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Review

Premier, Progress and Prospects in Renewable Hydrogen Generation: A Review

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Abstract: Renewable hydrogen production has an opportunity to reduce carbon emissions in the transportation and industrial sectors. This method generates hydrogen utilizing renewable energy sources, such as the sun, wind, and hydropower, lowering the number of greenhouse gases released into the environment. In recent years, considerable progress has been made in the production of sustainable hydrogen, particularly in the disciplines of electrolysis, biomass gasification, and photoelectrochemical water splitting. This review article figures out the capacity, efficiency, and cost-effectiveness of hydrogen production from renewable sources effectively comparing the conventionally used technologies with the latest techniques, which are getting better day by day with the implementation of the technological advancements. Governments, investors, and industry players are increasingly interested in manufacturing renewable hydrogen, and the global need for clean energy is expanding. It is projected that facilities for manufacturing renewable hydrogen, as well as infrastructure to support this development, would expand, hastening the transition to an environment-friendly and low-carbon economy.

Keywords: renewable hydrogen; renewable energy sources; greenhouse gases; environment friendly

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1. Introduction

Energy has emerged as a major issue for countries all over the world, regardless of their geographical location [1]. Air pollution, global warming, and climate changes are only some of the environmental problems caused by a huge increase in the use of fossil fuels since the Industrial Revolution. Solar, wind, hydro, and geothermal power are some of the examples of renewable energy that may be used to create electricity without the emission of greenhouse gases, which are a major contributor to climate change and, hence, global warming. As a means of delivering and storing renewable energy, hydrogen will play an important role in the future green energy system considering this need [2]. In recent years, renewable hydrogen production has gained popularity as a potential answer to climate change and energy insecurity [3].

The potential of hydrogen as a fuel source is being explored more and more. Hydrogen is one of the most essential resources which can be harnessed using a wide variety of sources, including water, biomass, and renewable power [4]. Furthermore, the only byproducts of hydrogen's combustion or interaction with oxygen in a fuel cell are heat and water, making it a clean fuel that produces no harmful greenhouse gases or pollutants. Hydrogen has high energetic density by weight but not by volume, which makes it complex for transporting from one place to another. Hydrogen is an adaptable and versatile fuel because it has a high energy density and can be stored and transported in a variety of forms, including compressed gas, liquid, and solid-state material [5,6]. The uses of hydrogen clearly dominate because of its adaptability and versatility [7]. It is used for vehicles, power plants, heating systems, and industrial processes. In addition, hydrogen has the potential to play a significant role in easing the transition to a low-carbon economy and a more sustainable future [8].

Hydrogen may be broken down further into subsets depending on how much carbon dioxide (CO_2) is released during its creation. Most hydrogen is "grey" hydrogen, which is created by steam methane reforming without carbon capture and, hence, releases a lot of carbon into the atmosphere [9]. Using carbon capture technology, blue hydrogen is created in the same way but with fewer carbon emissions [10]. Producing turquoise hydrogen from natural gas requires carbon capture and storage, leading to negligible emissions of greenhouse gases [11]. Carbon emissions are high because coal gasification is used to create black hydrogen. Renewable hydrogen can be generated using renewable power sources, whereas pink hydrogen is created via electrolysis with nuclear energy [12]. Choosing the right kind of hydrogen for energy production is important since various kinds of hydrogen have varied carbon emission rates and production costs.

The production of renewable hydrogen might play a crucial role in decarbonizing several industries, including transportation and energy [13]. However, several obstacles prevent its broad use at present. Electrolysis and biomass gasification are two examples of sustainable hydrogen generation methods; however, their high initial investment costs make them less competitive than conventional fossil fuels [14]. The constant generation of hydrogen also faces difficulties due to the intermittent nature of renewable energy sources such as solar and wind [7]. Hydrogen storage, transportation, and distribution infrastructure are still in the early stages of development [15].

Successful renewable hydrogen generation can also be conducted as a resource recovery in several wastewater treatment technologies such as microbial fuel cells (MFCs) involving graphene oxide-doped cost-effective and high-performance membranes [16–19]. This technology requires two chambers (anode and cathode) separated from each other using a cost-effective ion-selective membrane. A range of ion-selective membranes have been investigated and reported for their wide range of applications [16,20,21]. However, graphene is also suggested to be used as a superior hydrogen storage material [22]. Further, hydrogen is also advocated by several researchers employing a range of wastewater sources [23–25]. There are also concerns about the possible environmental effect of large-scale biomass production. The supply of renewable resources such as biomass may be limited [26]. Although these constraints provide obstacles, continuous research and development activities are aimed at resolving them, and renewable hydrogen is anticipated to play a more significant part in the shift to a low-carbon future.

This review paper went into detail regarding the various methods for obtaining renewable hydrogen. The most recent produced strategies have been contrasted with several routinely employed methodologies. A promising solution to the energy issues of the 21st century is renewable hydrogen generation. Hydrogen has drawn a lot of interest as a flexible and sustainable energy carrier in response to the rising demand for clean energy and the requirement to lower greenhouse gas emissions. The development of renewable hydrogen generation methods, such as water electrolysis, photoelectrochemical water splitting, biological processes, etc., has advanced significantly in recent years [27]. The creation of low-cost, high-performance catalysts for water electrolysis is one of the most important developments in this area. These catalysts, which are typically made of elements found in abundance on Earth, have the potential to cut the cost of hydrogen generation dramatically and raise the price of renewable hydrogen relative to fossil fuels. Hydrogen generation is also made possible through innovative technologies, such as the use of clean and sustainable energy sources, i.e., solar and wind power. The development of photoelectrochemical water splitting systems is another exciting field of research. These systems provide a very effective and ecologically benign technique for producing hydrogen by directly converting sunlight into hydrogen using semiconducting materials. Additionally, the use of biological processes, such as microbial electrolysis, can provide a sustainable and cost-effective method for producing hydrogen.

