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REVIEW ARTICLE

Review on the state of art on renewable energy based green hydrogen energy carrier production processes for sustainable energy supply system

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ABSTRACT

The worldwide increase in energy consumption is primarily driven by anthropogenic activities, resulting in harmful effects on the environment and climate change due to the reliance on fossil fuels. However, renewable hydrogen has emerged as a potential alternative energy source that is both abundant and environmentally friendly. Despite its advantages, the efficiency of commercially available electrolysis for hydrogen production remains a limitation. This study focuses on exploring various methods of producing hydrogen using renewable energy, specifically water and biomass. The analysis reveals that all renewable energy-based hydrogen production methods are more environmentally friendly than fossil fuel-based methods. However, further improvements are necessary to enhance the economic viability and technical simplicity of utilizing renewable energy sources for hydrogen production. Among the examined technologies, biomass electrolysis stands out due to its convenience in using raw biomass directly. Another promising approach is the utilization of solar and wind power to split water into hydrogen and oxygen, resulting in green hydrogen. This sustainable and clean fuel can be used in various sectors such as industry, power generation, and transportation, with lower environmental impact compared to other methods.

Keywords: *Renewable Energy, Hydrogen Production, Fossil Fuel, Biomass.*

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1. Introduction

Keeping up with the rise in global energy demand is one of the main concerns due to the improving living standards and population expansion of the twenty-first century [1]–[4]. Over the last few decades, there has been a constant, exponential increase in the need for energy [3], [5]. Global energy consumption is expected to increase by 50% in the next 15 years, from 2016 to 2030 [6], [7]. Approximately seven billion people worldwide utilized 15 TW of energy in 2011[3]. These figures show that in 2050 the population will be nine billion and needs 30 TW of energy. Fossil fuels are used extensively in worldwide energy production. The world's energy consumption is almost entirely derived from fossil fuels [3], [8], [9]. In 2018, approximately 96% of hydrogen production was based on nonrenewable sources, and the most commonly used processes were natural gas reforming (48%), oil reforming (30%), and coal gasification (18%) [10]. The fuel shares for the world's total primary energy supply (TPES), power generation, and CO_2 emissions are shown in Figure 1. Figure 1, shows that in 2011, fossil fuels accounted for 85% of the world's energy supply. Nevertheless, it is not anticipated that fossil fuels would be able to meet the rising demand for energy due to their finite supply and non-homogeneous distribution [11].

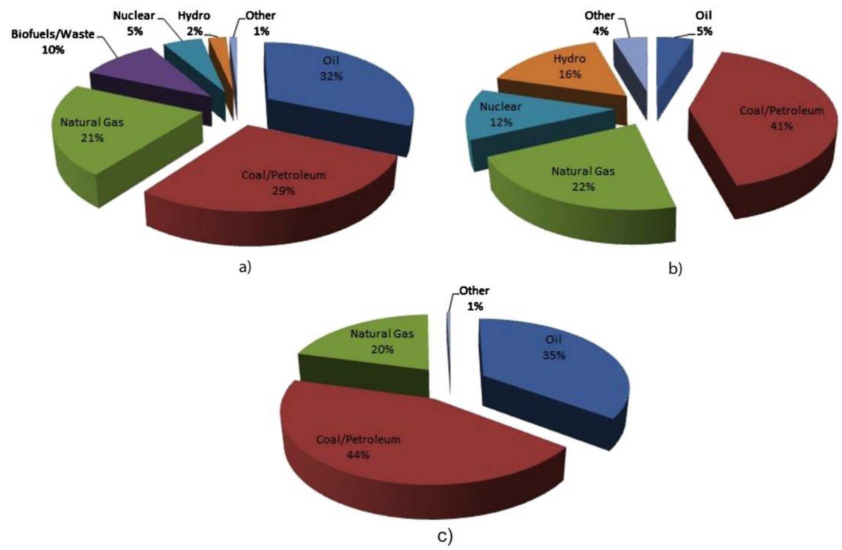


Figure 1. World's fuel shares of (a) total primary energy supply (TPES), (b) electricity generation, and (c) CO_2 emissions in 2011 (Other includes geothermal, solar, wind, heat, and waste etc.) [11].

To reduce the greenhouse gases (GHGs) emissions and the dependence of the energy market on fossil fuels [12], most countries in the world are focusing on the development of renewable energy sources (RESs) to drive the energy transition and to reduce their dependence on external supplies [13]. From data reported by the National Energy Administration, the surplus unused wind power in China accounted for 497×10^8 kWh in 2016, and unused solar power in the north west totaled more than 7×10^8 kWh; the total photovoltaic (PV) power output was 28.7 billion kWh, which means that ap proximately 20% of photovoltaic power was unused [14].

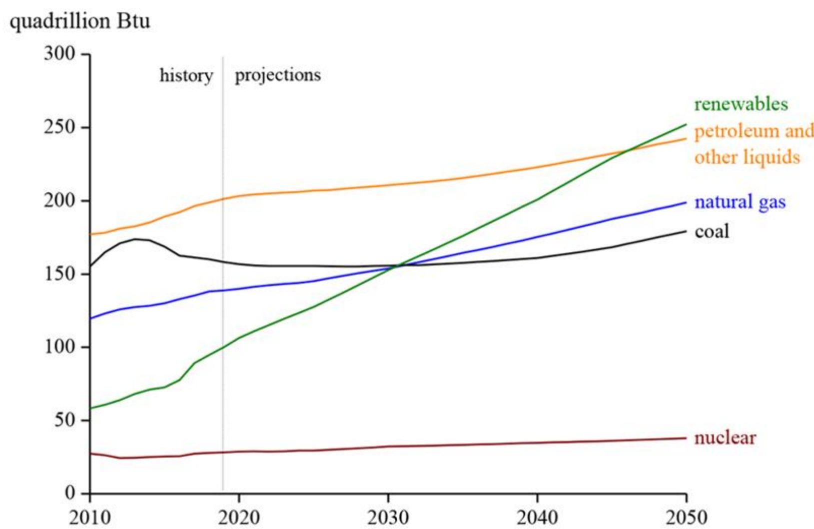


Figure 2. World primary energy consumption by energy source [15].

