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A Perspective on Hydrogen Production from Renewable Energy and Biomass

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Abstract

Transitioning to sustainable energy sources is crucial for combating climate change and reducing dependence on fossil fuels. The high consumption of fossil fuels leads to transportation issues and increased pollution, affecting the planet's quality of life. Hydrogen, a clean, abundant, lightweight, and easily stored fuel, has gained worldwide interest as a secondary energy carrier. It can generate electricity, cook food, fuel automobiles, hydrogen-powered industries, jet planes, and domestic energy needs. Further research is needed to solve production, storage, and transportation issues. This study presents a comprehensive research review on the production of energy from green hydrogen to biomass. The objective is to explore the potential of harnessing green hydrogen as a versatile energy carrier and integrating it with biomass technologies to create a sustainable and efficient energy production system. The review covers various aspects, including green hydrogen production methods, biomass energy generation, and the synergistic integration of these two technologies. The findings highlight the potential of green hydrogen and biomass as key components of a renewable energy system that can contribute to a greener and more sustainable future.

Keywords: biomass; climate change; carbon footprint; green hydrogen; renewable energy**.**

Introduction

In the face of increasing concerns about climate change and the need to transition to a sustainable energy future, the focus on renewable energy sources has never been more critical **(Wijayasekera et al., 2022**). Among the promising solutions gaining momentum are green hydrogen and biomass, both of which offer significant potential for clean and efficient energy production (**Energy. gov, 2020**). To start with, the necessary shift of today's global markets towards a sustainable future can only be achieved by integrated hydrogen production systems. In order to achieve the net-zero emissions goal by 2050, hydrogen would have to play a bigger role in the world's energy market, according to a report by the International Energy Agency (**IEA, 2019**). Green hydrogen, produced through water electrolysis using renewable electricity, is an environmentally friendly energy carrier that reduces carbon emissions, making it a viable alternative to fossil fuels, suitable for various sectors (**Cormos, 2023**). Meanwhile, Biomass, derived from plants, is a renewable energy resource that can be converted into heat, electricity, and biofuels through processes like combustion, gasification, and anaerobic digestion (**Christian, 2000**). The aim of this review is to prove that together, green hydrogen and biomass hold the potential to revolutionize the energy landscape by providing sustainable alternatives to conventional energy sources. This combination offers a unique advantage: the ability to store and transport energy efficiently. The production of green hydrogen can bridge the intermittent nature of renewable energy sources, enabling surplus electricity to be stored as hydrogen and later converted back into electricity or used as a fuel (**Moriarty & Honnery, 2007**). Biomass, on the other hand, provides a reliable and dispatchable source of renewable energy that can be used on-demand, complementing the intermittent characteristics of other renewables such as wind and solar power (**Delarue et al., 2015**). Technology for producing hydrogen is increasingly defined using a system based on distinct colors (**Newborough and Cooley, 2020**). The main colors that are being considered are the following as shown in Fig.1. (**Acciona, 2022**). Fossil fuels (mostly natural gas and coal) can produce grey (or brown/black) hydrogen, which releases carbon dioxide in the process; to prevent the majority of the process's GHG emissions (**Arcos and Santos, 2023**), blue hydrogen uses a mix of grey hydrogen and carbon capture and storage (CCS); turquoise hydrogen produced from the pyrolysis of fossil fuel with solid carbon as a byproduct; Yellow (or purple) hydrogen is created when electrolyzers using electricity from nuclear power plants are used to produce hydrogen; green hydrogen is created when electrolyzers using renewable electricity are used to produce hydrogen (and in some cases, through other bioenergy-based processes like solid biomass gasification or biomethane reforming) (**Hermesmann and Müller, 2022**).