There are still a few issues that need to be resolved in the field of renewable hydrogen generation, despite the advancements made. The need for additional cost reduction, improving hydrogen production efficiency, and creating dependable and expandable systems for hydrogen storage and delivery are a few of these. However, the encouraging developments in renewable hydrogen production portend a bright future for the creation of sustainable energy and a crucial step towards a low-carbon economy. A sizable community of academics, students, and businesspeople will undoubtedly benefit from this article's explanation of the state of the art in hydrogen generation technology.

2. Progress in Renewable Hydrogen Production

Hydrogen's potential use as a fuel source has been the subject of research since 1766 when Cavendish first discovered hydrogen [28]. In the first experiment ever recorded in the history of science, which took place in 1783, Jacques Charles and Nicholas-Joseph Cugnot burnt hydrogen gas. They propelled a miniature vehicle using a balloon filled with hydrogen that they inflated themselves. In the 1800s, gas plants started extracting hydrogen from coal so that it could be used in industry. In the year 1807, the Swiss inventor Francois Isaac de Rivaz constructed the first fully functional model of a vehicle that was powered by hydrogen. The electrolysis of water, which is now the most popular way of creating hydrogen, was first discovered at the beginning of the 20th century [29]. After the end of World War II, the United States began using hydrogen as a fuel for rockets, while Germany began using hydrogen as a fuel for airships [30].

The worldwide energy crisis that occurred in the 1970s led to an increase in the amount of research and development that was conducted into hydrogen fuel. The California Institute of Technology produced one of the first commercial-scale hydrogen production facilities in the 1980s by electrolyzing water using solar energy. This was one of the earliest hydrogen manufacturing facilities in the world [31].

Research on solar-powered water electrolysis was initiated in the 1970s, making the 1970s the starting point for the history of renewable hydrogen generation. Research on harnessing renewable sources of energy, such as wind and solar power, to power electrolysis and manufacture hydrogen was a primary focus of scientific investigation in the 1980s and 1990s [32]. However, at that time, the high cost of renewable energy rendered the idea economically impossible to implement. Table 1 illustrates different hydrogen generation techniques with their efficiency, pros, and cons. The efficiency ranges given are approximations and may change based on several variables, including the design of the system, environmental conditions, and the purity of the hydrogen generated. Additionally, each methodology has its own benefits and drawbacks, and the viability of a specific approach depends on elements such as the cost, the environmental impact, and the intended use of the technique.

Since the year 2000, there have been considerable advancements in the methods used to produce hydrogen from renewable sources. The enhanced efficiency of electrolysis, which has been accomplished via advancements in materials science and system design, is one of the most significant breakthroughs that has taken place in recent times [33]. Additionally, the utilization of renewable energy sources such as wind and solar power has grown more ubiquitous and cost-effective, which has made the creation of renewable hydrogen increasingly competitive with techniques that are based on fossil fuels. The gasification of biomass as well as several other novel approaches to the production of hydrogen from renewable sources have also been explored. Particularly in Europe and Asia, there has been a substantial rise in the number of demonstration projects as well as installations of renewable hydrogen production plants on a scale appropriate for commercial use [34]. In recent years, governments and industry stakeholders have established ambitious objectives for the deployment of renewable hydrogen, which is viewed as a critical component of a sustainable and decarbonized energy system. These targets are aimed at increasing the amount of hydrogen produced from renewable sources. To accomplish these objectives and make the transition to a future with lower carbon emissions, research and development on renewable hydrogen technologies must be maintained and expanded.

Table 1. Different hydrogen generation techniques.

Hydrogen Generation Technique	Efficiency	Pros	Cons
Steam Methane Reforming (SMR)	60–70%	Well-established, high production capacity	Reliance on fossil fuels, CO_2 emissions
Water Electrolysis	60–80%	Can utilize renewable energy sources	High energy input, capital-intensive
Alkaline Electrolysis	60–70%	Mature technology, relatively low cost	Limited scalability, sensitivity to impurities
Proton Exchange Membrane (PEM) Electrolysis	70–80%	Fast response time, compact design	Expensive materials, sensitivity to impurities
Solid Oxide Electrolysis (SOEC)	70–80%	High efficiency, potential for waste heat utilization	High operating temperature, higher cost
High-Temperature PEM Electrolysis	70–80%	High efficiency, faster operation at elevated temperatures	Higher cost compared to alkaline electrolysis
Biological Water Splitting (Photosynthetic and Cyanobacteria)	Varies	Utilizes sunlight and organisms for hydrogen production	Low efficiency, research stage, scalability challenges
Thermochemical Water Splitting	Varies	Potential for high efficiency, can use solar or nuclear heat	Complex process, limited commercial viability

2.1. Electrolysis

There are several methods to produce hydrogen from renewable sources. The most common and effective method of green hydrogen production is electrolysis, which splits water into hydrogen and oxygen to produce sustainable hydrogen [4]. Two electrodes, known as the anode and the cathode, are submerged in an electrolyte solution inside an electrolysis cell. The anode is responsible for attracting negatively charged hydroxide ions (OH^-), whereas the cathode is responsible for attracting positively charged hydrogen ions (H^+) from the electrolyte. At the cathode and the anode, respectively, the molecule of water disassembles into its component ions: hydrogen and oxygen. Hydrogen may be produced by the process of electrolysis using renewable energy sources such as the sun, wind, or water power [35]. The method may generate hydrogen without the use of fossil fuels or any emissions at all, making it an effective tool for reducing carbon emissions in the transportation sector, the industrial sector, and the power generation sector. Since electrolysis can produce hydrogen on demand, it is well suited for applications that need intermittent or variable hydrogen generation, such as renewable energy storage systems and vehicles that run on fuel cells [36].