As a result of these initiatives, the percentage of green power will rise as illustrated in Fig. 2, and green hydrogen will gradually be introduced [16],[3]. Most people agree that one of the elements in the cosmos with the highest abundance is hydrogen [17],[17]. Hydrogen energy is regarded as the potential clean energy in the 21st century, which has aroused great interest of researchers and policy makers around the world [3]. Hydrogen can be produced from a wide range of energy sources with currently 96% generated from fossil fuels (48% natural gas, 30% oil/napthal,18% coal) and 4% generated by electrolysis [18], [19]. The heat release per unit mass of hydrogen is calculated to be three times more that of gasoline [18], [20], [21]. As of the end of 2022, 476 operational hydrogen production facilities across Europe, boasting a cumulative hydrogen production capacity of approximately 11.30 Mt were identified. Notably, the largest share of this capacity is contributed by key European countries, including Germany, the Netherlands, Poland, Italy, and France, which collectively account for 56% of the total hydrogen capacity. The hydrogen consumption in Europe has been estimated at approximately 8.23 Mt, reflecting an average capacity utilization rate of 73% [22]. Portugal led the way with the highest average production capacity utilization, achieving 96% of its production capacity. Greece and Finland followed closely behind with an average production capacity utilization of 91% and 89% respectively. The five countries with the largest hydrogen production capacity had an average production capacity utilization of 88%. In contrast, Slovakia and Croatia reported the lowest average production capacity utilization levels, both falling below 50% [22].

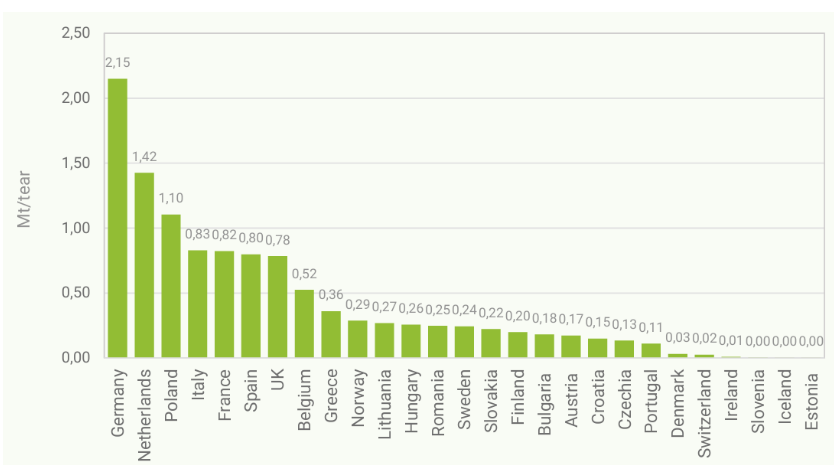


Figure 3. Production capacity (Mt/year) by country [22].

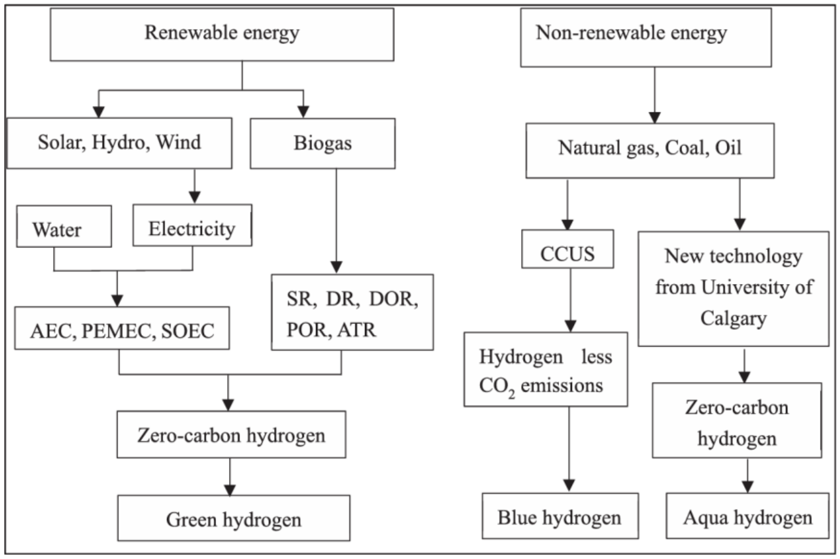


Figure 4. Low-carbon hydrogen production methods [23].

Moreover, it is a clean, renewable energy source when burned, releases only water vapor. Given the current environmental pollution difficulties resulting from the combustion of fossil fuels, hydrogen energy is therefore a potential answer for future energy needs; in fact, it is already a crucial component of various energy systems. The demand for hydrogen worldwide is expected to increase from 255.3 billion cubic meters in 2013 to 324.8 billion cubic meters by 2020, according to reports.

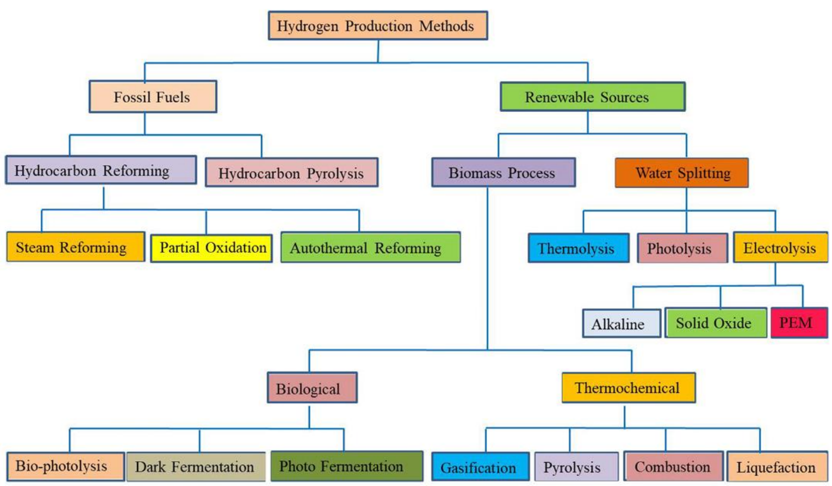


Figure 5. Various Hydrogen Production Methods [24].

Currently, more than 90% of the hydrogen in the world is produced from fossil fuels [20].

