A critical review on the role of hydrogen as a clean fuel source

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ABSTRACT

Due to population growth and increased human activity, the world's energy requirements have significantly increased. In the modern world, fossil fuels play a significant role in providing energy, but they also contaminate the environment by releasing greenhouse gases into the atmosphere. Hydrogen is a well-known efficient energy carrier and is found in both renewable and non-renewable sources. This review article gives a general overview of the biomass (biological and thermochemical) and water splitting (photolysis, thermolysis, and electrolysis) processes that are used to create hydrogen from renewable sources. Discussions about these methods' shortcomings are present. The study also looks at a number of important obstacles to the global development of the hydrogen economy. The lack of a clean hydrogen value chain, the storage and transportation of hydrogen, the high cost of production, the absence of international standards, and investment risks are among the most important of these challenges. The paper concludes with some recommendations for further research for scientists to aid in improving the technical efficacy of specific production mechanisms and policy

direction to governments to lessen investment risks in the sector to scale up the hydrogen economy.

Keywords: hydrogen production, biomass, dark fermentation, Hydrogen Power system Renewable energy

INTRODUCTION

Although fossil fuels now meet a significant portion of global energy demand, the adverse effects of fossil fuel burning are unavoidable: greenhouse gases, acid rain, and other environmental and human health consequences. To that aim, global energy transformation is gaining traction, which is aided by the fast growth of renewable energy. To boost this momentum and reduce pollutants, hydrogen has been investigated as an alternative energy carrier, while producing power from hydrogen using a fuel cell produces no local pollution because the sole waste is clean water. Another advantage of hydrogen is its high specific energy density. It can produce three times the energy per unit mass as petrol combustion [1]. Furthermore, hydrogen may be generated locally, reducing a country's reliance on external energy supplies [2]. The availability of water on Earth, in particular, ensures that hydrogen may be produced in a somewhat sustainable manner. Water splitting using electrolysis presents intriguing prospects for synergy with renewable energy. Because of the intermittent nature of some renewable energy supplies, hydrogen may be created before it is required, making it appropriate for distributed and centralised production that is directly connected to remote renewable resources. An electrolyzer's hydrogen is ideal for use with fuel cells. It offers an alternative to the standard power grid since, when paired with a fuel cell, energy may be generated when and where it is required, eliminating the requirement for hydrogen storage. Thirty years ago, hydrogen was identified as "a critical and indispensable element of a decarbonized, sustainable energy system" for providing safe, cost-effective, and non-polluting energy. Today, energy executives consider hydrogen to be the least impactful and least definite issue confronting the global energy system. "As a viable alternative fuel, hydrogen continues to promise a lot but deliver very little." Hydrogen products are now utilised in the industrial sector as raw materials. However, if we realise its full potential as a complete energy carrier, it has the potential to play a significant role in many more sectors. The majority of the estimated 50 million metric tonnes generated annually on a worldwide scale is used as a feedstock for ammonia synthesis, with oil refining accounting for 35% [2-3]. When it realises its role as a flexible energy carrier, it could have major applications in freight and passenger transport (i.e., internal combustion engines and fuel cell vehicles), storage (gaseous or liquid hydrogen), thermal (natural gas blending and solid oxide fuel cells) [3], electricity generation and power to gas generation, as shown in **Figure 1**. Hydrogen integration has progressed steadily in recent years, from production and storage through re-electrification and safety concerns. Extensive descriptions of current development may be found elsewhere, and a number of research are attempting to characterize current progress in hydrogen system integration using unique methodologies [3]. There is broad agreement that creating hydrogen from renewable energy sources (solar, wind, etc.) has significant potential for global sustainability [4]. According to Chi et al., switching to renewable power for hydrogen generation can improve the interconversion of electricity and hydrogen and broaden the hydrogen application.

A review of clean hydrogen generating technologies is offered in this publication. This is not the first time the various hydrogen production methods have been explored, since there have been some studies, covered in earlier sections, and some of them [5-6] have evaluated one or more kinds of the processes connected with hydrogen synthesis. Aside from the emphasis on clean technologies in this study, it also goes beyond a review of the technologies and exposes the constraints connected with them. There are additional challenges in the industry that are impeding the worldwide advancement of the hydrogen economy. The function of hydrogen in the world's energy industry is also discussed.

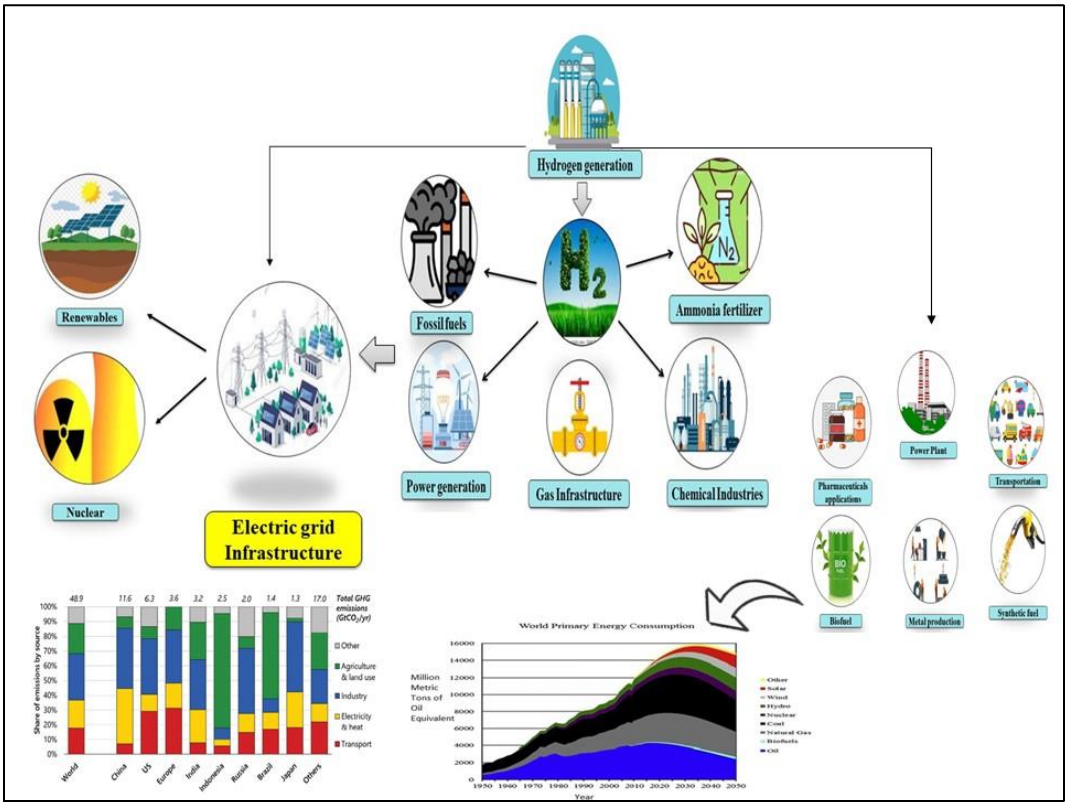

Figure 1. Representation of the Hydrogen production routes, including renewables, fossil fuels and nuclear, with hydrogen being produced in power plants, pharmaceutical applications, synthetic fuels or their upgrades in transportation, ammonia synthesis, metal production or chemical industry.

Status of the Global Hydrogen Production

According to the International Energy Agency (IEA) [6], technologies for producing hydrogen were especially resilient during the COVID-19 pandemic, and their momentum is expected to continue in 2020. According to the IEA study, 2020 was a record year for policy action and low-carbon output, with 10 countries worldwide adopting hydrogen policies. Two hydrogen generating plants from fossil fuels with Carbon Capture, Utilisation, and Storage (CCUS) went online, resulting in a 15% increase in production capacity [6]. According to reports, global total hydrogen consumption has grown by 27.2% in 7 years, rising from 255.3 billion cubic metres in 2013 to 324.8 billion cubic metres in 2020 [7]. **Figure 2** depicts the growth in demand for H_2 over time; it can be observed that the generated hydrogen is largely utilised in the manufacturing of ammonia (51%), while roughly 31% is used in oil refining, 10% is used in the production of methanol, and the remaining 8% has various applications [8]. Hydrocarbon steam reforming is now the most widely used method for producing hydrogen on a global scale, accounting for more than 90% of industrial hydrogen production plants. The Badische Anilin-und-Soda-Fabrik (BASF) created it in 1926 [7-8]. According to the Hydrogen Council and McKinsey & Company [8], of the 228 large-scale industrial, infrastructural, and transportation hydrogen projects planned across the world, more than half, 126, are expected to be located in Europe, 19 in North America, 24 in Oceania, and 46 in Asia. These projects are predicted to be worth 1.4% of the global energy fund, or $300 billion. According to the same research, 75 nations throughout the world have implemented net-zero carbon aspirations, accounting for more than half of global GDP, and over 30 have hydrogen-focused programmes.