Electrolysis may also be performed at a variety of scales, ranging from small, decentralized units that generate hydrogen for homes or companies to large industrial units that generate hydrogen for heavy-duty transportation or industrial operations. These devices can produce hydrogen for both residential and commercial use. Electrolysis suffers from a variety of limitations, each of which must be addressed before it can be made more productive and economical. One of the most significant challenges is to bring down the price of the energy needed to run the electrolysis process, which drives up the cost of renewable hydrogen [35]. Different electrolyzer types produce hydrogen with varying degrees of efficiency. For instance, one of the oldest and most established technologies is the alkaline electrolyzer, which operates with an alkaline electrolyte (usually potassium hydroxide). Based on the lower heating value (LHV) of hydrogen, they have an efficiency range of 60–70%. Proton exchange membrane (PEM) electrolyzers, which use solid polymer membrane as the electrolyte, are renowned for their quick response times and compactness. They can work at a variety of temperatures and have an efficiency of 70–80% (LHV); solid oxide electrolyzers (SOEC) that run at high temperatures use a solid oxide ceramic electrolyte that is commonly constructed of zirconia. They provide efficiencies between 70 and 80% (LHV) higher than alkaline and PEM electrolyzers, and they can also use waste heat to increase overall efficiency. PEM for high-temperature hybrid electrolyzers use both SOEC and PEM technology. They utilize an electrolyte with phosphoric acid as its basis to work at high temperatures, usually above 100 °C. They attain efficiency values between 70 and 80% (LHV) that are comparable to SOECs. It is crucial to remember that these efficiency values are only estimates and may change based on the design of the individual system, the environment it operates in, and the quality of the hydrogen produced. The effectiveness of electrolyzers is being improved through ongoing research and development to produce hydrogen more sustainably. Further challenges include enhancing the performance of electrolysis cells, developing electrode materials that are more long-lasting and competitively priced and lessening the harmful effects of electrolyte solutions on the surrounding environment [37]. There are still problems that need to be solved but electrolysis has the potential to produce a reliable and scalable source of renewable hydrogen that can aid in the transition to an economy with lower carbon emissions.

2.2. Thermochemical Process

The thermochemical process has gained popularity for hydrogen production owing to its cost-effectiveness and high efficiency. Pyrolysis is a leading thermochemical technology for hydrogen production due to its direct hydrogen production pathway and compatibility with a diverse array of substrates. Typically, pyrolysis is performed within an inert environment, with temperatures ranging from 200 °C to 1200 °C and under controlled pressure conditions. This process yields three distinct products, namely char, bio-oil, and gases. Moreover, the yield of these products can be influenced by parameters such as fast and flash pyrolysis, which are efficient for gas production. For example, Ruiz and co-researchers investigated the effect of conventional [38] and flash pyrolysis on the textile industry waste biomass and the H_2 production was found to be increased from 0.28% to 11%. However, the investigations also show that a large percentage of the gases contain oxygen and organic gases, and these can be further reformed through secondary gas-phase reactions to produce H_2 [39].

In addition, the constitution of the biomass has a significant impact on the gas composition, and the utilization of co-pyrolyzed mixed biomass can effectively augment the production of H_2 during the process [40]. However, the effective hydrogen index, moisture content, and composite analysis of the co-feedstocks need to be evaluated for synergistic enhancement during the process. Furthermore, it has been observed that the utilization of a catalyst during the process can lead to the augmentation of H_2. The implementation of a catalyst has been demonstrated to be an effective means of elevating the production of gas and oil by means of decarboxylation, aromatization, dehydration, and hydrogenation. For example, mixing biomass (80%) with plastic (20%) significantly increases hydrogen production from 15% to 36.1%, and the addition of the Ni/Al_2O_3 catalyst enhances the H_2 production up to 56.1% [41]. Hence, future investigation needs to implement catalyst-based pyrolysis for industrial-scale hydrogen production plants.

2.3. Photobiological

Solar energy can be exploited for the green synthesis of hydrogen through the biological pathway by the oxygenic and anoxygenic photosynthetic microbes. As illustrated in Figure 1, oxygenic microbes such as algae and cyanobacteria are photoautotrophic organisms that can grow to utilize CO_2 and sunlight. The hydrogen is produced during the metabolic activity of the algae and cyanobacteria via hydrogenase (Fe–Fe hydrogenase and Ni–Fe hydrogenase). For instance, *Chlorella vulgaris* (microalgae)-based photobiological reactor was operated for H_2 production and an average H_2 production rate of 4.98 mL/L/h during the day time and 2.08 mL/L/h during the night time was observed with the hydrogenase enzyme activity of 830 nmoles H_2/µg of biomass/h [42].

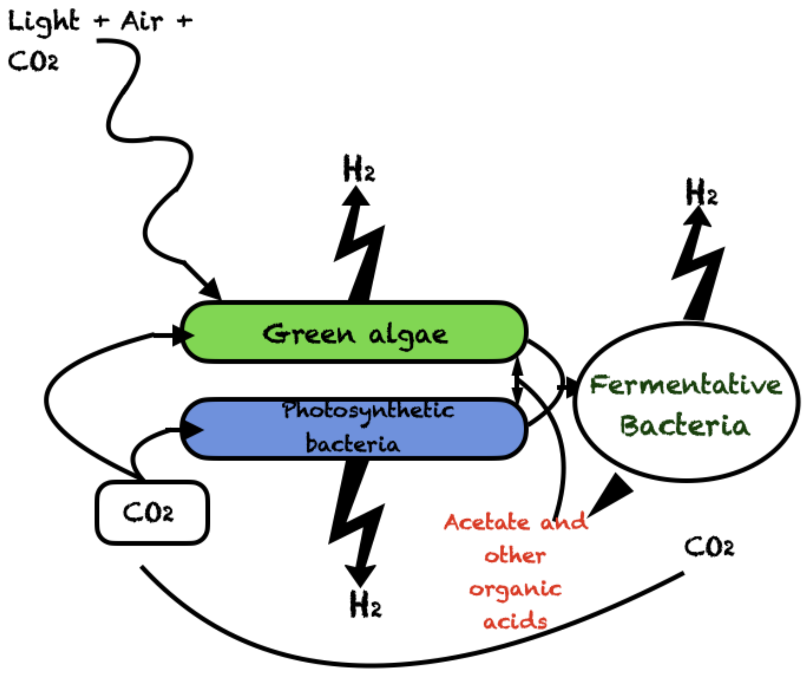

Figure 1. Hydrogen generation using photobiological process.