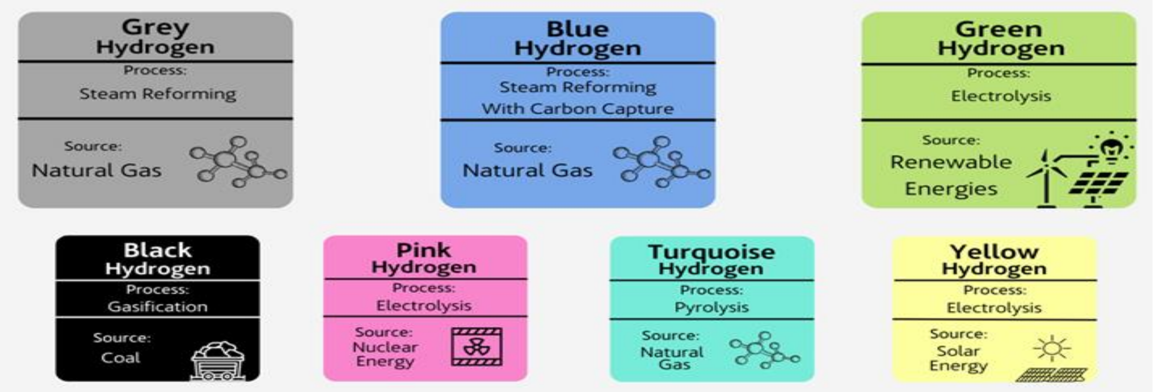


Fig.1. The colors of hydrogen and what do they mean?

This essay explores the potential of biomass energy conversion and green hydrogen as flexible energy carriers in a sustainable energy production system. It explores biomass energy production, eco-friendly hydrogen manufacturing methods, and their joint application, highlighting the potential for a more eco-friendly and sustainable future (**Noussan et al., 2021**).

In this research, we delve deeper into the production and applications of green hydrogen and biomass, highlighting their environmental benefits, technological advancements, and the challenges and opportunities associated with their widespread adoption. By harnessing the power of green hydrogen and biomass, we can pave the way for a cleaner, more sustainable energy future, reducing our reliance on fossil fuels and mitigating the impacts of climate change.

Green Hydrogen Production by Electrolysis

Green hydrogen production through electrolysis is a crucial aspect of sustainable energy strategies, utilizing electricity to convert water into hydrogen and oxygen. Electrolysis is a clean and sustainable method for producing hydrogen, utilizing renewable electricity sources like wind, solar, nuclear, and hydropower, thereby reducing carbon emissions (**Ishaq et al., 2022**).Green hydrogen production through electrolysis is a key component of integrating renewable energy sources into the energy system, storing excess energy for future hydrogen conversion **(Razmi et al., 2023**). Research focuses on cost reduction in green hydrogen production, with falling renewable power costs making it more economically viable. Further efforts are underway to scale up electrolyzers (Renewables Competitiveness Accelerates, Despite Cost Inflation, n.d.). Electrolysis is a crucial element in the hydrogen economy, enabling the decarbonization of sectors like transportation, industry, and power generation through hydrogen as a clean energy source (**Brandon & Kurban, 2017)**.

Renewable Energy Sources for Electrolysis

Renewable energy sources play a crucial role in making this production process environmentally friendly and carbon-neutral; Solar and wind energy are abundant and renewable sources that can power the electrolysis process. Solar panels and wind turbines generate electricity that can be directly used for electrolysis, ensuring green hydrogen production with zero carbon emissions. (**Cho, 2021**). The International Renewable Energy Agency (IRENA) promotes green hydrogen production through electrolysis, emphasizing the use of renewable-based electricity for water electrolysis, ensuring environmental sustainability in green hydrogen production **(Razmi et al., 2023**). Green hydrogen, produced from renewable energy sources, is a carbon-neutral solution for transportation, industry, and power generation, offering a scalable and sustainable solution for energy storage and distribution, contributing to a transition to clean energy (**Mneimneh et al., 2023**).

Technological Advances in Electrolysis

Technological advancements in electrolysis as in Fig. 2. **(Yue et al., 2021**) have significantly improved the efficiency, cost-effectiveness, and environmental sustainability of green hydrogen production. In order to conduct current, two electrodes are positioned in the electrolyte solution and linked to the power source. Pure hydrogen and oxygen gas are formed as water breaks down, appearing at the cathode and the anode, respectively.Advanced electrode materials and membrane systems minimize energy losses, and electrolysis can integrate with renewable energy sources like wind and solar. High-performance electrolyzers like Proton Exchange Membrane and Solid Oxide Electrolysis Cells offer diverse options for green hydrogen production (**Yue et al., 2021**). Electrolysis powered by renewable energy sources produces green hydrogen with minimal greenhouse gas emissions and reduced environmental impact, aligning with sustainability and carbon reduction goals (**IEA, 2021**). Electrolysis plants equipped with smart control systems can provide grid-balancing services by adjusting hydrogen production based on electricity demand, contributing to grid stability.Advances in technology have made it possible to scale up electrolysis operations, enabling large-scale green hydrogen production to meet growing demands.