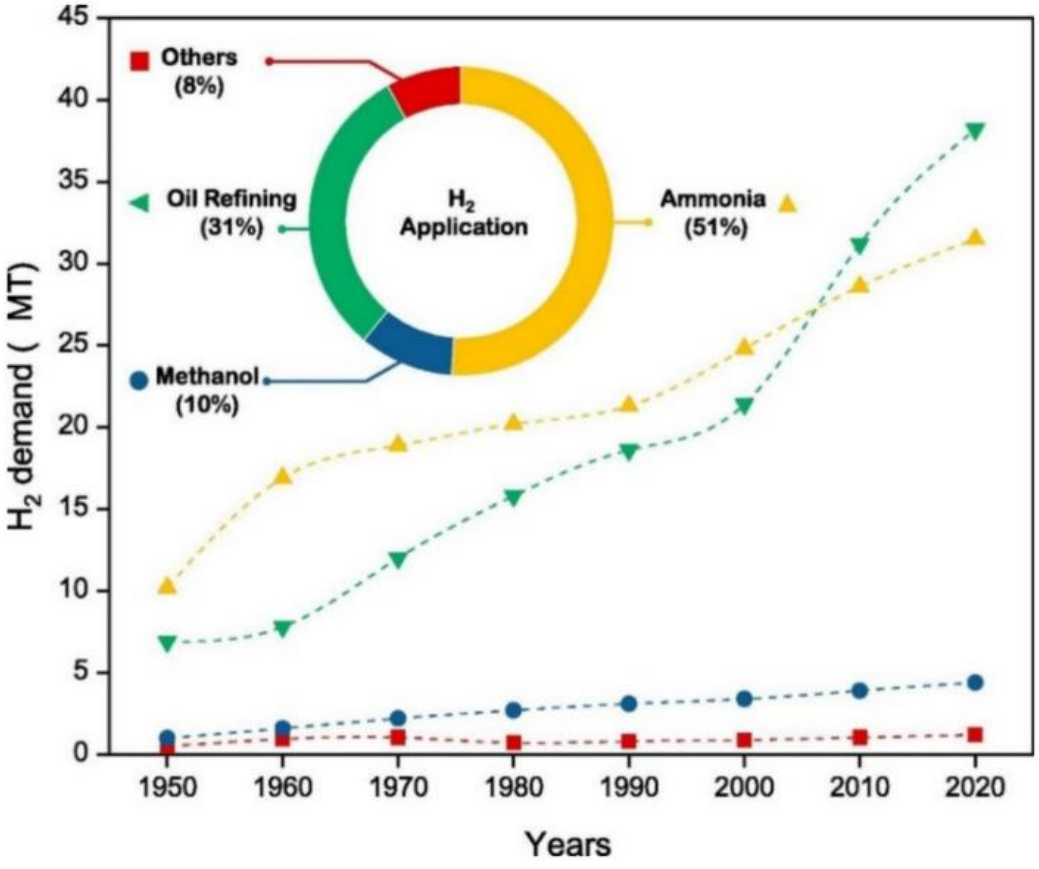

Figure 2. Hydrogen demand worldwide and its share on various uses https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8880752/figure/membranes-12-00173-f002/

Hydrogen technologies

This section introduces some hydrogen technologies often utilized in hydrogen power plants. They include electrolytic hydrogen generation, hydrogen re-electrification via fuel cells, hydrogen storage, and converter technologies. The properties of these technologies are given and proved by certain experimental findings.

Electrolytic hydrogen production

Steam reforming, coal gasification, and water electrolysis are the most common industrial hydrogen generation technologies today. Other hydrogen generation technologies, such as reforming ethanol and sugars, water biophotolysis, photochemical water splitting, and high-temperature water splitting, are still in the early stages of development and are seldom used in industry [9-10]. With the decreasing cost of renewable power, there is an increasing interest in water electrolytic hydrogen production, which uses electricity to extract hydrogen from water while emitting no carbon byproducts such as CO_2.

Water electrolysis principle

Two electrodes are placed in the electrolyte solution and linked to the power source to conduct current in a water electrolysis cell, as illustrated in **Figure 3**. Water is degraded to create hydrogen on the cathode and oxygen on the anode when a sufficiently enough voltage is placed between the electrodes [11]. The inclusion of an electrolyte increases the conductivity of the water, allowing it to conduct electricity continuously. In water electrolysis, acids and solid polymer electrolytes are often utilised, and diverse ions are used as charge carriers: H^+, OH, O_2, and so on. Water electrolysis reactions at various charge carriers' electrodes may change, but the overall reaction is always the same

$$\mathbf{2H_2O + electricity + heat \rightarrow 2H_2 + O_2}$$

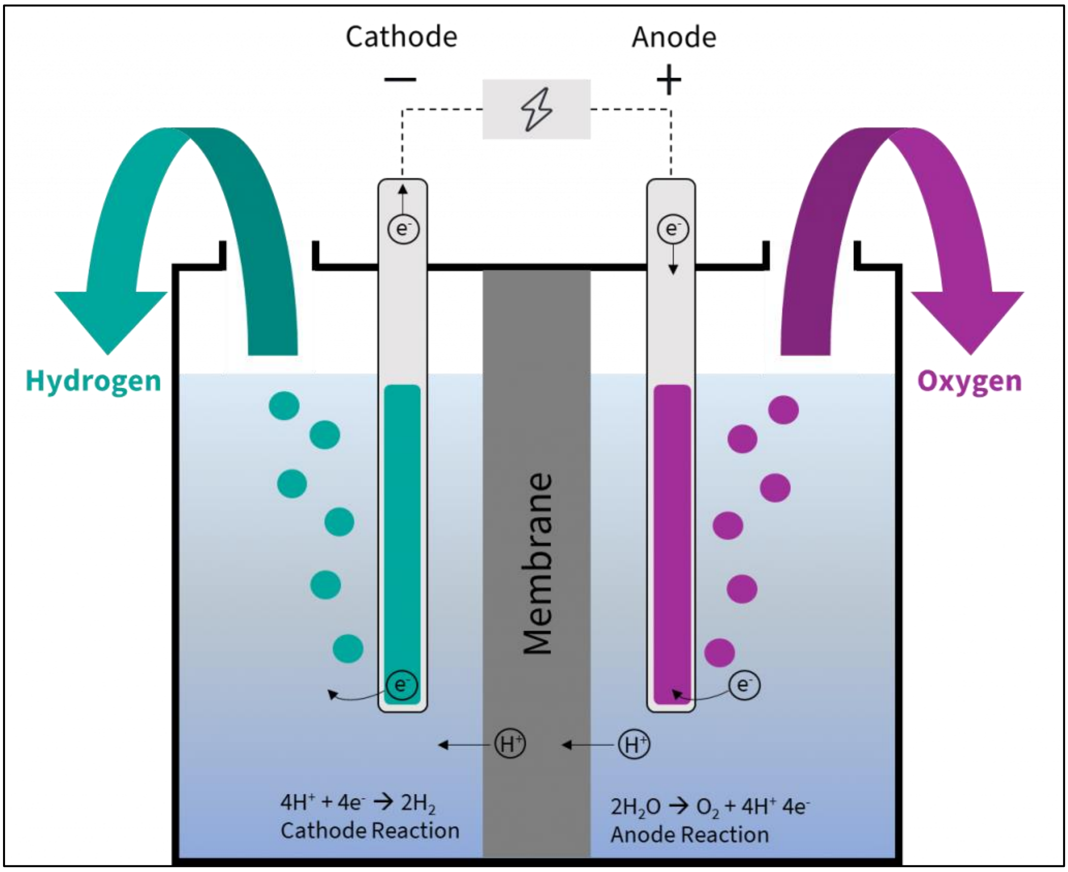

Figure 3. Representation of the Water electrolysis principle: Two electrodes are placed in the electrolyte solution, which are connected to the power supply to conduct current. Water is decomposed into pure hydrogen and oxygen gas, appearing at the cathode and the anode, respectively.