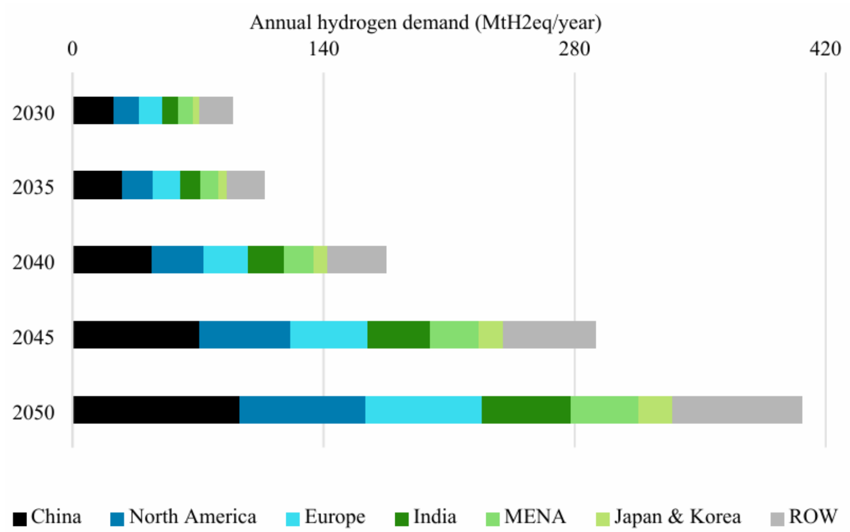


Figure 6. Clean hydrogen demand evolution for the low-demand scenario between 2030 and 2050 by key regions of the study [25].

There are several ways to use hydrogen energy, one of which is in a fuel cell, which has a high energy conversion efficiency [12]. Furthermore, a variety of renewable energy generating technologies can be used to make hydrogen. Therefore, this review introduces hydrogen-manufacturing systems based on various energy sources, such as nuclear, solar, and wind energy. Furthermore, covered are biomass-based methods for producing hydrogen, such as those that involve chemical, microbiological, and electrolytic breakdown of biomass. Specifically, our current study analyzes and thoroughly compares the technological, economic, and environmental effects of various hydrogen production technologies.

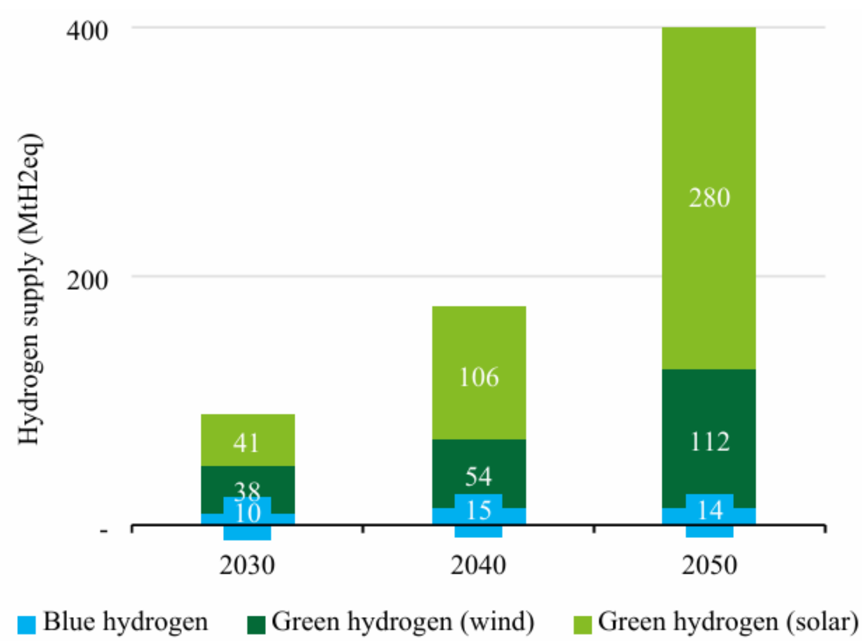


Figure 7. Hydrogen supply mix for the low-demand scenario between 2030 and 2050 [25].

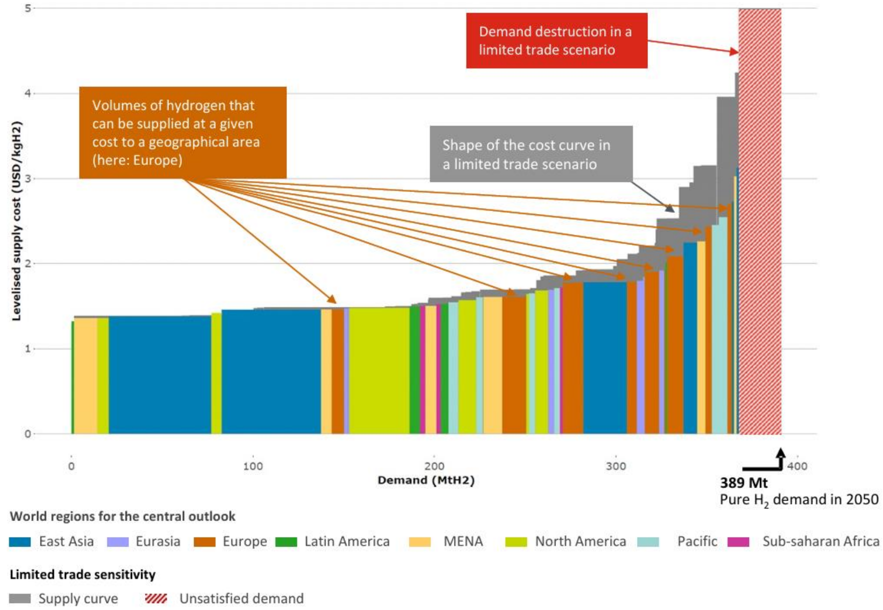


Figure 8. Worldwide supply curve for hydrogen in 2050 under the limited trade scenario.