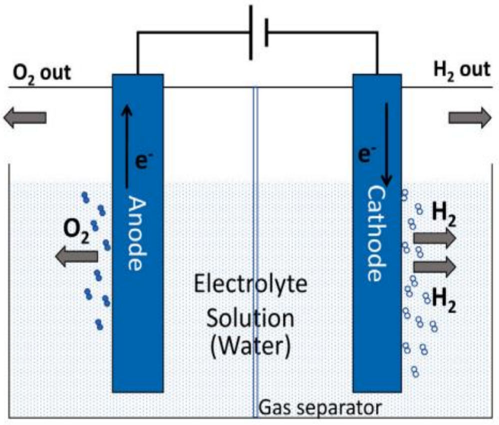


Fig.2. Electrolysis process is using electricity to produce hydrogen and oxygen.

Challenges and Limitations

Green hydrogen production through electrolysis faces challenges like energy intensity, cost, intermittent reliance on renewable electricity, and infrastructure development. Reducing production costs, ensuring sustainable energy sources, and developing energy storage solutions are crucial for widespread adoption (**Cho, 2021**). Limited geographical access to renewable energy sources affects green hydrogen production feasibility. Innovations in storage, transportation, and environmental impact are needed for safety and efficiency. The environmental impact of producing the renewable energy used in electrolysis, such as the manufacturing of solar panels or wind turbines, must be considered (**Younas et al., 2022)**. The green hydrogen market is still emerging, and achieving economies of scale is a challenge.Creating supportive policies and regulations to encourage green hydrogen adoption and investment is crucial (**IEA, 2021**).

Addressing these challenges and limitations is vital to advancing the production of green hydrogen through electrolysis. Overcoming these obstacles will contribute to a sustainable and clean energy future that leverages hydrogen and biomass resources effectively.

Biomass Energy Generation

1. Biomass Types and Sources

Understanding biomass types and sources is crucial for producing green hydrogen from biomass. Biomass is a major source of renewable energy, accounting for a significant portion of global production. Sustainable management, including responsible forestry practices, crop rotation, and minimizing environmental impact, is essential for ensuring a continuous supply **(Dhillon & von Wuehlisch, 2013**). Adhering to environmental regulations and sustainability standards is crucial for harnessing biomass's potential for clean energy generation **(Noussan et al., 2021; Buffi et al., 2022)**.

2. Biomass Conversion Technologies

A well-known method for converting biomass into hydrogen and other products without burning is called biomass gasification. In the presence of oxygen and steam, biomass is heated under regulated conditions. Carbon monoxide, hydrogen, and carbon dioxide are produced when organic or fossil-based carbonaceous materials are gasified at high temperatures (>700°C), without burning, with a regulated quantity of oxygen and/or steam. The carbon monoxide then undergoes a water-gas shift reaction with water to produce carbon dioxide and additional hydrogen. The hydrogen in this gas stream can be extracted using adsorbers or certain membranes **(Sanchez et al., 2021**).

Simplified-example-reaction

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species} \quad (1)$$

Note: In the aforementioned reaction, glucose is used in place of cellulose. The content and complexity of real biomass vary greatly, with cellulose being one of the main constituents.

Water-gas-shift-reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+ small amount of heat)} \quad (2)$$

Biomass is gasified during pyrolysis without the presence of oxygen. In general, biomass does not gasify as quickly as coal, and when no oxygen is utilized, it creates additional hydrocarbon molecules in the gas mixture that comes out of the gasifier. In order to produce a clean syngas combination of hydrogen, carbon monoxide, and carbon dioxide, it is usually necessary to go through an additional step of reforming these hydrocarbons with a catalyst. The carbon monoxide is then changed to carbon dioxide in a shift reaction stage using steam, precisely like in the gasification process used to produce hydrogen. The generated hydrogen is then sorted and cleaned.

3. Biomass-"recycles"-carbon-dioxide.

As part of their normal growing process, plants absorb carbon dioxide from the environment to create biomass, which balances the carbon dioxide emitted during the production of hydrogen through biomass gasification and leads to minimal net greenhouse gas emissions (**Olah et al., 2009**).