On the other hand, anoxygenic photosynthetic bacteria, such as purple nonsulfur bacteria, utilize the substrate as an electron donor and oxidize it to produce H_2 and CO_2. Nitrogenase plays a critical role in the anoxygenic bacteria to produce H_2 and has been found to have lower activity compared to hydrogenase. However, the critical challenge of the photobiological method is that the availability of oxygen inhibits the hydrogenase and nitrogenase from hydrogen production. Hence, the investigation needs to be focused on decreasing the oxygen sensitivity of these microorganisms.

2.4. Biomass Gasification

Gasification of biomass to generate renewable hydrogen is an intriguing and possibly productive technique for generating sustainable energy. Through a thermochemical process known as biomass gasification, syngas may be created from organic materials such as wood, agricultural waste, and other forms of biomass [14]. Syngas can generate power, liquid fuels, and hydrogen. Syngas is a sustainable energy source that can be turned into renewable hydrogen. Gasification is the process of heating biomass at high temperatures in the absence of oxygen to convert it into carbon monoxide, hydrogen, and other gases [43]. Syngas may be separated and cleaned to remove impurities. The conversion of biomass to gas for the generation of renewable hydrogen contributes to reducing greenhouse gas emissions. Because plants absorb carbon dioxide while growing and then expel it when burnt, biomass has no net carbon effect. In contrast to steam methane reforming, biomass gasification produces hydrogen with no emissions of fossil fuels [44]. Using biomass gasification, it may be feasible to produce sustainable hydrogen from locally accessible feedstocks.

In comparison to fossil fuels, biomass may be obtained locally, resulting in economic savings and lower carbon emissions. The utilization of biomass gasification, which may handle agricultural waste, forestry leftovers, and energy crops, can enhance the feedstock's flexibility [45]. There are various drawbacks to the biomass gasification process, which is utilized to generate sustainable hydrogen. A big issue is that the technique is more costly than more traditional ways of manufacturing hydrogen. Gasification's poor efficiency relative to other processes of energy conversion may restrict its potential to grow [46]. The research on biomass gasification for hydrogen production, on the other hand, is focused on enhancing efficiency and lowering costs. Finally, biomass gasification has the potential to generate renewable hydrogen, which may be utilized to power sustainable energy. It can minimize greenhouse gas emissions, employ local biomass feedstocks, and provide feedstock flexibility. Although there are obstacles involved with the process of biomass gasification for hydrogen production, research and development are increasing both efficiency and cost.

2.5. Anaerobic Digestor

The production of renewable hydrogen by anaerobic digestion might be a significant step towards a more sustainable energy future. Some microbes will consume organic materials in the absence of oxygen and create biogas as a byproduct [47]. Biogas reformation is a method that converts methane-rich biogas into hydrogen. This technique may extract hydrogen from methane in biogas using heat and steam. Anaerobic digestion employing readily available material may sustainably create hydrogen [48,49].

Leftover food and food scraps, as well as agricultural waste and sewage sludge, may be used for anaerobic digestion. Waste decomposition in landfills emits methane and other greenhouse gases that contribute to global warming. Anaerobic digestion of organic waste may result in the creation of renewable hydrogen and a decrease in greenhouse gas emissions. Renewable hydrogen generated by anaerobic digestion has several uses. Fuel cell cars are powered by hydrogen and release only water vapor as a byproduct. This technology has the potential to minimize greenhouse gas emissions produced by transportation, which account for a large fraction of overall emissions. A variety of barriers must be overcome before anaerobic digestion hydrogen may be sold on the market.

The production of hydrogen on a larger scale is a difficult task [50]. Biogas reformation is still in its early phases, while anaerobic digestion has attained its full potential [51]. The cost of creating renewable hydrogen by anaerobic digestion is higher than that of traditional hydrogen production [32]. Finally, anaerobic digestion has the potential to generate renewable hydrogen. This might minimize greenhouse gas emissions, supply renewable hydrogen, and shut the loop on organic waste management. Further research and development will be required to overcome the technical and economic barriers to the commercialization of this technology. A two-stage procedure called dark fermentation followed by microbial electrolysis can be utilized to produce hydrogen from anaerobic digestion. Organic biomass, such as food waste, agricultural waste, or sewage sludge, is used in the initial/first stage of dark fermentation and is subjected to anaerobic digestion in the absence of light. During this process, the organic material decomposes, creating a mixture of gases that includes hydrogen (H_2), carbon dioxide (CO_2), and traces of other gases. The primary process is the creation of intermediate molecules known as volatile fatty acids (VFAs).

2.6. Microbial Electrolysis

Microbial electrolysis, also known as microbial electrolysis cells (MECs) or microbial electrolysis fermentation cells (MEFCs), is also used in the second stage, which is referred to as the microbial electrolysis process. By oxidizing organic material at the anode, electrons are liberated, forming an electrical circuit. Hydrogen generation rates, hydrogen volume, energy recovery, columbic efficiency, inoculum, electrode materials, MEC architecture, catalysts, etc., are some of the performance metrics used to assess MECs. Parameters are further divided into biological and nonbiological factors. While nonbiological factors include reactor design, electrode materials, membrane, pH, temperature, applied voltage, anolyte and catholyte concentration, etc., biological factors include substrates and their concentration, microorganism species whether a pure culture or mixed culture, biological electrodes, the presence of methanogens, etc. Pure cultures of microorganisms as well as enriched mixed consortia of microorganisms with various hydrolytic enzymes are both used in the synthesis of biohydrogen from waste organic material [40].