Figure 8 shows the worldwide supply curve for hydrogen in 2050 under the limited trade scenario. In the limited trade scenario, the unmet demand is represented by the hashed red line, while the supply curve is represented by the grey space [25]. Here, we go further to compare hydrogen with other conventional fuels in terms of Environmental Impact Factor (EIF), Greenization Factor (GF) and Hydrogen Content Factor (HCF) to emphasize the importance of hydrogen as a unique option [11], through the following equations:

$$EIF = \frac{\text{Kg } CO_2 \text{ product of combusition reaction}}{\text{Kg Fuel}} \quad (1)$$

$$EIF = \frac{EIF_{max} - EIF}{EIF_{max}} \quad (2)$$

$$EIF = \frac{\text{Kg of } H_2 \text{ in the fuel}}{\text{Kg fuel}} \quad (3)$$

Where EIF_{max} is the maximum value of EIF among the evaluated options. In this specific case with 3.6, coal is selected as the EIF_{max}.

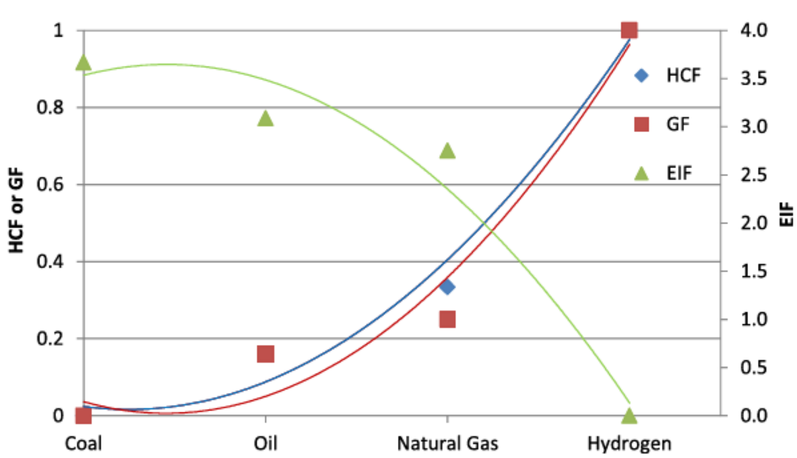


Figure 9. Hydrogen Content Factor (HCF), Greenization Factor (GF),and Environmental Impact Factor(EIF)of hydrogen and other fossil fuels [11].

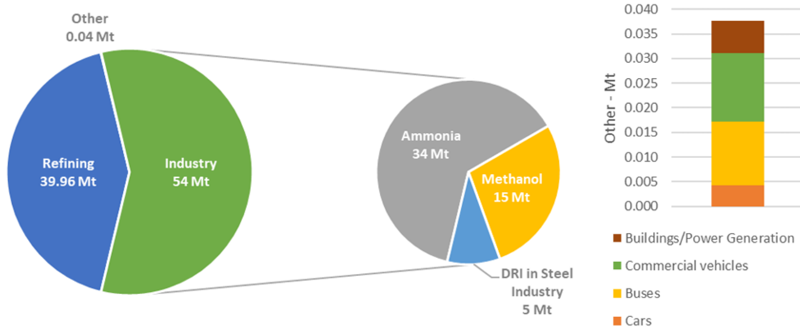


Figure 10. Global hydrogen demand in 2021, million metric tons (Mt) [26].

2. Hydrogen production technology based on water

These are the major technology currently utilized for hydrogen production based on water. Water electrolysis [14], [27], [28],water thermolysis [29], [30], photocatalytic water splitting [31], and thermochemical water splitting [32], are some of the processes that can be used to produce hydrogen using water [33]. Nuclear, solar, and wind energy are examples of renewable energy sources that can be used to properly carry out these procedures. Specifically, hydrogen can be produced using the thermal, radiant, or electrical energy produced by these renewable sources. The ensuing subsections cover the application of these renewable energy sources for water-based hydrogen generation.

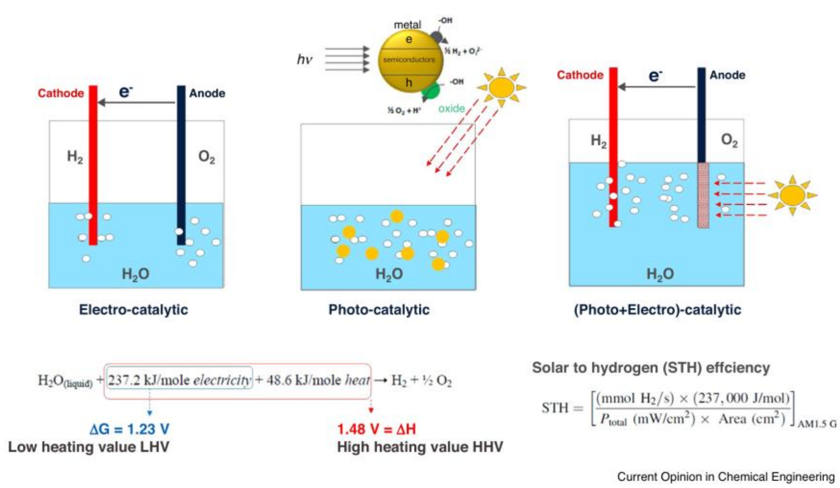


Figure 11. Schematic description of electro-catalysis, photo-catalysis, and photo-electro-catalysis. Also shown are the low and high heating values for water splitting as well as solar to hydrogen efficiency [33].

Table 1. Summary of Hydrogen Production Technologies from Water

Technology	Energy source	Operating condition	Maturity

Electrolysis	Electricity	Up to 30 bar, 50-900°C (depending upon the method	Commercial
Electrolysis	Heat	Temperature of > 2500°C (< 1000°C *for thermochemical cycle*	Research and development
Photo electrolysis	Solar	Ambient conditions	Research and development
Bio-photo electrolysis	Microorganism metabolism	Ambient conditions	Commercial

A standalone PV (SAPV) system is an autonomous system that converts solar energy The components of a photovoltaic (PV) water electrolysis system include hydrogen storage canisters, accumulator battery set, DC bus bar, AC grid, and PV panels. Inside a given range, this system may supply steady and dependable electricity, making up for the occasional instability of solar power generation, which causes low reliability [34]. A structural diagram of the PV water electrolysis system is presented in Fig. 12.