4. Biomass Energy Efficiency

Integrating renewable energy sources like solar or wind power in biomass-to-hydrogen processes enhances efficiency, ensuring green and sustainable hydrogen production. Research and development focus on gasification technology and syngas cleaning, considering environmental factors and economic feasibility (**Hosseini** and **Wahid, 2016**). Cost-effective processes and valorization of biomass gasification are crucial for widespread adoption. Government policies and regulations shape biomass efficiency, promoting sustainable practices and setting emissions and environmental standards (**IEA, 2021**).

5. Biomass Environmental Considerations

Biomass environmental considerations are crucial for green hydrogen production, as it can be carbon-neutral and contribute to a sustainable future. Sustainable forestry and agriculture practices are essential to maintain this balance. Biomass production can impact land use, biodiversity, and water consumption, requiring proper management and technology optimization. Proper emission control and technology optimization are essential for reducing greenhouse gas emissions. Policies and regulations promote sustainable biomass practices and emissions reductions in hydrogen production. Continued research and development are essential for improving the environmental performance of biomass-to-hydrogen processes **(Lepage et al., 2021**).

Synergistic Integration of Green Hydrogen and Biomass

Classification of biomass-based hydrogen production methods

Several alternative techniques may be used to transform biomass into usable energy products. The kind and volume of biomass feedstock are factors that affect the process selection (**Milne et al., 2002**). There are two ways to convert biomass into hydrogen-rich gas, namely.

I. Thermo-chemical conversion,
II. Bio-chemical/biological conversion.

Thermo-chemical conversions

For the purpose of releasing hydrogen, thermochemical conversion requires a series of cyclical chemical processes (**Kalinci et al., 2009**). The primary three techniques for producing hydrogen from biomass are as follows:(1) pyrolysis, (2) conventional gasification and (3) Supercritical Water Gasification (SCWG), respectively Fig.3. (**Buffi et al., 2022**).

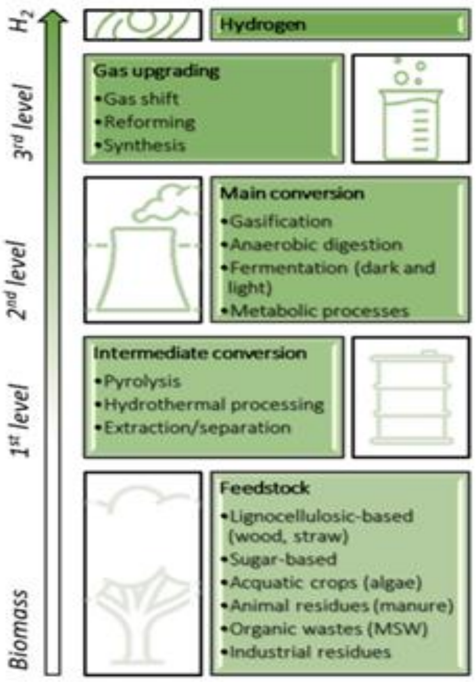


Fig.3. Pathways for producing hydrogen from biomass at various degrees of conversion.

Biological conversion

The biological conversion of biomass into hydrogen is another technique Fig. 4. These may be summed up as the photosynthetic process, fermentative hydrogen generation, and hydrogen production via Biological Water Gas Shift (BWGS). Enzymes that produce hydrogen are necessary for every process **(Aziz et al., 2021**).

Green Hydrogen-Biomass Integrated Power Plants

In this case study, oxygen and steam are used to gasify pine wood in a downdraft gasifier for the analysis of energy and performance (**Kalinci et al., 2009**).