The electro-hydrogenesis process, in which bacteria release electrons to mix with protons to produce hydrogen gas, provides the foundation for MECs. Electroactive microorganisms use organic materials to create CO_2, H^+, and electrons in the MEC when a voltage is applied. Through a series of redox processes, electrochemically active bacteria (EAB) catalyze and oxidize the organic substrate. The electrochemically active biofilm (EABF), which serves as the MEC's bioanode, is essential for its operation. Most of the bacterial species that make up an EABF are *Geobacter* and *Shewanella*. Additionally, only a few studies have demonstrated the use of algae species as a feed or bioelectrode in bioelectrochemical systems. Although many electrode materials have been investigated, carbonaceous electrode materials perform better [40]. However, it is crucial to consider the overall effectiveness of the process, as well as the availability of feedstock and the circumstances needed for optimum performance.

2.7. Solar Water Splitting

Renewable hydrogen might be produced through a process known as solar water splitting, which breaks down water molecules into hydrogen and oxygen. The use of commonly available, nonhazardous components, along with exceptional energy output and versatility makes solar water splitting an appealing technique [52,53]. Solar water splitting is powered by the generation of electrons and holes, which occur when semiconductor materials absorb sunlight. To produce hydrogen and oxygen gas, electrons and holes must first be separated and directed toward the water molecule [54,55]. A semiconducting material is required to divide water using solar energy. This substance must effectively absorb sunlight, generate, and separate charges, and maintain the process. Solar-powered water-splitting materials have become increasingly efficient and dependable during the past decade. Metal oxides, metal chalcogenides, and perovskites' characteristics have been enhanced by changing the chemistry of their surfaces, as well as their forms and compositions [56–58]. Because of breakthroughs in nanotechnology and materials science, materials with enhanced light absorption and charge separation have been developed. These materials have a high level of structure and control.

Despite these advances, solar water splitting for large-scale hydrogen production still faces several obstacles. The technique must be more efficient and the components must be able to preserve their shape and integrity under extreme circumstances [59]. Before the technique can be competitive, the costs of both the materials and the system must be reduced. Finally, solar water splitting has the potential to generate renewable hydrogen and contribute to the transition to a carbon-neutral, sustainable energy system [43]. Even though materials for solar water splitting that are both effective and stable have been developed, further research is required to realize this technology's full potential.

2.8. Wind-to-Hydrogen

The wind-to-hydrogen technology uses the electrolysis process, which is powered by wind energy, to split water molecules into hydrogen and oxygen [60]. This way of creating hydrogen is one of the most ecologically beneficial and effective methods since it creates electricity using wind power, which is a renewable and clean energy source [61]. Electrodes in an electrolyzer oversee separation of individual water molecules. The process of capturing hydrogen gas entails compressing it before storing it for use as fuel or in manufacturing. This technology might replace the use of fossil fuels, which have a limited supply and contribute to climate change and greenhouse gas emissions [62]. The technology that transforms wind energy into hydrogen has the potential to lessen our reliance on oil while also creating jobs in the green energy industry.

2.9. Dark Fermentation

The oxidation of biomass and wastewater through dark fermentation (DF) has been widely recognized as an environmentally sustainable method for biohydrogen production. The process of anaerobic digestion (apart from methanogenesis) is involved in the conversion of biomass into VFAs and other metabolites, such as CO_2 and H_2, through various microorganisms and pathways. During DF, enzymes such as hydrogenases play a regulatory role in the evolution of H_2 by facilitating the reduction of H^+ to H_2. However, the biohydrogen yield (maximum 4 mol H_2 per mol of glucose) through the DF process has been reported to be lower than the thermotical value (12 mol H_2 per mole of glucose) of H_2 conversion, and the metabolic pathway of the dark fermentation process has been identified as the cause of the reduced hydrogen production. In addition to its theoretical significance, the production of hydrogen is also subject to a reduction in output because of various process parameters [63]. These parameters include organic loading rates, pH levels, substrate type, microbial competition, byproducts, temperature, and the availability of macronutrients and micronutrients.

3. Hydrogen Separation Methods

Separation methods are necessary to produce renewable hydrogen. These methods are used to separate hydrogen gas from other gases and contaminants. These contaminants tend to degrade hydrogen purity, as well as the efficiency and safety of their production [64]. Table 2 illustrates different types of hydrogen separation methods, along with their efficiency, cost, and the environmental impact. Separation techniques may also be used to collect and recycle catalysts and other components left over from the manufacturing process, which increases the overall sustainability and productivity of the operation [65].

Table 2. Comparative illustration of the different hydrogen separation methods.

Process	Description	Efficiency	Cost	Environmental Impact
Steam Methane Reforming (SMR)	Reaction between natural gas and steam	High	Low	Moderate CO_2 emissions
Partial Oxidation (POX)	Combustion of hydrocarbons with limited air	High	Moderate	Moderate CO_2 emissions
Autothermal Reforming (ATR)	Combination of SMR and POX	High	Moderate	Moderate CO_2 emissions
Water Electrolysis	Electrochemical splitting of water	Variable	High	None (with renewable energy)
Alkaline Electrolysis	Electrolysis using an alkaline solution	Moderate	Moderate	None (with renewable energy)
Proton Exchange Membrane (PEM)	Electrolysis using a proton exchange membrane	Moderate	High	None (with renewable energy)
Solid Oxide Electrolysis (SOEC)	Electrolysis using a solid oxide electrolyte	Moderate	High	None (with renewable energy)
Biomass Gasification	Conversion of biomass into hydrogen gas	Moderate	Moderate	Carbon-neutral (with sustainable biomass)
Photobiological Processes	Utilization of photosynthetic organisms	Low	Moderate	None (with renewable energy)
Photocatalytic Water Splitting	Use of catalysts and solar energy	Low	High	None (with renewable energy)

As a result, dependable and efficient separation methods are critical for maintaining the quality and long-term profitability of renewable hydrogen production.