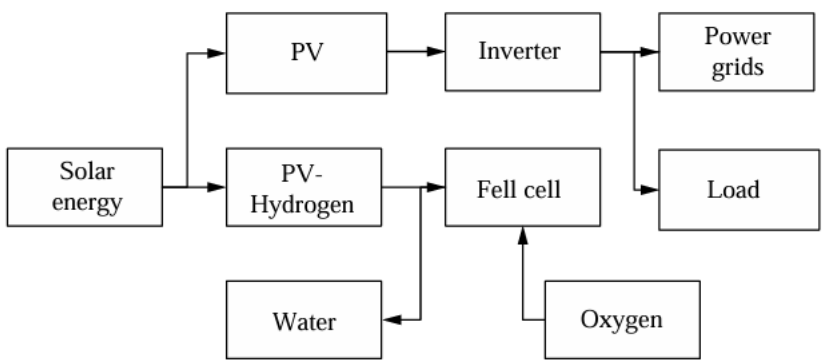


Figure 12. Structural diagram of the PV water electrolysis system

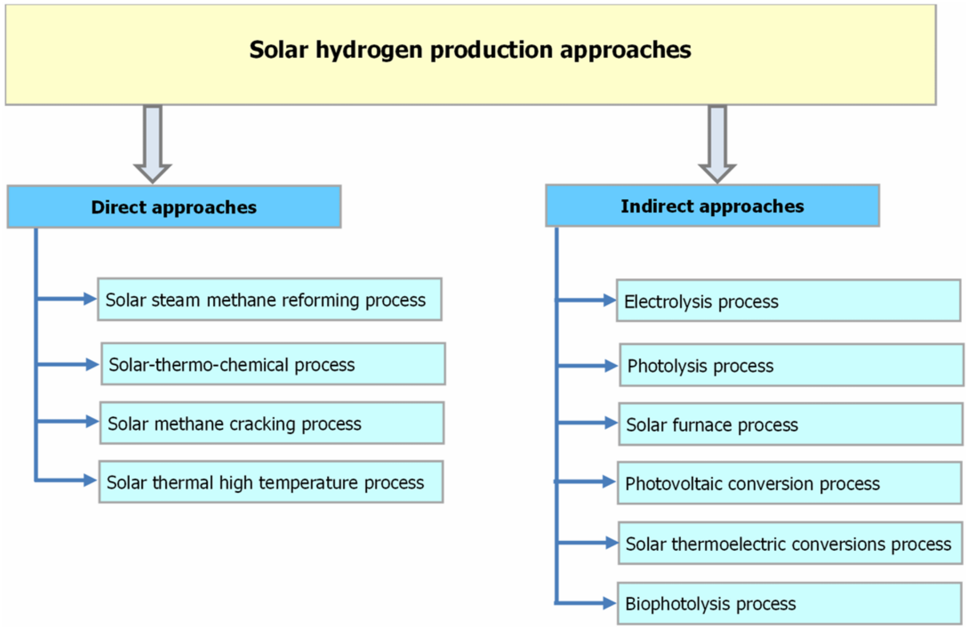


Figure 13. Solar water splitting approaches [35].

2.1 Water thermolysis

Using water to produce hydrogen Utilizing solar concentrators to directly gather solar energy, thermolysis based on solar energy entails heating water to 2500 K, when it breaks down into H_2 and O_2. This method is not without its issues, though; the two main ones are heating up the process with a solar concentrator and efficiently separating the H_2 and O_2. Kogan suggested using a catalyst in water to solve these issues. This would enable water to break down in several stages and significantly, lower the heating temperature needed [14], [27], [28].

2.1.1 Photo electrolysis and photocatalytic decomposition

When a PV electrolytic cell is exposed to solar radiation, photo electrolysis occurs when heterogeneous photo catalysts are applied to one electrode of the cell. Sunlight is absorbed by the cell's photo anode, which causes the semiconductor at the anode to produce electrons [36]. Following their transfer to the cathode by external current, these electrons cause the cathode to produce H_2. Still, only approximately 13% can be achieved even with the use of superior semiconductor materials as electrodes, such as double-interface. Water breaks down into H_2 and O_2 in solar photocatalytic hydrogen generation, while the concept is identical to that of solar photo electrolysis because the anode and cathode are on the same particle [31].

However, the electron holes created on the same particle readily recombine because the breakdown of water into H_2 and O_2 happens simultaneously. A "sandwich" structural material system based on quantum theory was created in a study at the University of Science and Technology of China in order to successfully prevent the reverse reaction of O_2 and H_2 generated via photo electrolysis back to water [37].

2.2 **Nuclear-assisted hydrogen production using water**

One of the main renewable energy sources that can be used to both meet a nation's energy needs and maintain its national security is nuclear energy. In particular, linking an electrolyze to a nuclear power plant-which is also a means of manufacturing hydrogen via thermochemical reactions-makes nuclear-assisted hydrogen synthesis using water possible. The high heat produced by the reactor is used in the nuclear-assisted hydrogen production process to thermolyze water; this is accomplished using a fourth-generation reactor using cycles like the I-S cycle, Cu-Cl cycle, Ca-Br cycle, or U-C cycle [38], [39]. There are various dangers associated with scaling up these thermochemical cycles. Moreover, there are strict requirements for the materials and equipment employed due to the considerable corrosively at high temperatures. As of right now, the Japan Atomic Energy Agency has finished a pilot project to produce hydrogen using the I-S cycle, achieving a 150 L/h production rate. Furthermore, Tsinghua University researchers have set up an I-S cycle experimental system at laboratory scale (60 L/h) that has accomplished long-term operations [40], [41].

3. Hydrogen production technology based on biomass

As an environmentally friendly renewable source of energy, if we can achieve industrialization of hydrogen production using biomass, not only will this have a positive impact on energy use optimization, but also on reduction in environmental pollution, which is the primary cause of climate change [42].

Table 2. Summary of Hydrogen Production Technologies from Biomass [15].

Technology	Principal	Energy Source	Operating Condition	Maturity
Dark fermentation	Biological	Carbohydrate rich substance	Anoxic condition	Research & development
Photo fermentative	Biological	Small organic molecule	An aerobic condition	Research & development
Pyrolysis	Thermochemical	Dried biomass	Dried biomass 300-1000°C in the absence of	Commercial
Gasification	Thermochemical	Dried biomass	800-900 °C	Commercial
Hydrothermal liquefication.	Thermochemical	Wet biomass	250-370 °C	Research & development
Steam reforming	Thermochemical	Biomass driven liquid	800-1000 °C	Commercial

3.2 Hydrogen production via gasification of biomass

The process of utilizing a gasification medium to transform biomass-forming hydrocarbons into gaseous fuel is known as biomass gasification. At the moment, catalysts are usually used to achieve biomass gasification; they lower the temperature and quicken the gasification process in the middle [43]. The three main steps in the gasification of biomass process for the production of hydrogen are hydrogen separation and purification, synthesis gas catalytic reforming, and biomass gasification [44].