Paths to Hydrogen production

Production of hydrogen is mainly done using either fossil fuels or through RS, which is presented in **Figure 4**. The most common method is known as "steam reforming." Because of its high hydrogen-to-carbon ratio within the hydrocarbons group, methane is the most commonly employed fuel in this process; hence, the created byproducts are minimized [12]. The steam methane reforming (SMR) process is commonly divided into two phases, which are illustrated below [12] **Table 1**. The reformation process begins with the mixing of methane with steam, which is then moved over a catalyst bed at a high pressure of 1.5-3 MPa and a temperature range of 700-900 °C to form a mixture of carbon monoxide (CO) and hydrogen, as shown in Equation (1). The second phase comprises the shift reaction, which involves the interaction of extra steam with the CO from the previous phase to create additional hydrogen and CO_2, as shown in Equation (2):

$$\mathbf{CH_4+H_2O \rightarrow CO+3H_2} \quad \textbf{(1)}$$

$$\mathbf{CO+H_2O \rightarrow CO_2+H_2} \quad \textbf{(2)}$$

The other method for producing hydrogen that involves fossil fuels is coal gasification. In this technique, coal is partially oxidized at high pressure, roughly 5 MPa, and temperature with the help of steam and oxygen to produce CO, methane, CO_2, and other chemicals [13]. At temperatures above 1000 °C and pressures above 1 bar, hydrogen and CO are usually stable [Table 3]. The procedure is depicted in Equations (3) and (4) [13-16].

$$\mathbf{C + \frac{1}{2}O_2 \rightarrow CO} \quad \textbf{(3)}$$

$$\mathbf{C+H_2O \rightarrow CO+H_2} \quad \textbf{(4)}$$

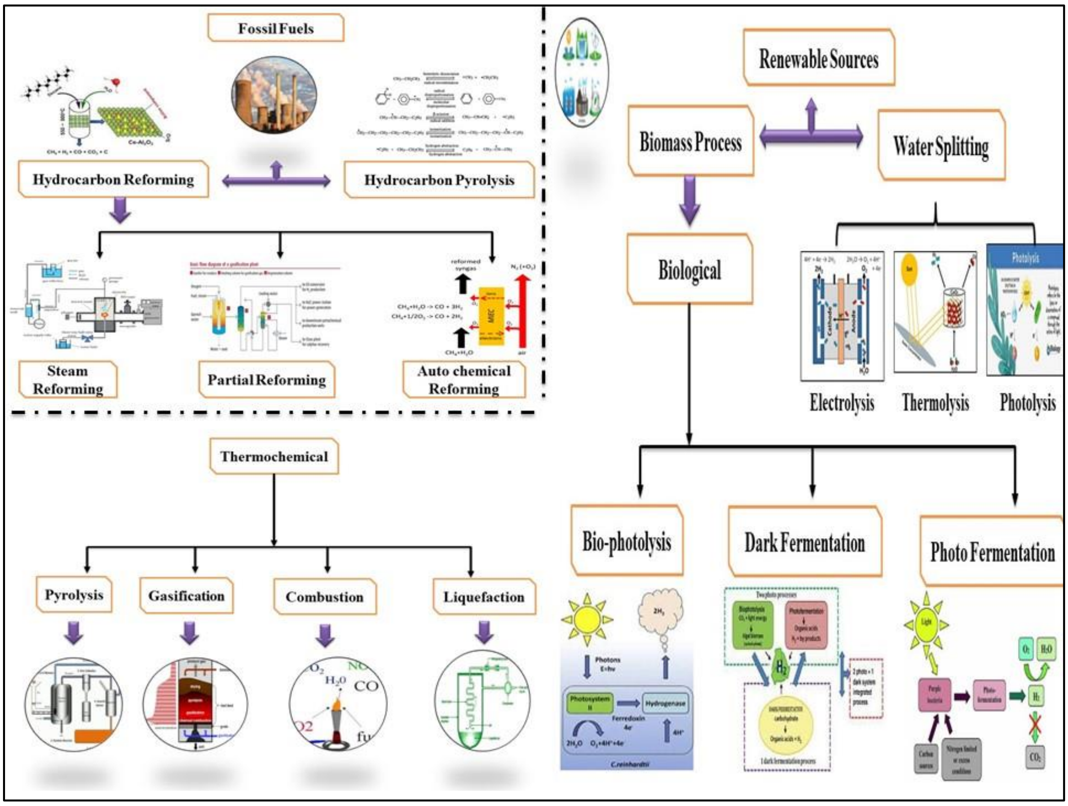

Figure 4. Representation of various Routes to hydrogen production.

Table 1: Representation of the hydrogen production technologies involves from biomass

Technology	Principle	Source as a energy	Operating Condition
Dark fermentative	Biological	Carbohydrate-rich substrates	Anoxic conditions
Photo fermentative	Biological	Small organic molecules	Anaerobic Conditions
Pyrolysis	Thermochemical	Dried biomass	300-1000°C in the absence of oxygen
Gasification	Thermochemical	Dried biomass	800-900°C
Hydrothermal Liquefaction	Thermochemical	Wet biomass	250-370°C and 4-22 MPa
Steam reforming	Thermochemical	Biomass-derived liquids	800-1000°C

Hydrogen Production with the Biomass Processes

Despite the hydrogen production potential of the various biomass technologies outlined in the preceding section, the various processes have several restrictions that can prevent their usage for hydrogen generation. A review of recent studies using different methodologies are presented in **Table 4**.

Biological process

Photo-fermentation: Photo-fermentation method has a modest yield in comparison to H_2 generation; it is also essential for bacterial control. Furthermore, it necessitates a large surface area and has a significant energy need. The H_2 output is expected to be between 9 and 49 grammes per kilo gramme of feedstock [17-19]. The reaction for the production of hydrogen using photo fermentative mechanism using acetate is presented in Equation (5).

$$2CH_3COOH + 2H_2O \rightarrow 4H_2 + 2CO_2, \Delta G^o = +104\ kJ \qquad (5)$$

Dark fermentation: Dark fermentation procedure necessitates pre-treatment and has a significant number of by-products, as well as a poor rate of generation and yield of H_2. The H_2 output is expected to be between 4-44 g/kg feedstock [19] **Figure** 5.

1. Pyruvate: formate lyase:

Pyruvate + CoA → acetyl − CoA + formate

2. Pyruvate: ferredoxin oxido reductase:

Pyruvate + CoA + 2Fd(ox) → acetyl − CoA + CO_2 + 2Fd (red)

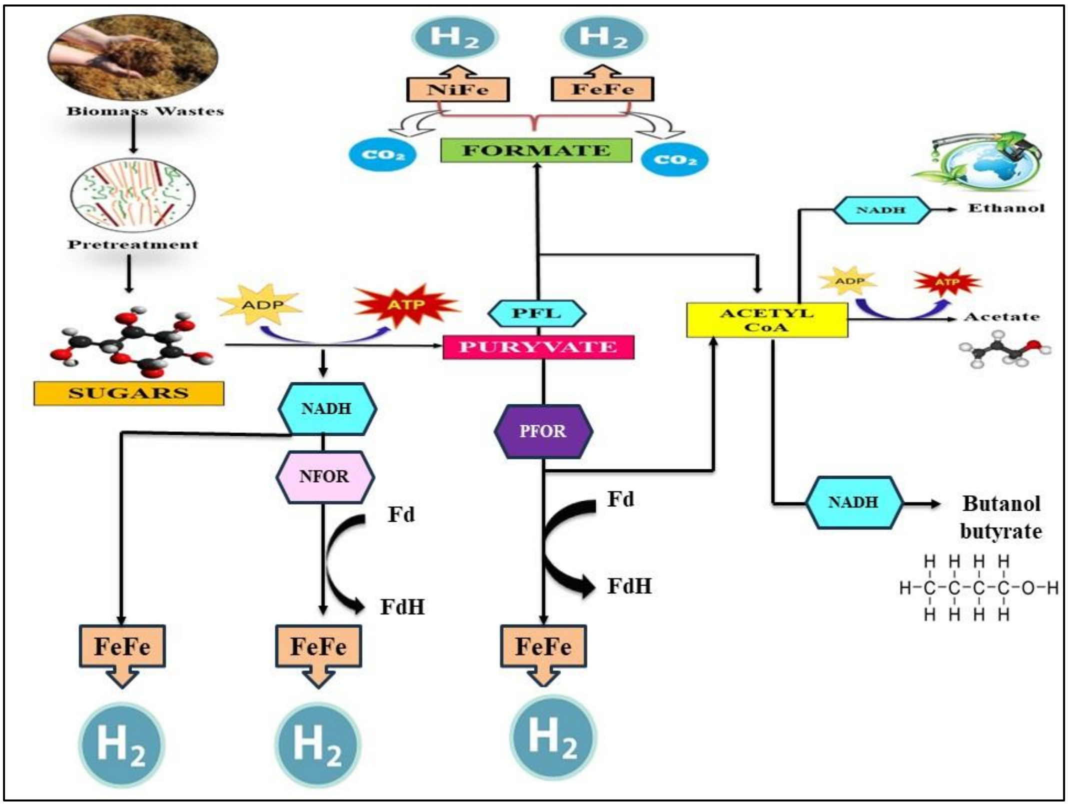

Figure 5. Dark Fermentation process Metabolic ways for converting substrate to hydrogen.