3.1. Membrane-Based Separation Process

Membrane separation technologies are necessary for the generation of renewable hydrogen. Membranes are used in these technical breakthroughs to selectively enable molecules of hydrogen to flow through while inhibiting molecules of carbon dioxide and methane [66]. It is feasible to effectively extract hydrogen from the incoming gas combination using biomass or electrolysis. Figure 2 is an illustration of extracting hydrogen using a membrane. As can be seen in Figure 2, a simple membrane-based hydrogen generation assembly consists of two chambers, anode, and cathode, separated by a membrane. A hydrogen-containing feed stream is facilitated through the anodic chamber. A power source connects the anode and the cathode, followed by the specialized proton exchange membrane placed at the intersection of the two compartments for enhancing the flow of protons from anode to cathode through them. The generated hydrogen is collected from the cathodic compartment and is used for a wide range of applications.

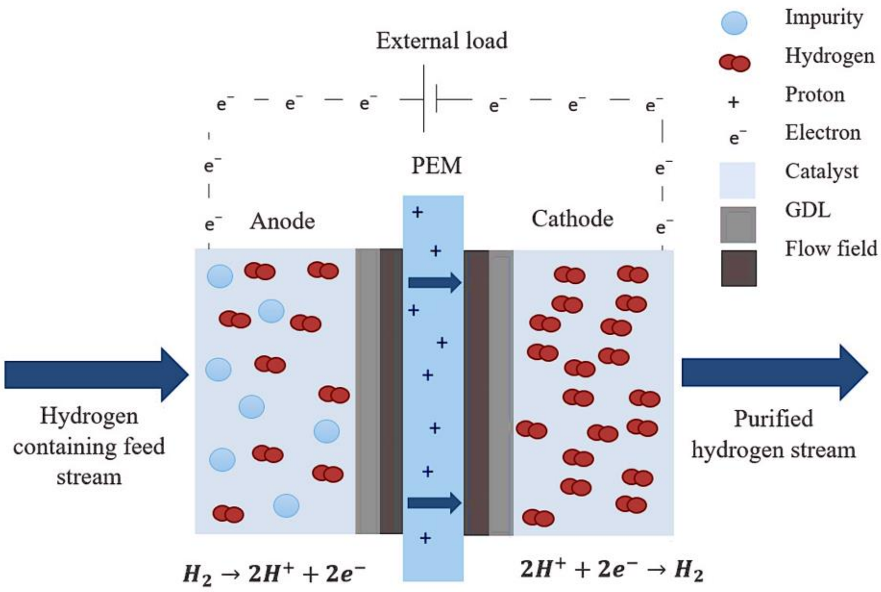

Figure 2. Effective membrane-based hydrogen generation (adapted from [66]).

Membrane-based separation methods have great potential for the sustainable production of hydrogen due to their low energy consumption, scalability, and environmental friendliness. Polymer membranes are customizable and simple to manufacture. Membranes with the appropriate pore diameters may be manufactured and employed in the process to remove contaminants that are damaging to fuel cells and/or selectively separate gases and liquids from a mixture [67]. Polymer membranes may be useful in the creation of hydrogen, which requires a high degree of purity. Polymer membranes used in hydrogen generation have high permeability and selectivity.

Polymer membranes are excellent for separating hydrogen from other gases or liquids due to their capacity to selectively permeate specific molecules while inhibiting the passage of others. The polymer's composition influences its selectivity as well as its permeability, allowing for fine separation control [68]. Separation technologies based on polymer membranes are much more energy-efficient than distillation and adsorption. Energy efficiency is required for the generation of renewable hydrogen to be cost-competitive and sustainable.

Ceramic and metallic inorganic membranes have various benefits over other types of membranes. They can operate despite being exposed to extreme temperatures and pressures, as well as being chemically stable, thermally resistant, and physically durable. They are suitable for harsh environments, as well as operations involving the creation of hydrogen at high temperatures [69]. The narrow pore size dispersion of inorganic membranes makes it possible to accurately separate gases based on the size and form of their molecules.

For the generation of hydrogen from renewable sources, inorganic membrane separation is required. It is conducted in an efficient and precise manner to extract hydrogen from other gases. Inorganic membranes are highly suited for use in hydrogen generation because they are robust to both high temperatures and severe environments [70]. The use of membrane-based separation methods in conjunction with other separation technologies has the potential to increase the efficiency of hydrogen production and the use of renewable hydrogen as a carrier for sustainable energy.

3.2. Non-Membrane-Based Separation Process

Non-membrane separation technique is required for renewable hydrogen generation. It is required for the purification of hydrogen gas obtained from renewable sources such as water electrolysis and biomass gasification. These technologies are not only more energy efficient, but also less expensive than membrane-based systems, which need costly maintenance and replacement. The ability to produce ultra-pure hydrogen without the need for membranes makes these technologies ideal for usage in industrial applications [71]. Separation technologies that do not depend on membranes are critical to produce renewable and sustainable hydrogen.

Figure 3 depicts the flow diagram of the conventional pressure swing adsorption (PSA) system. In order to recover H_2 from coal gas with N_2 as a significant contaminant, Ahn et al. [72] used two-bed and four-bed PSAs. With a H_2 purity of 96–99.5% and a recovery rate of 71–85%, the four-bed PSA process outperformed the two-bed PSA process in terms of efficiency. PSA is a common technique for isolating hydrogen from gas mixtures. This technique might potentially be used to harvest hydrogen from renewable sources. Temperature swing adsorption (TSA) and vacuum swing adsorption (VSA) are used in the process of separating renewable hydrogen via the use of PSA. TSA changes the temperature that is maintained throughout the adsorption and desorption processes, which affects the adsorbent's capacity [73]. VSA may vary the adsorbent's capacity by modifying the pressure during the adsorption and desorption operations. The technique employed is determined by the application as well as the available sustainable hydrogen feedstock. The objective is to manufacture high-purity hydrogen at a low cost and with little energy use.