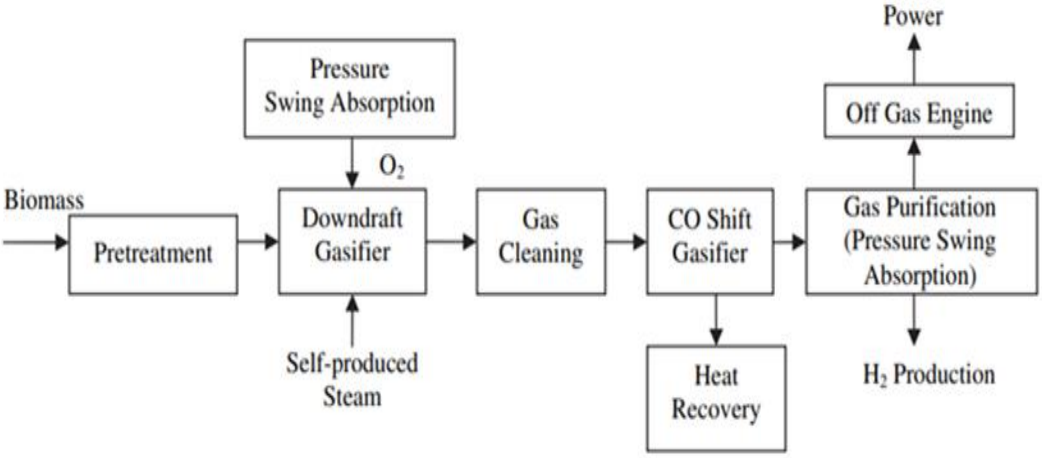


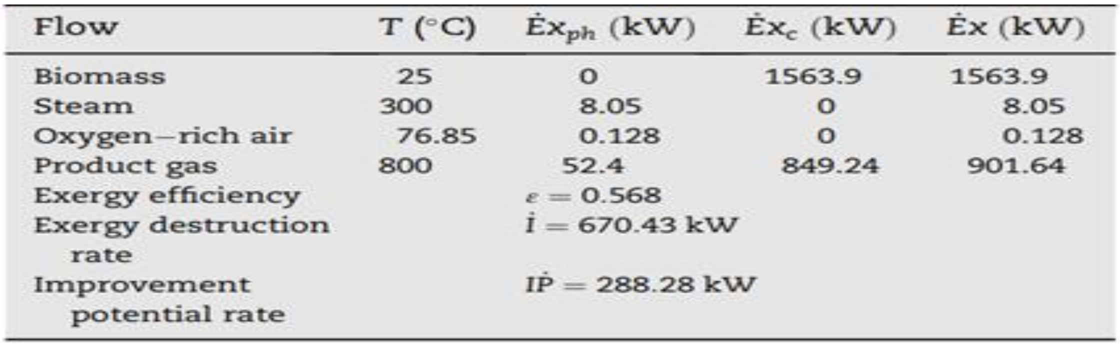
Fig.4. Process flow for the system that produces hydrogen.

This study investigates thermochemical (gasification, pyrolysis, supercritical water SCW) and biochemical conversions for producing hydrogen from biomass (fermentation, photosynthesis, and biological water gas shift reaction). Temperatures and operating pressures vary from 480°C to 1400 °Cand 0.1 to 50 MPa, respectively. The most frequent gasifying agent is steam, and pyrolysis temperatures vary from 480 to 790 °C (**Lv et al., 2008)**.

A material stream's physical and chemical energy rates are included in its energy rate. The biomass exhibits a chemical exergy rate (ĖXc) of 1563.9 kW and a physical energy rate (ĖXph) of zero due to its presence at the reference temperature and pressure. Chemical energy in steam and O2-rich air is zero, but physical energy is estimated to be 8.05 and 0.128 kW, respectively. The primary sources of product gas are H2 and CO2. The products exhibit physical and chemical energy rates of 52.4 and 849.24 kW, respectively, when considering the gasification reaction. Energy efficiency is calculated to be 56.8% using these facts. It should be noted that because all the data was unavailable, this efficiency figure was only determined for the gasifier and not for the entire system.The energy destruction rate was also calculated to be 670.43 kW, while improvement potential rate was found to be 288.28 kW, as illustrated in Table 1 and Fig. 5. Energy destruction occurs in the gasifier, while exergy is essentially lost with the products. To minimize energy destruction, operating parameters, such as temperature, pressure, steam biomass ratio (SBR) and equivalence ratio (ER), should be optimized, and the type of gasifier should be carefully selected (Kalinci et al., 2009).

The following final observations are taken from this study: It was discovered that the downdraft gasifier used as a case study has an energy efficiency of 56.8%. The computed irreversibility and improvement potential rates are 670.43 and 288.28 kW, respectively. Additionally, the downdraft gasifier's energetic fuel and energetic product rates are computed to be respectively 1572.08 and 901.64 kW, while the fuel depletion and productivity lack ratios are respectively 43 and 74.3 percent. According to statistics from the literature, the hydrogen component in the produced gas ranges between 40 and 80% (**Lv et al., 2008**).

Table 1. Results of an energy study for the gasifier.