Thermochemical process:

Biomass pyrolysis: Biomass pyrolysis method necessitates catalyst regeneration, CO_2 emissions, the creation of char and tar, and variation in H_2 as a result of biomass complexity and composition fluctuation; the reactor is also expensive. The H_2 production is expected to be between 25 and 65 g/kg feedstock [19].

Biomass gasification: The limitations linked to this process are high operating temperature, variation in H_2 as a result of complexity in biomass and variation in composition, formation of char and tar, which leads to catalyst deactivation, expensive reactor, and that CO_2 emissions and catalyst regeneration are required. The H_2 yield is estimated to be around 40–190 g/kg feedstock [20].

Steam reforming: Steam reforming requires catalyst renewal, runs at high temperatures, and generates CO_2. The H_2 output is expected to be between 40 and 130 g/kg feedstock [20].

$$\mathbf{C_6H_{10}O_5 + H_2O \rightarrow 6CO + 6H_2}$$

$$\mathbf{C_6H_{10}O_5 + 3H_2O \rightarrow 4CO + 2CO_2 + 8H_2}$$

$$\mathbf{C_6H_{10}O_5 + 7H_2O \rightarrow 6CO_2 + 12H_2}$$

Partial oxidation: This also operates under high temperature, includes CO_2 emission, is adapted for only few molecules, and requires a high amount of oxygen. The H_2 yield is estimated to be around 16–140 g/kg feedstock [20-21].

$$\mathbf{C_6H_{10}O_5 + 12O_2 \rightarrow 6CO + 5H_2}$$

$$\mathbf{C_6H_{10}O_5 + O_2 \rightarrow 5CO + 5H_2 + CO_2}$$

$$\mathbf{C_6H_{10}O_5 + 2O_2 \rightarrow 3CO + 5H_2 + 3CO_2}$$

Biomass gasification

Biomass gasification is widely recognized as one of the most feasible, sustainable, and possibly carbon-neutral hydrogen generating processes. Because biomass is a renewable feedstock that absorbs atmospheric carbon dioxide during growth, it has a substantially smaller net CO_2 footprint than fossil-based fuels. However, the economic viability of producing hydrogen from biomass must be closely tied to the availability and cost of raw materials in the local region. The major characteristics of the supply materials are their physicochemical qualities, distribution, and hydrogen rate. Because biomass feedstocks vary greatly in structural composition and form, all of these properties must be considered when combining the feedstock with the right conversion process [22]. As a result, moisture, energy, and ash content are the primary parameters for evaluating biomass utilization in this pathway. Because the hydrogen content of biomass is roughly 5.9 wt% compared to 25 wt% for methane (natural gas), the hydrogen generation is correspondingly low, and the energy content is equally low due to the biomass's high oxygen concentration of 40%. Thus, techno-economic studies backed up by sufficient life cycle assessment evaluation are critical in this topic. Because biomass has a lower density, transportation and storage expenses for either the biomass feedstock or the generated hydrogen should be adequately justified in terms of economies of scale. In some aspects, these qualities would make biomass-based hydrogen generation hard to compete with typical natural gas production methods such as steam methane reforming unless new regulatory frameworks such as carbon taxes favored competitively viable hydrogen production pathways.

Biomass gasification, like coal, is the most practicable method for biomass feedstocks because it generates the highest output at high temperatures, typically

500-1400 °C, where the total reaction is shown in Equation below. Surprisingly, combining biomass gasification with carbon capture and storage might potentially result in a negative carbon footprint **Figure 6**.

$$\textbf{Biomass}+H_2O \leftrightarrow CO+CO_2+CH_4+H_2+\textbf{char}+\textbf{tar}$$

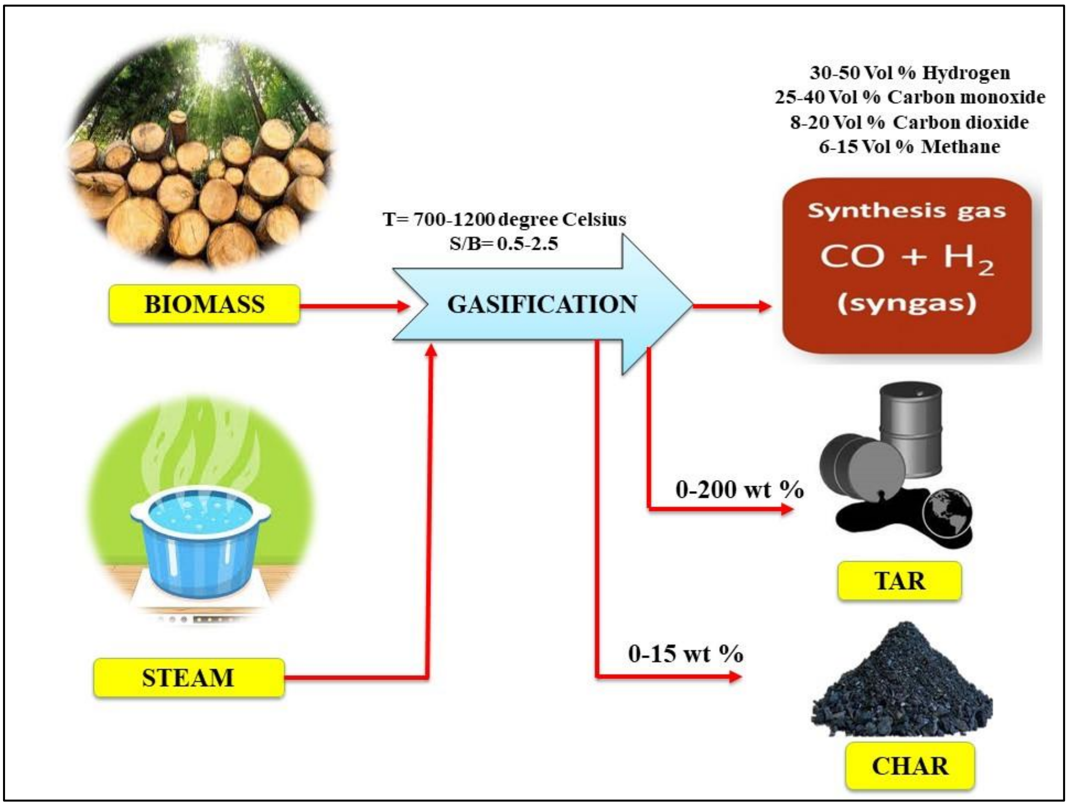

Figure 6. Representation of the biomass steam gasification procedure for hydrogen production.

Hydrogen Utilization

Fuel and Power Systems

Domestic and industrial heat comprise 33 and 50% of global carbon dioxide emissions and universal energy consumption rate, respectively. The bulk of gases generated by the typical burning method of natural gas are implicated in several environmental pollution concerns (i.e. greenhouse gaseous emissions). The principal source of carbon dioxide emissions was energy consumption, with a global emissions rate of 33.1 gigatonnes in 2018, primarily due to the combustion of fossil fuels. In contrast, using hydrogen gas as an alternative fuel to natural gas has proven to be an effective strategy to minimize greenhouse gas emissions. Because of its reactive nature, it may immediately contribute in the decarbonization process in the energy sector after it is created from renewable energy sources, as illustrated in **Figure 7**. The hydrogen is currently generated by conventional (non-renewable sources) at a rate of 18%, 30%, and 48% from coal, heavy oil/naphtha, and natural gas, respectively, resulting in the release of about million 560 tonnes of CO_2 each year [23]. Furthermore, excess electricity generated by power plants may be turned into hydrogen, which can be either directly consumed or chemically processed into chemicals utilised in other industrial aspects [23]. Furthermore, hydrogen can be employed as a single propellant in the aerospace sector or in conjunction with oxygen. The indicated liquid mixture (oxygen and liquid) creates a high quantity of energy, making it more appropriate for space applications. Because of the release of water during hydrogen combustion, as well as its high effectiveness relative to petrol, these characteristics qualify it for usage as an automobile fuel [24-25].