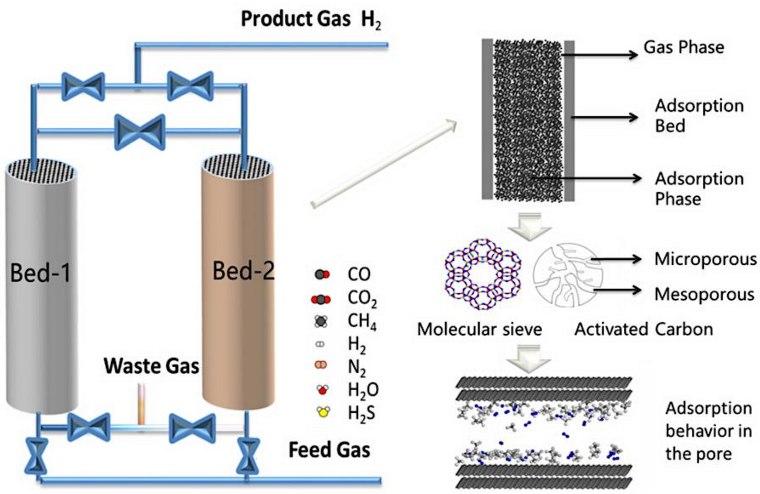

Figure 3. Hydrogen generation for industrial applications using pressure swing adsorption process (adapted from the [71]).

Cryogenic distillation is an efficient method for separating renewable hydrogen from feedstocks. A variety of cryogenic distillation processes are used to achieve this purpose. The most prevalent approach is cryogenic air separation, which entails chilling air to very low temperatures before separating it into its constituent elements, one of which is hydrogen. Cryogenic distillation can extract hydrogen from natural gas by freezing and separating it. During the cryogenic distillation of biofuels such as ethanol, hydrogen is separated from gasified biomass [74]. These cryogenic distillation technologies efficiently and reliably isolate renewable hydrogen from a broad range of feedstocks.

Chemical adsorption is often used to separate renewable hydrogen due to its great efficiency and selectivity. Chemical adsorption involves the employment of both physisorption and chemisorption [75]. During the physisorption process, hydrogen molecules and the adsorbent's surface form extremely weak van der Waals connections. The separation of low-pressure hydrogen gas is a frequent result of applying this procedure. Chemisorption produces a stable adsorption complex by interacting hydrogen molecules with the adsorbent's surface [76]. High-pressure hydrogen gas separation is usual. Adsorption procedures need purity of hydrogen, pressure, and adsorbent material.

Carbon nanotubes, with their massive surface area and unique physicochemical features, might be utilized to extract renewable hydrogen [77,78]. Both physisorption and chemisorption contribute to the process of chemical adsorption on carbon nanotubes.

Physisorption is a weak and reversible connection, while chemisorption results in the creation of strong chemical connections between gas molecules and the atoms that comprise the nanotube surface. Gas molecules and nanotubes both regulate the adsorption process. Chemisorption is more successful at catching lager molecules than physisorption, which traps very small gas molecules. Carbon nanotube chemical adsorption has tremendous promise for application in ecologically friendly hydrogen separation.

4. Factors Affecting the Production of Renewable Hydrogen

A range of variables impact the efficacy, cost, and scalability of renewable hydrogen generation [4,79]. The production of renewable hydrogen is both difficult and expensive due to the intermittent and unpredictable nature of various energy sources. The efficiency and durability of electrolysis have an impact on sustainable hydrogen generation. The operating conditions, electrode materials, and system design may all have an impact on the cost-effectiveness and efficiency of electrolysis systems [80]. Durability influences both the lifetime and the expenses of generating hydrogen.

The cost of catalysts and the availability of water influence the creation of renewable hydrogen. The availability and quality of water in a location influence the performance and lifespan of an electrolysis system [81]. Because they speed up the electrochemical processes necessary to make hydrogen, catalysts are critical to the economic feasibility and scalability of hydrogen production. Infrastructure and legislation have an impact on renewable hydrogen generation. Infrastructure for transportation and storage influences both the distribution and use of renewable hydrogen [82]. Regulations that encourage the production and use of renewable hydrogen may also have an impact on market development. Finally, competition from other sources of alternative energy may influence renewable hydrogen generation and usage. The cost and availability of solar and wind power may have an impact on the demand for renewable hydrogen and the market's competitiveness [34]. Batteries and fuel cells may influence the quantity of renewable hydrogen absorbed in certain applications and sectors.

5. Environmental Impact and Global Scenario of Hydrogen Generation Using Biomass

Hydrogen generation using biomass is an emerging technology that has the potential to reduce carbon emissions and contribute to sustainable development. This review evaluates the environmental impact and global scenario of renewable hydrogen generation. Biomass is a renewable resource that can be used to produce hydrogen through various processes, such as gasification, pyrolysis, and fermentation. The environmental impact of these processes depends on the type of biomass used, the energy efficiency of the process, and the method of hydrogen production. One of the main advantages of hydrogen generation using biomass is its potential to reduce carbon emissions. Biomass is a carbon-neutral resource, meaning that the carbon released during combustion is offset by the carbon absorbed during growth. However, the efficiency of the process and the method of hydrogen production can have a significant impact on the carbon footprint of the technology. For example, gasification of biomass can produce a significant amount of carbon dioxide and other greenhouse gases if not properly controlled. Similarly, the use of fossil fuels for hydrogen production can negate the carbon benefits of using biomass as a feedstock. Another important consideration is the sustainability of biomass resources.

The demand for biomass as a feedstock for hydrogen generation could lead to deforestation, land-use change, and competition with food crops. Therefore, it is important to ensure that biomass is sourced sustainably and that the use of biomass does not lead to negative environmental and social impacts. In terms of the global scenario, hydrogen generation using biomass is still in the early stages of development. Currently, most of the hydrogen production is from fossil fuels, particularly natural gas. However, there is growing interest in developing renewable hydrogen sources, including biomass. Governments and industry are investing in research and development of biomass-to-hydrogen technologies, and pilot projects are underway in several countries.