Flow	T (°C)	$\dot{E}x_{ph}$ (kW)	$\dot{E}x_c$ (kW)	$\dot{E}x$ (kW)
Biomass	25	0	1563.9	1563.9
Steam	300	8.05	0	8.05
Oxygen−rich air	76.85	0.128	0	0.128
Product gas	800	52.4	849.24	901.64
Exergy efficiency		$\varepsilon = 0.568$		
Exergy destruction rate		$\dot{I} = 670.43$ kW		
Improvement potential rate		$I\dot{P} = 288.28$ kW		

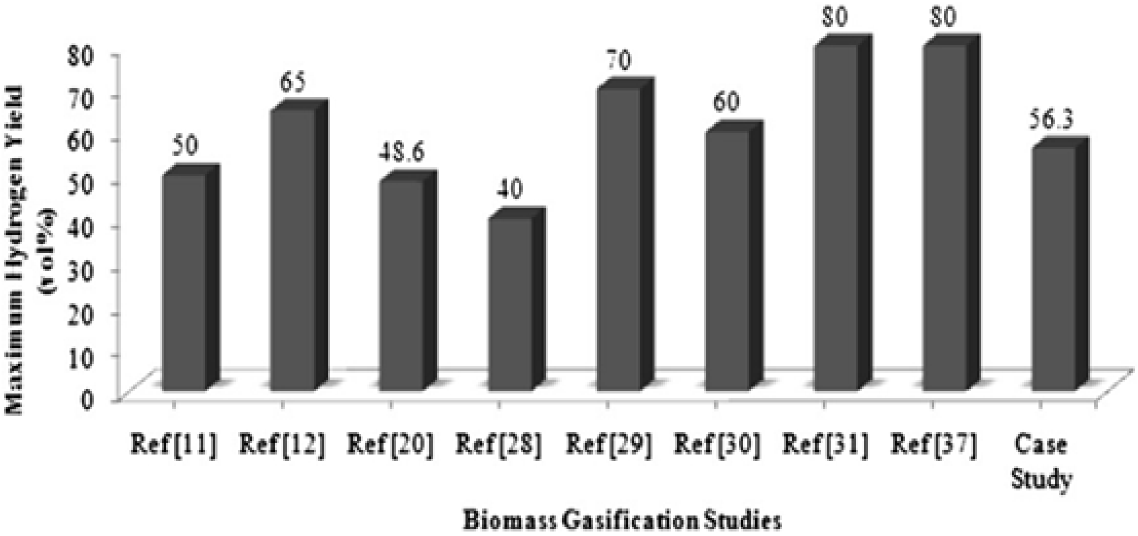


Fig.5. A comparison of the hydrogen yields achieved from several research.

Industrial Applications and Demonstrations

Downdraft gasifiers are used in various applications and have been subject to demonstrations and research. Downdraft gasifiers are versatile in various applications, particularly in biomass gasification and clean fuel production (**Boravelli et al., 2017**). They produce low tar content producer gas, making them suitable for engine applications and clean fuel applications. Research on downdraft gasifiers includes identifying key operating factors, conducting experimental studies, understanding the thermo-chemical process, providing a practical guide, and exploring fuel gas generation systems based on biomass gasification. Researchers continue to optimize their performance for specific use cases.

Challenges and Future Research Directions

Technological Challenges

In one way or another, hydrogen has been created for a very long period. Since much of time and until today, it has been generated using unsustainable environmental practices, decarbonizing hydrogen production is one of the scientific community's most urgent and vital objectives (**Vidas & Castro, 2021**).

Steam Methane Reforming

To produce a mixture of carbon monoxide and hydrogen, methane is cooked with steam (often also using a catalyst) (Navas-Anguita et al., 2021). Equation shows how methane from natural gas reacts with steam at a pressure of up to 25 bar and separates into hydrogen and carbon monoxide molecules—as shown in Equation (3). Because this is an endothermic reaction, heat must be supplied to the process for it to occur:

$$CH_4 + H_2O \xrightarrow{(heat)} CO + 3\,H_2 \quad (3)$$

Oil and Naphtha Reforming(catalytic reforming)

The process of turning petroleum refinery naphtha (distilled from crude oil) into high-octane liquid reformates, which are stocks for gasoline (**Hienuki, 2017**). The process converts linear hydrocarbons into branched alkanes and cyclic naphthene, which are then partially dehydrogenated to produce high-octane aromatic hydrocarbonsand significant amounts of hydrogen gas, as a byproduct.