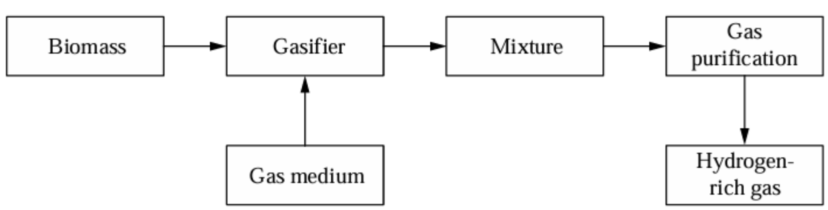
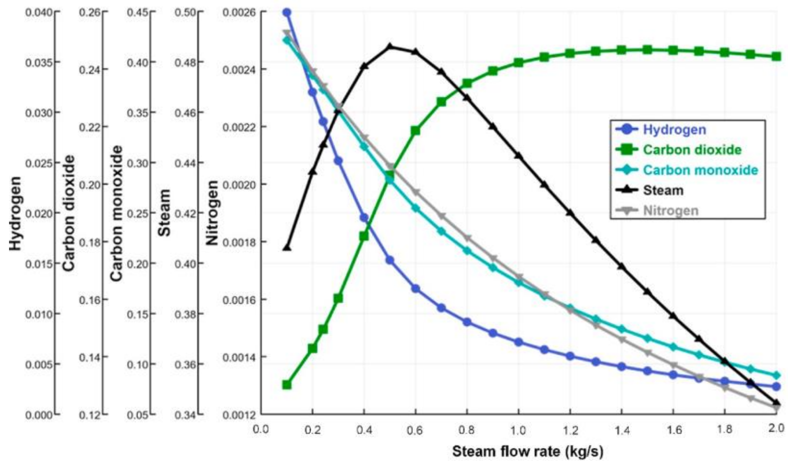
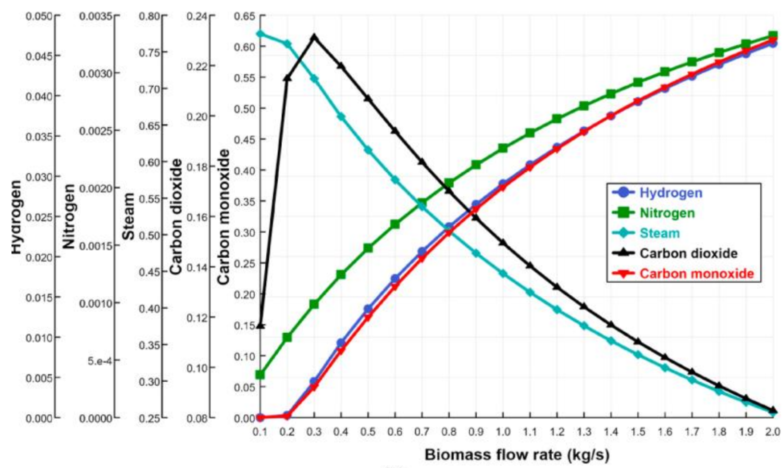


Figure 14. Hydrogen production via gasification of biomass

The supercritical water gasification (SCWG) method of producing hydrogen was initially put forth in the middle of the 1970s. A number of intricate thermochemical processes, including pyrolysis, hydrolysis, condensation, and dehydrogenation, convert biomass in supercritical water to produce a variety of gases, including methane, carbon dioxide, and hydrogen. This process also doesn't require dry pretreatment, which can save energy [45].



(a)



(b)

Figure 15. Effect of biomass gasification parameters on mass fractions of each component (a) Steam flow rate effect (b) Biomass flowrate effect [45].

Table 3. Summary of investigations on hydrogen production from typical biomass gasification [19].

Inside diameter, m	Height, m	Fuel used	Gasification medium	Operating pressure	Operating temperature, K	H_2 yield (%)
0.300	2.90	Wood Wood/Plastic	Air	P_{atm}	1016	9.20
0.083	6.00	Miscanthus	Air	NA	1026	6
Variable	14.80	Biomass	Air	P_{atm}	1123	25
0.040	1.400	Pine sawdust	Air	P_{atm}	1073	32.22
0.06	0.700	Pinewood chips	Air	P_{atm}	1053-1103	22
0.300	8	Wood	Air/steam	NA	NA	9
NA	NA	Wheat straw	Air/steam	P_{atm}	970	20.96
NA	NA	Wheat straw	Air/steam	P_{atm}	933	18.7
NA	NA	Wheat straw	Air/steam	P_{atm}	882	21.1
NA	NA	Wheat straw	Air/steam	P_{atm}	1039	18.27
NA	NA	Wheat straw	Air/steam	Patm	1013	18.46
NA	NA	Wheat straw	Air/steam	P_{atm}	1089	20.80
NA	NA	Wheat straw	Air/steam	P_{atm}	1065	19.06
NA	NA	Wheat straw	Air/steam	P_{atm}	992	21.07
0.070	0.500	Pine and eucalyptus wastes	Steam	P_{atm}	1153	41
0.089	NA	Sawdust	Steam	P_{atm}	1073	57.4
0.150	NA	Pine sawdust and wood	Steam	P_{atm}	1023	40
0.700	0.500	Sawdust wood	Steam	P_{atm}	1023	62.5
NA	NA	Biomass	Steam	P_{atm}	1050	59
0.04	0.75	*Cynara cardunculus* L.	Steam	0.53 P^a_{atm}	923	52.1
0.04	0.75	*Cynara cardunculus* L.	Steam	0.53 P^a_{atm}	973	58.7
0.04	0.75	*Cynara cardunculus* L.	Steam	0.53 P^a_{atm}	1023	60.0
0.04	0.75	*Cynara cardunculus* L.	Steam	0.53 P^a_{atm}	1073	60.4
0.060	NA	Crushed almond shells	Steam	NA	1093	47.5
0.070	0.500	Pine	Steam	P_{atm}	1073	34.4
0.070	0.500	Helm oak	Steam	P_{atm}	1073	42.13