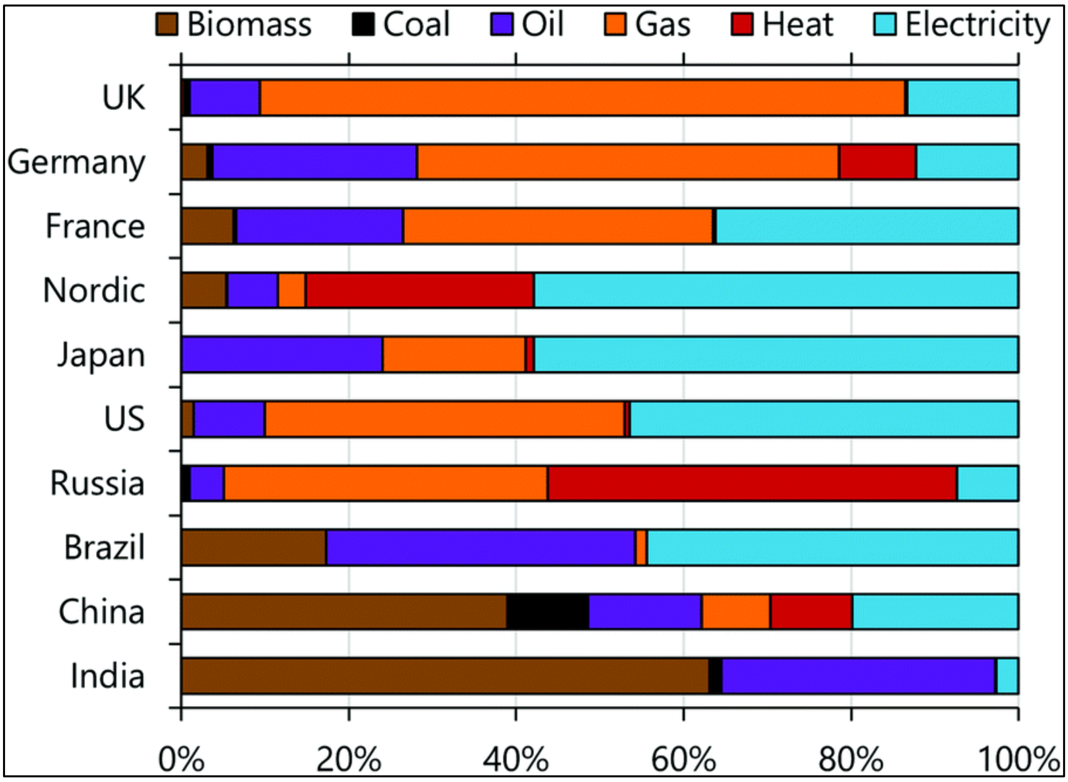

Figure 7. Representation of fuels used for domestic heating in ten countries, estimated using the DESSTINEE model with data from the IEA. Biomass includes both traditional (wood, dung) and modern (wood and miscanthus products); heat is generated off-site and sold to users; electricity includes both traditional (resistance and night-storage heaters) and modern (heat pumps).

Power-to-gas

Power-to-gas is a technique that uses electrical energy to produce a flammable gas. Power-to-hydrogen methods are becoming increasingly popular due to the assumption that hydrogen is a combustible gas with a high-power density. Because of the combustibility of hydrogen, it has been used in gas applications. The hydrogen produced by the electrolyzer may be transformed into methane via the methanation process, which can then be injected into the natural gas grid operating system or stored to meet the financial budget for the energy market [23]. According to the literature, multiple pilot projects have begun globally, with

Europe having the greatest establishment rate of 85%, followed by the United States and Japan [24]. Germany, among other European nations, built a power-to-gas plant with a maximum output capacity of (40-100 megawatts) for industrial applications, and it will pump into the natural gas grid operating system beginning in 2022 [25].

Fuel cells

Fuel cells have recently attracted international interest for their efficiency and environmental friendliness as energy producers. In practice, they are integrated electrochemical devices that are commonly utilized to transform given chemical energy into electrical energy via redox processes [25]. In terms of energy generating efficiency, they can act as energy carriers. Fuel cells are made up of two electrodes (anode and cathode) separated by electrolytes that allow ions to migrate between them [24-25]. Alkaline fuel cells, direct carbon fuel cells, direct methanol fuel cells, microbial fuel cells, molten carbonate fuel cells, phosphoric acid fuel cells, proton exchange membrane fuel cells, and solid acid fuel cells are among the several types of fuel cells.

Biomass Process of Hydrogen Production

Biomass is viewed as more promising than fossil fuels in terms of hydrogen generation due to its enormous reserves and supply, ease of oxidation, and high yearly output. As seen in **Figure 8**, hydrogen may be created in a variety of ways in connection to biomass. This comprises thermochemical conversion of wood waste, photocatalysis (PC) of municipal solid waste, lignin, sawdust, forest residues, agricultural waste, cellulose, polyols, fermentation of microalgae and cassava, biomethane (biogas), steam reforming of gasified biomass tar, and so on [24]. Despite the fact that CO_2 is released during the creation of hydrogen from biomass, the number of gaseous emissions is equivalent to the amount absorbed by organisms during their lifetime. [14]. The two ways that may be employed to manufacture hydrogen from biomass are biological and thermochemical processes. These will be covered in following sections. In comparison to coal, biomass has a relatively high hydrogen-to-carbon ratio. $C_6H_{10}O_5$ (pure cellulose) is thought to have a hydro-carbon ratio of about 1.7, compared to 0.8 for typical bituminous coal [14]. Using biomass can help to reduce reliance on hydrocarbons. Through a technique known as photosynthesis, biomass may restore CO_2 equilibrium in the atmosphere [24].

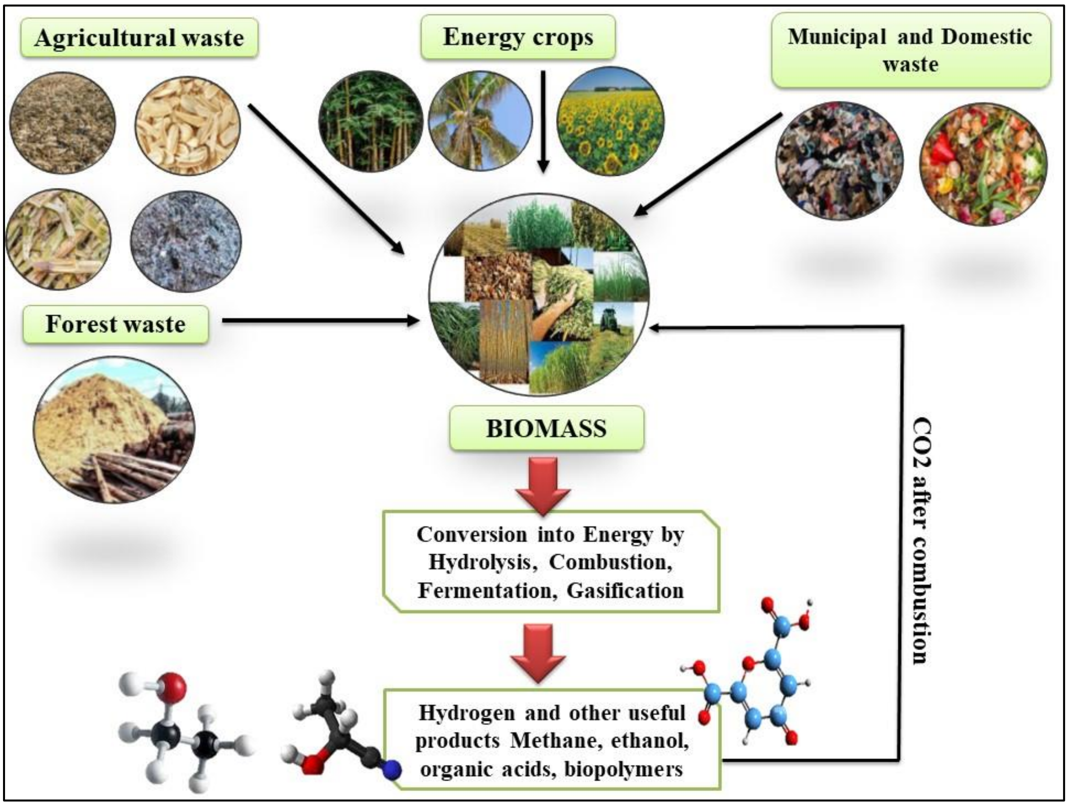

Figure 8. Sources of biomass and their conversion into hydrogen and other beneficial products.

Transportation sector

Cars based on hydrogen fuel (hydrogen-fuelled cars) provide a possible alternative to outperform traditional battery-powered powertrains. Globally, hydrogen-fueled vehicle sales are expected to be 3% in 2030 and 36% in 2050 (Path to Hydrogen Competitiveness: A Cost Perspective - Hydrogen Council. https://hydrogencouncil.com/en/). Currently, several automobile firms are developing hydrogen-based operating systems, citing its dependability and quality. Toyota's Mirai fuel cell cars are powered by proton exchange membrane fuel cells with volume power density and maximum power productivity of 3.1 km/L and 144 kilowatts, respectively. Different kinds of hydrogen (liquid and compressed) can be used to power hydrogen-powered vehicles. The compressed (high pressured) hydrogen is the most suited form in the Clarity and Nexo vehicle storage systems; hydrogen-based fuel cell cars developed by Honda and Hyundai, respectively. At the same time, liquid hydrogen powers the BMW Hydrogen 7 car [22]. Furthermore, regional multi-unit trains fueled by hydrogen have entered operation in Europe and are expected to earn significant economic benefits. The aviation industry is recognised as the quickest transportation option, with yearly growth in air traffic expected. Kerosene is the most popular aeroplane fuel. Various aviation fuels frequently exhibit a set of requirements, such as resistance to corrosion and extreme temperature fluctuations [22]. It's worth remembering that petroleum accounts for the vast bulk of aviation fuel. Alternative, less hazardous fuels such as liquid hydrogen are being created and are expected to be eco-friendly in order to increase energy preservation and lessen the negative environmental consequences of fossil fuels. **Table 2** shows how the physicochemical parameters of hydrogen and kerosene fuels differ. As an aviation fuel, chilled hydrogen fuel has the potential to outperform kerosene. It generates less greenhouse gases emissions and is easily manufactured from a range of sources. Aside from that, running hydrogen-powered aircraft is distinguished by low maintenance costs, long-life engines, high energy content, and improved combustion.