6. Challenges and Prospects

Renewable hydrogen generation is a promising technology with the potential to provide a sustainable source of hydrogen. However, there are several challenges that must be addressed before this technology can be widely adopted. Here are some of the challenges of hydrogen generation using biomass:

Efficiency: One of the main challenges of hydrogen generation using biomass is achieving high conversion efficiency. The conversion efficiency of biomass to hydrogen is typically lower than that of fossil fuels, and the energy required for hydrogen purification can further reduce the overall efficiency of the process. Future research should focus on developing more efficient biomass-to-hydrogen conversion technologies to improve the economics of this technology.

Scale-up: Hydrogen generation using biomass is still in the early stages of development and the technology has not yet been scaled up to commercial levels. The scaling up of biomass-to-hydrogen technologies will require significant investments in infrastructure, including biomass collection, storage, and transportation systems.

Cost: The cost of producing hydrogen from biomass is currently higher than that of producing hydrogen from fossil fuels. The high cost of biomass feedstocks, low conversion efficiency, and the need for expensive purification systems all contribute to the high cost of producing hydrogen using biomass. Future research should focus on developing low-cost biomass feedstocks and improving conversion efficiency to reduce the cost of hydrogen production.

Sustainability: The sustainability of biomass resources is another challenge that must be addressed in hydrogen generation using biomass. The demand for biomass as a feedstock for hydrogen production could lead to deforestation, land-use change, and competition with food crops. Therefore, it is important to ensure that biomass is sourced sustainably and that the use of biomass does not lead to negative environmental and social impacts.

The prospects for hydrogen generation are bright, driven by the demand for sustainable and low-carbon energy solutions in the transition to a cleaner and more resilient energy system. However, hurdles still exist, including lowering costs, scaling up production, and creating infrastructure. The future of hydrogen generation looks bright for several reasons:

1. Decarbonization and climate change mitigation. Hydrogen is regarded as a clean and adaptable energy source since, when employed in fuel cells or combustion processes, it emits no greenhouse gases. It can significantly contribute to the decarbonization of several industries, including transportation, business, and power generation, assisting in the reduction in greenhouse gas emissions.
2. Integration of renewable energy. Hydrogen can be electrolyzed utilizing renewable energy sources as hydroelectric, solar, and wind energy. This makes it possible to produce hydrogen alongside the production of renewable energy, giving a way to store and use extra renewable energy when demand is low. The integration of renewable energy sources and grid flexibility may be significantly aided by hydrogen.
3. Hydrogen storage. Hydrogen can be stored and used as a long-term energy storage solution, addressing the erratic nature of renewable energy sources. Hydrogen can also be used to balance the grid. When there is an abundance of energy, it can be converted into hydrogen and stored to be used later when there is a shortage of energy. This can support grid balancing and guarantee a dependable and robust energy system.
4. Sector integration and decentralization. By facilitating the use of renewable energy in industries that have historically been challenging to decarbonize, such as heavy industry, shipping, and aviation, hydrogen can help with sector integration. By offering localized energy options, such as off-grid uses and fueling facilities for hydrogen-powered vehicles, it can help assist decentralization.
5. Technology improvements and cost savings. Research and development efforts are continually enhancing hydrogen generation technologies, raising their effectiveness, lowering their costs, and boosting system performance. Hydrogen generation is

becoming more effective, scalable, and financially viable due to improvements in electrolysis technologies, such as PEM and SOEC.

The European Union, along with other nations across the world, has been actively encouraging the use of hydrogen as a part of its attempts to make the switch to a low-carbon and sustainable energy system. The vision and goals for the development of hydrogen in Europe are laid out in the EU's hydrogen plan, which was released in July 2020 [35]. Developing hydrogen strategies that lay out the objectives, benchmarks, and legal frameworks for the development of hydrogen is one of the shared strategies and initiatives throughout EU member states, even though specific policies and regulations may vary. The development of infrastructure, market adoption of hydrogen technologies, and support for research and development are frequently included in these plans. Through numerous funding programs and initiatives, emphasis has also been placed explicitly on providing the required funding and financial support. These include funding sources such as grants, subsidies, and investment plans for initiatives involving the use of hydrogen.

Additionally, a thorough regulatory framework to promote the expansion of hydrogen technologies has been developed. This covers certification rules, security requirements, grid interconnection, and sustainability standards for hydrogen generation. It appears that attention has also been paid to member state collaboration and cross-border co-operation to encourage the growth of a pan-European hydrogen market. Building a cross-border infrastructure, coordinating rules, and exchanging best practices are all part of this. To enhance the proportion of renewable sources in their energy mix, EU nations have also developed renewable energy policies and targets. This inadvertently promotes the production of sustainable hydrogen using renewable energy sources to power procedures such as electrolysis.

7. Conclusions

The production of hydrogen from renewable sources is showing promising results. Renewable hydrogen technologies have improved because of global attempts to decarbonize energy production and promote environmentally friendly practices. Research and development, as well as lower renewable energy costs, have all contributed to the rise of the renewable hydrogen industry. The future of renewable hydrogen is bright because of regulations and incentives put in place by governments all around the world. As the price of renewable hydrogen falls in comparison to that of fossil fuels, it will be possible to meet the world's growing energy demand while both cutting greenhouse gas emissions and making headway against climate change. Hydrogen generation using biomass has the potential to contribute to sustainable development and reduce carbon emissions. However, the environmental impact and sustainability of the technology depend on the efficiency of the process, the method of hydrogen production, and the sustainability of biomass resources. Further research and development are needed to optimize the technology and ensure its sustainability before it can be widely adopted as a renewable hydrogen source. In conclusion, hydrogen generation using biomass is a promising technology with the potential to provide a sustainable source of hydrogen. However, there are several challenges that must be addressed before this technology can be widely adopted. Future research should focus on developing more efficient conversion technologies, reducing costs, and ensuring the sustainability of biomass resources.

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