3.3 Hydrogen production via pyrolysis and microbial action on biomass

The process of producing hydrogen from biomass via pyrolysis involves heating the biomass in the presence of oxygen or insulating air to produce a gas that is rich in hydrogen [19]. In addition, CO, CO_2, CH_4, and other hydrocarbons will be present in the resultant gas. Based on the temperature at which it occurs, pyrolysis can be classified as low-temperature slow pyrolysis, medium-temperature rapid pyrolysis, or high-temperature flash pyrolysis. Microbial techniques of producing hydrogen can be classified into two categories: methods based on fermentation and methods based on photosynthesis. The first approach produces H2 by using photosynthetic bacteria to break down biomass or water. It is not practical for industrial production due to its poor H_2 yield and high operational costs.

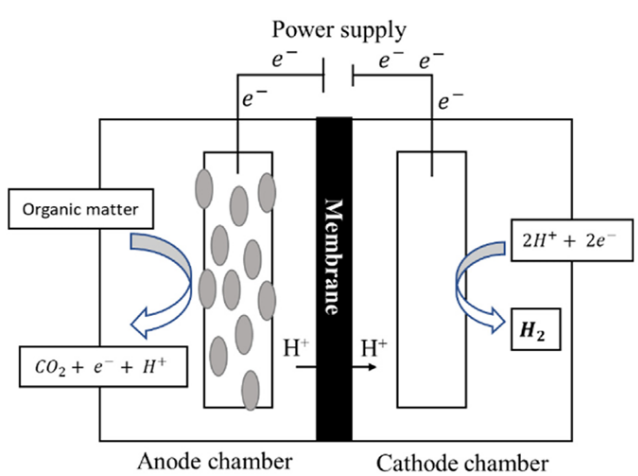


Figure 16. Working principle of the microbial electrolysis for hydrogen production [46].

On the other hand, the latter process, known as dark fermentation, entails transforming the biochemical energy that is stored in organic materials into alternative types of energy when light is not present. Because dark fermentation does not require solar input processing, the bioreactors used for this process are simpler and less expensive than those used for photosynthesis-based microbial hydrogen production. However, there are technical difficulties with both of these microbial action-based methods. These difficulties include low catalyst durability, low heat efficiency, and contaminants in the products [47],[48].

3.4 Hydrogen production via electrolytic method using biomass

Using polyoxometalate (POM) solution as a catalyst and charge carrier, researchers at the Georgia Institute of Technology have reported an electrolysis method for directly producing hydrogen from nearly all native biomasses. This method is highly efficient and low energy consumed, making it suitable for a variety of applications. The electrolyte for the anode in their system is the biomass-POM solution, while the electrolyte for the cathode is an aqueous solution of phosphoric acid. This method breaks down biomass and constantly oxidizes it into smaller derivatives, producing CO_2 as the byproduct of the oxidation process [48].

3.5 Wind-driven hydrogen production

Wind turbine manufacturing costs can be greatly lowered, which has an economic consequence. For instance, if the grid-connected method is chosen for a wind farm with tens of millions of kilowatts of capacity, the estimated cost will be ¥100 billion [49]. On the other hand, wind-driven electrolysis with a plant capacity of 28% might lower the cost of the producing units alone to ¥30 billion or less when the hydrogen production mode is selected; they calculated the generation cost for hydrogen to be \$4.67/kg [50]. Additionally, it is estimated that the cost of producing hydrogen utilizing alkaline electrolyzes powered by wind and proton-exchange membranes (PEM) is \$7.6/kg and \$5.0/kg, respectively. Examined the financial viability of a hybrid power station in the Pays de la Loire region of France that combined an offshore wind farm with a technology for producing and storing hydrogen. The cost of producing hydrogen for the chosen projects would vary depending on the type of application, from \$3.5 to \$11.8/kg of H_2 [50].

3.6 Solar energy-based hydrogen production

An economic study was conducted on a solar PV panel linked to a 1200 t/day PEM electrolysis system; the cost of hydrogen produced using their method was calculated to be \$8.98/kg [1]. Additionally, using a combination of fossil fuel and solar energy to offset the heat need for the S-I cycle; they reported that the cost of hydrogen was \$7.53/kg, with a daily production amount of 71 kg for 65% plant performance. provided a conceptual design and carried out an economic study for a hydrogen production plant that coupled a solar central receiver with thermochemical water splitting; they calculated that the long-term specific cost of hydrogen production would be at least \$3.19/kg. According to Boudries' assessment, the concentrating PV (CPV) electrolysis approach is more cost-effective than the PV electrolysis method, offering a substantially greater production rate (in this case, \$3.6/kg of hydrogen). Furthermore, Boudries carried out an additional investigation in which he employed a hybrid solar parabolic trough-gas power plant electrolysis system to produce hydrogen. The study's findings suggested that the suggested technology might produce hydrogen for as little as \$6.0/kg [36].

$$\text{Biomass} + xH_2O + y\,\text{POM}_{(Ox)} \xrightarrow{\Delta \text{ or } h\nu} \text{Oxidized products} + CO_2 + yH\text{ - POM}_{(Red)}$$

$$H\text{ - POM}_{Red} \xrightarrow{\text{Anode}} \text{POM}_{(Ox)} + H^+ + e^-$$

$$H^+ + e^- \xrightarrow{\text{Cathod}} \frac{1}{2} H_2$$

3.7 Nuclear-assisted hydrogen production

A daily hydrogen production capacity of 580 tons was evaluated for the cost of producing hydrogen using a hybrid sulfur cycle (HyS) on a modular helium reactor (MHR); the revised cost of producing H_2 for such an integrated facility is \$2.29/kg [39]. The cost of producing hydrogen was estimated to be \$0.02 and \$0.08/kWh in terms of the cost of thermal energy and electricity utilized, respectively, for a hybrid thermochemical Cu-Cl cycle coupled to a supercritical water reactor (SCWR) with a daily capacity of 125 tons and a 15-year plant lifetime. This led to an updated production cost of \$3.60/kg [41].