Table 2: Representation of the physico-chemical properties [25]

S.No	Physicochemical properties	Kerosene	Hydrogen
1	Chemical formula	$C_{12}H_{26}C_{15}H_{32}$	H_2
2	Density	0.8	0.071
3	Boiling point	167-266	-252.7
4	Melting point	-50	-259.2
5	Vol% for combustion limit	1.1-3.3	13-65
6	Combustion heat	42.8	120
7	Flame temperature	2126.9	2026.9
8	Vaporization heat	360	440
9	Standard heat of formation	-208.4	0
10	Minimum ignition energy	0.25	0.02
11	Thermal efficiency	42.9	120.0

Production of ammonia

Ammonia is regarded as one of the most important compounds, with massive global production rates. Brightling (2018) projects that the largest ammonia manufacturing facility will have a daily capacity rate of 3300 metric tonnes. Ammonia can be used as a fertilizer in agriculture. It is also used in polymer manufacturing, explosives, refrigerants, medicines, gas sensors, and fuel cells. The catalytic interaction between hydrogen and nitrogen elements via the Haber process promotes the ammonia synthesis process [25]. It is carried out in the as-designed reactor at pressure and temperature operating parameters of 20-30 Mpa and 300-500 °C, respectively, using KOH-promoted finely split iron catalysts and the needed energy of 2.5 EJ. [25]. Furthermore, the hydrogen used in the ammonia synthesis process is generally generated from steam gas reforming, which is not considered ecologically favorable. As a result, there is growing interest in alternative green and sustainable ammonia synthesis processes, such as electrochemical hydrogen manufacture approaches and photocatalytic nitrogen fixation (artificial photocatalysis). **Figure 9** The energy sources used determine the distinctness of the electrochemical ammonia production processes. Hydrogen may be created from water using an electrolysis technique that uses sustainable green energy sources (such as wind and solar energy) and so reduces harmful greenhouse gases emissions [25].

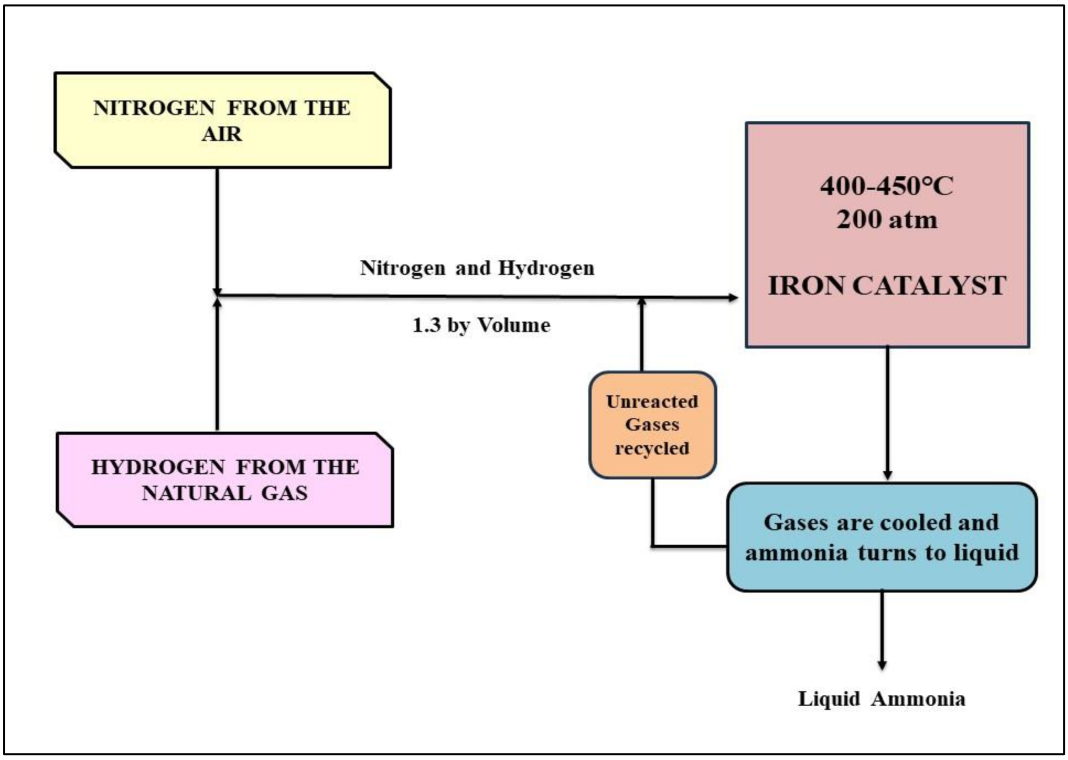

Figure 9. Flow chart scheme for the process of production of ammonia.

Metallurgical industries

In general, hydrogen may form oxy-hydrogen flames and function as a reducing agent in industrial metallurgical processes to extract metals from their ores. During the oxy-hydrogen flames synthesis process (exothermic reaction), hydrogen is allowed to combine with oxygen at very high temperatures (3000 °C) to form oxy-hydrogen flames, which are then utilised for cutting and welding on non-ferrous metals. Otherwise, hydrogen is distinguished by its exceptional capacity to recover (reduce) metals from aqueous solutions of their salts (hydrogen reduction). The metals can be pulverised and used in metallurgical applications later on, or they can be included into a composite material. Chemically, hydrogen can interact with periodic table elements in three ways: (1) ionic bond formation between Ia and IIa groups, (2) interstitial solid solution between VIa, VIIa, and VIII groups, and (3) metallic bond formation between IIIa, Iva, and Va groups. Furthermore, the electrostatic shielding effect can be attributed to hydrogen's propensity to grab free electrons and metal self-trapping. Similarly, the tiny particle size of hydrogen enhances the metal-hydrogen interaction process [25].

Role of Hydrogen in the World's Future Energy Generation

As previously said, hydrogen energy has the ability to act as an energy carrier, and this form of energy has become critical in terms of global sustainable growth, both in developed and developing nations [12-25]. According to research, the globe will require 600 to 1000 EJ of primary energy by 2050 [13]. Energy consumption is predicted to rise considerably higher in emerging nations, where power is critical for development and poverty reduction [22-25]. However, the current global primary energy mix is dominated by fossil fuels, which are expected to be exhausted in around 50 years at the current pace of consumption. [24]. Fuel cells and hydrogen are widely regarded as critical future energy-supply technologies. It is predicted that RS shares of 36% by 2025 and 69% by 2050 on total energy consumption might result in 11% by 2025 and 34% by 2050 [25]. Hydrogen can be transported and stored, and it can be converted into electrical energy using fuel cells. Hydrogen is environmentally beneficial, depending on the source of energy used to produce it; in the case of water-based manufacturing, it returns to water after oxidation. There are several reasons why hydrogen is an excellent and reasonable choice as a chemical fuel for the replacement of fossil fuels. The fundamental reason is that it is a supplementary energy carrier to electricity [15-20]. Hydrogen is viewed as a possible source of energy creation that might help reduce CO_2 emissions. **Figure 10** depicts a comparison between fossil fuel and hydrogen technology. It is projected that using hydrogen produced through traditional methods can reduce carbon emissions by roughly 20% when utilised in fuel cells. As a result, carbon emissions may be greatly decreased by employing RS to produce hydrogen [24-25]. According to the Hydrogen Council's research, H_2 demand and supply might reach 10 EJ per year by the end of 2050, with an additional 5-10% rise every year after that. As a result, H_2 can be considered a possible powerful rival in the world's energy system in the future [18].