Coal Gasification

Because of its chemical complexity and wide range, coal may be used to create a wide range of goods. One way to generate electricity, liquid fuels, chemicals, and hydrogen from coal is gasification (**Li & Cheng, 2020**).When coal combines withoxygen and steam at high pressures and temperatures to produce hydrogen, synthesis gas is specifically produced (a mixture consisting primarily of carbon monoxide and hydrogen), like is shown in Equation (4).

$$2\,CH + O_2 + H_2O \xrightarrow{(Heat + Pressure)} CO + 4\,H_2 + CO_2 \quad (4)$$

The synthesis gas is purified by eliminating impurities, and the carbon monoxide then interacts with steam to produce additional hydrogen and carbon dioxide., following the reaction of Equation (5).

$$CO + H_2O \longrightarrow H_2 + CO_2 \quad (5)$$

In a separation system, hydrogen is removed, and the stream of highly concentrated carbon dioxide is then caught and stored.

Biomass

Other renewable organic resources, including agricultural and forestry crop residues, animal and other organic solid waste, and biomass are frequently included (**Cao et al., 2020**), and it may be gasified to yield hydrogen as well as other byproducts. As seen below, in Equation (6), Using high temperatures, regulated oxygen or steam input, and no combustion, this process transforms organic carbonaceous materials into carbon monoxide and hydrogen.

$$C_6H_{12}O_6 + O_2 + 2\,H_2O \longrightarrow 2\,CO + 4\,CO_2 + 8\,H_2 \qquad (6)$$

Then, through a water-gas shift reaction, carbon monoxide combines with water to produce additional carbon dioxide and hydrogen (Equation (5), and special membranes separate the hydrogen from this gas stream.

Due to its difficulties in gasifying, pyrolysis is a biomass gasification process that does not employ oxygen to produce hydrocarbon compounds.

Biological Hydrogen Production

Photobiological processes involve microorganisms and sunlight converting water and organic matter into hydrogen, with green microalgae and cyanobacteria splitting water into oxygen and hydrogen ions (**Sivaramakrishnan et al., 2021**). Researchers are exploring photo fermentative hydrogen production, where photosynthetic microbes break down organic matter to release hydrogen, aiming to improve their energy collection and usage for better hydrogen production.

Water Electrolysis

Using electrodes and a DC electrical power supply, electrolysis is a process that separates water molecules into hydrogen and oxygen. Electrocatalysts and an electrolyte are added to improve it. Efficiency, durability, cost, and problems are discussed in recent advances. Due to its cheap cost and efficiency, steam reforming of methane, which creates less-pure hydrogen, accounts for the majority of the world's hydrogen production(Hnát et al., 2020).Water electrolysis, which generates high-purity hydrogen and releases oxygen as a byproduct, is being investigated as a potential replacement for the present energy system. as seen in Equation (7).

$$H_2O \xrightarrow{\text{Electricity + Heat}} H_2 + 12O_2 \qquad (7)$$

However, due to high energy consumption costs and poor hydrogen output rates, water electrolysis is still not economically viable (**Lee et al., 2018**). For more efficiency, researchers are looking for cheaper electrocatalyst options. Alkaline electrolysis (AEL), proton-exchange membrane electrolysis (PEMEL), and solid oxide electrolysis are the three primary types of electrolysis procedures (SOEL).

Research and Development Opportunities

Research in hydrogen and biomass energy production presents promising opportunities for sustainability and energy challenges, with future directions focusing on advanced technologies like electrolysis and photoelectrochemical processes. (**Vidas and Castro, 2021**). Research on innovative biomass gasification methods for hydrogen production is crucial for improving yield and environmental impact, addressing feedstock availability and logistics challenges, and enhancing energy conversion efficiency. A wider range of biomass feedstocks, techno-economic analyses, and collaboration with policymakers can promote the integration of hydrogen and biomass energy solutions into national and international energy strategies.

Conclusions

This review paper aims to provide a comprehensive understanding of the potential for energy production from green hydrogen to biomass. By examining various production methods, integration strategies, and environmental and economic considerations, this review highlights the feasibility and benefits of combining these two renewable energy technologies. The findings can serve as a valuable resource for policymakers, researchers, and industry professionals in advancing the transition towards a sustainable and decarbonized energy system.It is essential to take biomass environmental concerns into account while producing hydrogen so that it continues to be ecologically benign and helps to a sustainable and green energy future. When handled properly, biomass may be a key factor in cutting carbon emissions and expanding the usage of green hydrogen across a range of industries.

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