in advancing carbon neutrality objectives.

The paper's cost comparison reveals the economic attractiveness of green hydrogen, affirming its potential as a feasible solution for achieving carbon neutrality. As technologies mature and economies of scale are realized, production costs are expected to further decrease, enhancing the competitiveness of green hydrogen.

The exploration of green hydrogen production from saline water showcases its potential to utilize abundant resources, addressing water scarcity concerns while producing a clean energy carrier. The assessment of specific energy consumption underscores the efficiency of different production techniques, paving the way for informed decision-making in process selection.

This paper not only provides a comprehensive overview of green hydrogen production but also underscores its pivotal role in moving towards carbon neutrality

In essence, the research paper underscores the transformative potential of green hydrogen as a cornerstone in the journey towards carbon neutrality. By elucidating cost dynamics, saline water utilization, and specific energy consumption, the paper not only informs the present discourse but also shapes a sustainable and innovative energy future. The findings present a compelling case for its adoption and lay the groundwork for future endeavors in realizing a cleaner, more sustainable energy landscape and also underscores pivotal role of Green Hydrogen in moving towards carbon neutrality

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