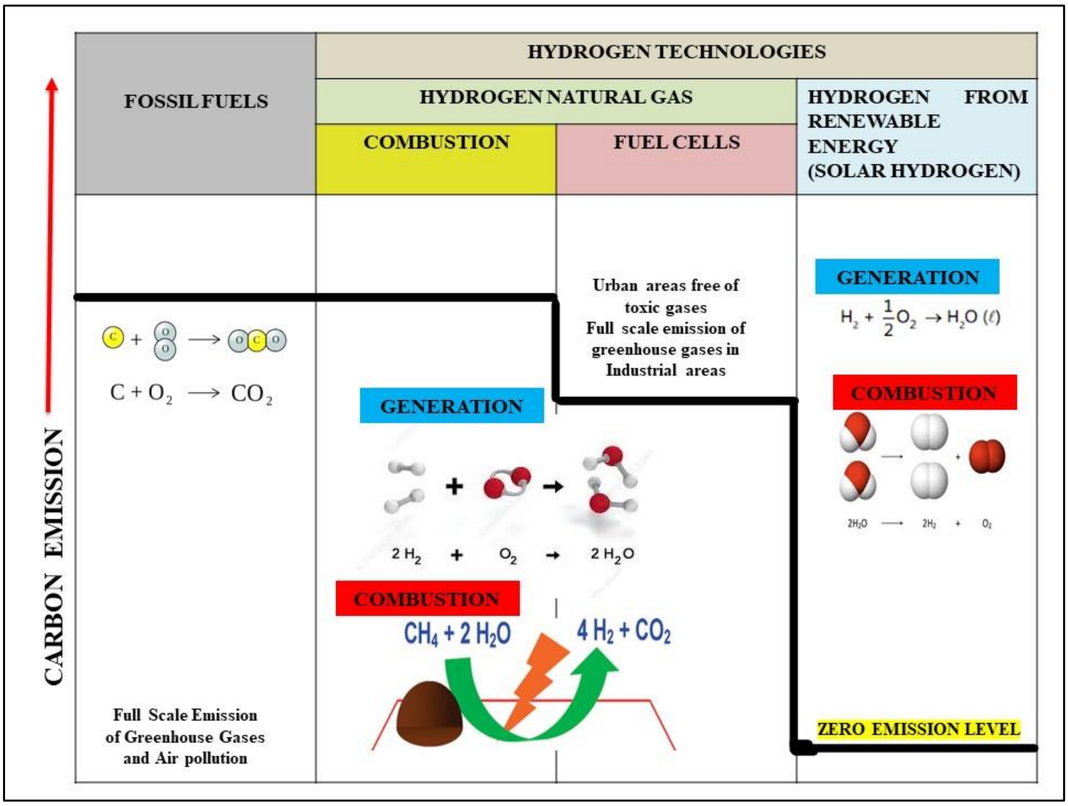

Figure 10. Impact of hydrogen production and combustion on emission of carbon

CONCLUSION

To ensure long-term production of clean and green hydrogen, it is necessary to perform a comprehensive review of potential production methods and their environmental consequences, as well as seasonal storage and utilization choices. Hydrogen may be produced using either fossil-based or renewable feedstocks; however, each process has advantages and disadvantages. The existing hydrogen colour coding is inaccurate, presuming that green hydrogen always has fewer carbon emissions than blue or grey hydrogen, which is not necessarily true. Water electrolysis is gaining traction; nonetheless, fulfilling 24% of energy demand with hydrogen under a 1.5-degree scenario of climate change mitigation will entail vast quantities of extra renewable electricity generation. In this scenario, essentially 31,320 terawatt-hours of electricity would be required to power electrolysers, which is more than is presently generated globally from all sources combined.

The cost and accessibility of freshwater is one side of the coin, and the closeness of these two suppliers, namely renewable energy and freshwater, is the other. Water electrolysis research goals include decreasing the capital cost of electrolysis technology, discovering water supplies, finding utilization pathways for the generated oxygen, and boosting process efficiency. The economic viability of manufacturing hydrogen from biomass must be strongly tied to the availability and affordability of raw materials in the surrounding region when it comes to biomass gasification. The biomass physicochemical characteristics, dispersion, and hydrogen rate are the most important features of the supply materials. Because biomass feedstocks vary so significantly in structural composition and form, all of these aspects must be taken into account when combining the feedstock with the proper conversion method. In conclusion, the most prevalent hydrogen generating routes, such as steam methane reforming, water electrolysis, coal or biomass gasification, and methane pyrolysis with or without carbon capture and storage technologies, are fraught with difficulties.

AUTHORS CONTRIBUTION

All the review, interpretation, and conclusion were discussed and planned by both the authors. The first author (Dr. Shobhana Ramteke) wrote the first draft of the manuscript and critically re-viewed the whole manuscript for further valuable intellectual content. The second author (Dr. Bharat Lal Sahu) collected all the information, wrote and edited the whole manuscript and meanwhile both the authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interest that could have appeared to influence the work reported in this paper.

REFERENCES

1. Abe J.O.; Popoola A.P.I.; Ajenifuja E.; Popoola O.M.; Hydrogen energy, economy and storage: review and recommendation. Int J Hydrog Energy. 2019, 44:15072–15086. https://doi.org/10.1016/j.ijhydene.2019.04.068

2. Abou Rjeily M.; Gennequin C.; Pron H.; Abi-Aad E.; & Randrianalisoa J.H.; Pyrolysis-catalytic upgrading of bio-oil and pyrolysis-catalytic steam reforming of biogas: a review. Environ Chem Lett 2021, 19:2825–2872. https://doi.org/10.1007/s10311-021-01190-2

3. Agyekum, E.B.; Energy Poverty in Energy Rich Ghana: A SWOT Analytical Approach for the Development of Ghana's Renewable Energy. Sustain. Energy Technol. Assess. 2020, 40, 100760

4. Gyamfi, B.A.; Adebayo, T.S.; Bekun, F.V.; Agyekum, E.B.; Kumar, N.M.; Alhelou, H.H.; Al-Hinai, A. Beyond Environmental Kuznets Curve and Policy Implications to Promote Sustainable Development in Mediterranean. Energy Rep. 2021, 7, 6119–6129.

5. Oh, S.; Nam, W.; Joo, H.; Sarp, S.; Cho, J.; Lee, C.-H.; Yoon, J. Photoelectrochemical Hydrogen Production with Concentrated Natural Seawater Produced by Membrane Process. Sol. Energy 2011, 85, 2256–2263

6. Oliveira, A.M.; Beswick, R.R.; Yan, Y. A Green Hydrogen Economy for a Renewable Energy Society. Curr. Opin. Chem. Eng. 2021, 33, 100701

7. Malerød-Fjeld, H.; Clark, D.; Yuste-Tirados, I.; Zanón, R.; Catalán-Martinez, D.; Beeaff, D.; Morejudo, S.H.; Vestre, P.K.; Norby, T.; Haugsrud, R.; et al. Thermo-Electrochemical Production of Compressed Hydrogen from Methane with Near-Zero Energy Loss. Nat. Energy 2017, 2, 923–931.

8. Ishaq, H.; Dincer, I. Multi-Objective Optimization and Analysis of a Solar Energy Driven Steam and Autothermal Combined Reforming System with Natural Gas. J. Nat. Gas Sci. Eng. 2019, 69, 102927.

9. Kamaroddin, M.F.A.; Sabli, N.; Nia, P.M.; Abdullah, T.A.T.; Abdullah, L.C.; Izhar, S.; Ripin, A.; Ahmad, A. Phosphoric Acid Doped Composite Proton Exchange Membrane for Hydrogen Production in Medium-Temperature Copper Chloride Electrolysis. Int. J. Hydrogen Energy 2020, 45, 22209–22222.

10. Okonkwo, P.C.; Bhowmik, H.; Mansir, I.B.; Al, M.A.A.A.S.; Al Sfarini, N.F.A. Effect of Electrode Spacing on Hydrogen Production Using a Home-Made Alkaline Electrolyzer. Mater. Lett. 2022, 306, 130841
11. Salari, A.; Hakkaki-Fard, A.; Jalalidil, A. Hydrogen Production Performance of a Photovoltaic Thermal System Coupled with a Proton Exchange Membrane Electrolysis Cell. Int. J. Hydrogen Energy 2021, 47, 4472–4488.
12. Lu, C.; Li, W.; Zhang, Q.; Liu, L.; Zhang, N.; Qu, B.; Yang, X.; Xu, R.; Chen, J.; Sun, Y. Enhancing Photo-Fermentation Biohydrogen Production by Strengthening the Beneficial Metabolic Products with Catalysts. J. Clean. Prod. 2021, 317, 128437.
13. Ratnakar, R.R.; Gupta, N.; Zhang, K.; van Doorne, C.; Fesmire, J.; Dindoruk, B.; Balakotaiah, V. Hydrogen Supply Chain and Challenges in Large-Scale LH2 Storage and Transportation. Int. J. Hydrogen Energy 2021, 46, 24149–24168.
14. Abdalla, A.M.; Hossain, S.; Nisfindy, O.B.; Azad, A.T.; Dawood, M.; Azad, A.K. Hydrogen Production, Storage, Transportation and Key Challenges with Applications: A Review. Energy Convers. Manag. 2018, 165, 602–627.
15. Turn, S.; Kinoshita, C.; Zhang, Z.; Ishimura, D.; Zhou, J. An Experimental Investigation of Hydrogen Production from Biomass Gasification. Int. J. Hydrogen Energy 1998, 23, 641–648.
16. Aydin, M.I.; Karaca, A.E.; Qureshy, A.M.M.I.; Dincer, I. A Comparative Review on Clean Hydrogen Production from Wastewaters. J. Environ. Manag. 2021, 279, 111793.
17. Zhao, B.; Zhang, X.; Sun, L.; Meng, G.; Chen, L.; Xiaolu, Y. Hydrogen Production from Biomass Combining Pyrolysis and the Secondary Decomposition. Int. J. Hydrogen Energy 2010, 35, 2606–2611.
18. Wang, Y.; Jing, Y.; Lu, C.; Kongjan, P.; Wang, J.; Awasthi, M.K.; Tahir, N.; Zhang, Q. A Syntrophic Co-Fermentation Model for Bio-Hydrogen Production. J. Clean. Prod. 2021, 317, 128288
19. Qiu, Z.; Martín-Yerga, D.; Lindén, P.A.; Henriksson, G.; Cornell, A. Green Hydrogen Production via Electrochemical Conversion of Components from Alkaline Carbohydrate Degradation. Int. J. Hydrogen Energy 2021, 47, 3644–3654.
20. Nikolaidis, P.; Poullikkas, A. A Comparative Overview of Hydrogen Production Processes. Renewable Sustainable Energy Rev. 2017, 67, 597−611.
21. Dincer, I.; Acar, C. Review and Evaluation of Hydrogen Production Methods for Better Sustainability. Int. J. Hydrogen Energy 2015, 40 (34), 11094−11111.
22. Shiva Kumar, S.; Himabindu, V. Hydrogen Production by PEM Water Electrolysis. A Review. Mater. Sci. Energy Technol. 2019, 2 (3), 442−454.

23. Lepage, T.; Kammoun, M.; Schmetz, Q.; Richel, A. Biomassto-Hydrogen: A Review of Main Routes Production, Processes Evaluation and Techno-Economical Assessment. Biomass Bioenergy 2021, 144, 105920.
24. Gollakota, A. R. K.; Kishore, N.; Gu, S. A Review on Hydrothermal Liquefaction of Biomass. Renewable Sustainable Energy Rev. 2018, 81, 1378−1392.
25. Agyekum, E.B.; Nutakor, C.; Agwa, A.M.; Kamel, S. A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. Membranes 2022, 12, 173.,https://doi.org/10.3390/membranes12020173

Table 3. Recent studies different findings on the production of hydrogen

S.No	Year	Mechanism Used	Objective of Study	Results	Ref
1	2011	Photoelectrochemical	To investigate the hydrogen evolution rate for a photoelectrochemical system, which consists of platinum as a photoanode and cathode, and anodized tubular TiO2, solar cell, as well as seawater, which is prepared using a nanofiltration membrane.	The rate hydrogen evolution was found to be 270 mol/cm^2 h.	Oh, S.; et al., 2011
2	2017	Thermo electrochemical production protonic membrane reformer	To obtain high-purity hydrogen within a single-stage process in an almost zero energy loss	The study achieved a balanced thermal operating regime. A total energy efficiency more than 87% was obtained for the modeled hydrogen plant	Malerød-Fjeld, H.; et al., 2017
3	2019	Evaluation of solar driven natural gas reforming system	To assess the impact of a combination of steam methane reforming with carbon dioxide as well as steam-based autothermal reforming.	There was an improvement in both exergy and energy efficiencies. The exergy efficiency is 31.1%, while the energy efficiency is 59.1%.	Ishaq, H.; Dincer, I. 2019
4	2019	Proton exchange membrane	To propose a synthesized polybenzimidazole (PBI) composite membrane from the addition of zirconium oxide (ZrO2) followed with phosphoric acid.	The efficiency of the copper chloride (CuCl) electrolyzer ranged from 91–97%, which indicates that the hybrid PBI/zirconium phosphide (ZrP) membrane can serve as an alternative to the Nafion membrane.	Kamaroddin, M.F.A.; et al., 2020
5	2021	Alkaline water electrolysis	To investigate the effect of electrode spacing on the production of hydrogen.	It was identified that smaller spacing distances for electrodes increases the interaction between the immersed electrode and the ionic electrolyte, which increases the rate of the electrochemical reaction, efficiency, and production of hydrogen.	Okonkwo, P.C.; et al., 2022
6	2021	Proton exchange membrane electrolysis cell (PEMEC)	To assess the performance of PEMEC, which is operated by a photovoltaic thermal (PVT) system. It assessed the impact of thermoelectric generator (TEG) and phase change materials (PCM) on the production of hydrogen.	A combination of the PVT/TEG/PEMEC system performed better than other systems. The PVT/PEMEC/PCM system recorded negligible effect.	Salari, A.; et al., 2021
7	2021	Photo fermentation	To assess the role of catalysts in energy conversion efficiency enhancement and the yield of photo-fermentation biohydrogen from a corn stalk (CS) via strengthening the beneficial metabolic product.	The hydrogen yield was increased by 15.93% when 0.2 g/g CS of kieselguhr was added to the liquid culture.	Lu, C.; et al., 2021
8	2021	Bio-hydrogen production based on lignocellulosic biomass	To explore the syntrophic co-fermentation model for microbial community evolution evaluation and the route of carbon transfer for the co-fermentation system.	The highest level of hydrogen production is 165 mL/g with a mean hydrogen concentration of 52.3%.	Wang, Y.; et al., 2021
9	2021	Water electrolysis, electrochemical conversion	To propose an efficient strategy to replace the oxygen evolution reaction with a partial oxidation of degradation products originating from carbohydrate.	The results indicate that there exists the potential to use industrial waste streams for sustainable hydrogen production.	Qiu, Z.; et al., 2021

Table 4: Representation of Different Hydrogen Production Technologies

S.No	Technology	Advantages	Drawback	Energy efficiency (%)	H_2 yield	Cost	Reference
WATER							
1	Electrolysis	Simplicity, low temp, zero carbon emissions, O_2 as a byproducts	Required High pressure, problem in energy storage, low system efficiencies	55‒50%	111[a]	4.15-10.30	Nikolaidis, P. et al., 2017
2	Thermolysis	Clean and sustainable, zero carbon emissions, O_2 as a byproducts	Separation step is required to avoid the recombination, High capital cost	2-50	111[a]	7.98-8.40	Dincer, I.; Acar, C. 2015
3	Photoelectrolysis	Contributes to the sustainability of the energy supply photonic and electrical energies can be converted to chemical energy	Low efficiency requires a significant surface	0.06‒14	111[a]	4.98-10.36	Nikolaidis, P. et al., 2017
4	Biophotolysis	Low operating temperature and pressure can be produce hydrogen at ambient conditions	Photocatalytic material is required a significant surface area to collect enough sunlight	10-15	111[a]	1.42-2.13	Shiva Kumar, S.; Himabindu, V. 2019
BIOMASS							
5	Dark fermentation	Can produce hydrogen at any time because light is not required	Hydrogen yield is metabolically restricted, high byproduct generation, low efficiency	60-80	4-44	1.68-2.57	Shiva Kumar, S.; Himabindu, V. 2019
6	Photo fermentation	Allows for hydrogen production from a wide range of substrate, including waste streams	Strict control of environmental conditions is required	0.1-12	9-49	2.57-2.83	Shiva Kumar, S.; Himabindu, V. 2019
7	pyrolysis	Developed technology, abundant and cheap feedstock. Solid, liquid and ga product streams, carbon neutral emission	Hydrogen yield depends upon the feedstock tar formation	35-50	25-65	1.59-2.20	Lepage, T. et al., 2021
8	Gasification	Abundant and cheap feedstocks, carbon-neutral emission	Requires oxidation agents, hydrogen yields upon the feedstock tar formation	30-60	40-190	1.77-2.05	Dincer, I.; Acar, C. 2015
9	Hypothermal liquification	Abundant and cheap feedstocks, drying step is not required, high energy efficiency, solid, liquid and gas product strams	Hydrogen yield depends upon the feedstock presence of nitrogenated compounds	85-90	0.3-2	0.54-1.26	Gollakota, A. R. K. et al., 2018
10	Steam reforming	Developed technology, avoid the costly upgrading of the bio-oil	Produce carbon co-products	74-85	40-130	1.83-2.35	Shiva Kumar, S.; Himabindu, V. 2019