A modified Mg-Cl cycle was studied using the optimal input parameters from the previous work, and the estimated cost of hydrogen was \$3.87/kg. In addition, a recent study that examined the S-I cycle in conjunction with SCWR estimated the cost of hydrogen at \$3.56/kg for large capacity applications [39].

3.8 Biomass based hydrogen production

Evaluated a downdraft biomass oxygen gasification method at atmospheric pressure using CO-shift, and found that the cost per kilogram of hydrogen produced was $1.69. created a heat-integrated flow sheet that uses a steam gasification method in a fluidized bed with in-situ CO_2 capture to produce hydrogen from the empty fruit bunches of palm oil plants [51].

An S/B of four and a sorbent/biomass ratio of 0.87 were attained at 1150 K, resulting in an H_2 yield of 0.0179 kg/h and a cost per kg of $1.91. Additionally, research was done on the use of biogas for hydrogen generation using PEM and alkaline electrolysis, high temperature steam electrolysis (HTSE), dark fermentation, and H_2S electrolysis technologies for micro-scale plant capacities. The results showed that, when all approaches were taken into account and full capacity operation and electricity prices were held constant, the dark fermentation approach had the highest cost of hydrogen generation. Examined a one MW indirect heated gasification system using water gas shift (WGS) at 400 °C and catalytic filter candles at 200 °C. The anticipated cost per kilogram of hydrogen produced was $9.4. Overall, nuclear-assisted and biomass-based hydrogen production technologies resulted in the lowest prices for hydrogen production, whereas solar-energy-based and wind-driven hydrogen production approaches resulted in the highest costs. In light of this, the latter technologies remain unfeasible in comparison to traditional hydrogen technologies based on fossil fuels. Nonetheless, methods for producing hydrogen based on biomass may hold promise for the future [51].

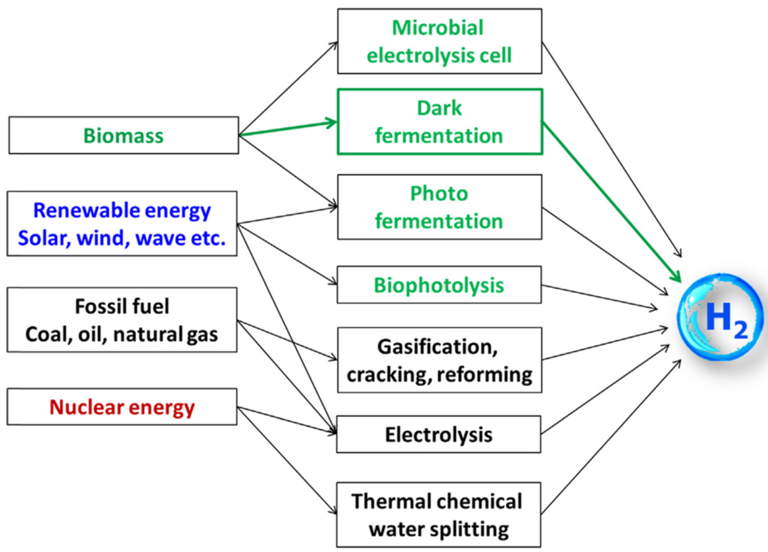


Figure 17. Sources and production methods of hydrogen [52].

Table 4. Cost ranges for hydrogen production via different production techniques

Hydrogen production technique	cost($/kg)
Wind-driven hydrogen production	3.5-11.8
Solar energy-based hydrogen production	3.19-8.98
Nuclear assisted hydrogen production	2.29-3.87
Biomass based hydrogen production	1.69-1.91

4. Environmental impact of hydrogen production

A system's life cycle assessment (LCA) evaluates the advantages and disadvantages of its energy use and environmental impact. This work focuses on analyzing the environmental effects of several advanced hydrogen production technologies, such as wind-powered hydrogen generation, hydrogen produced through photovoltaic electrolysis, nuclear-assisted hydrogen generation using water thermolysis and thermochemical cycle, and hydrogen produced by gasifying biomass. Additionally, since biomass electrolysis is a more scalable method of producing hydrogen than other methods, it was considered a promising choice for hydrogen generation [53].

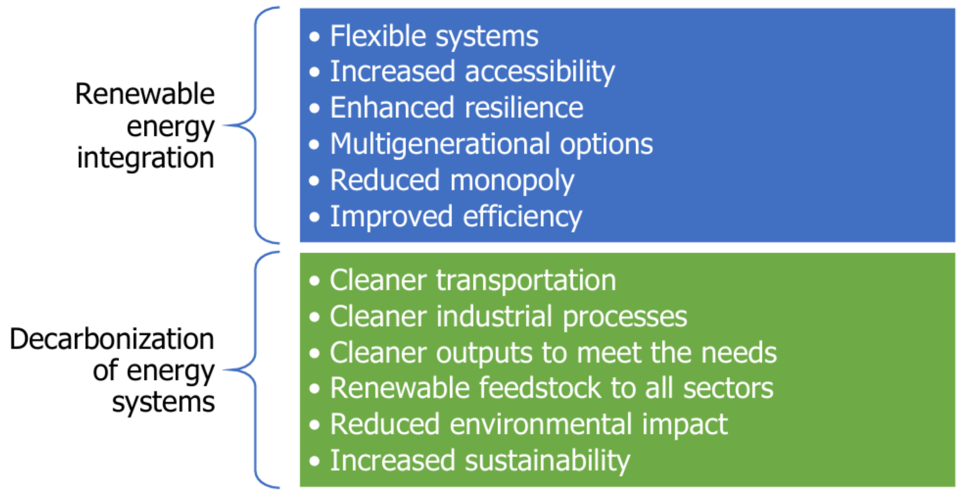


Figure 18. Hydrogen's critical roles during the energy transition to combat global warming [54].

1.1 Wind driven hydrogen production

A life cycle assessment (LCA) of five different methods of producing hydrogen: natural gas steam reforming, coal gasification, water electrolysis using solar and wind power, and thermochemical water splitting using a Cu-Cl cycle. Their findings indicate that the carbon dioxide equivalent emission from wind power-powered hydrogen production was 970 gCO_2/kgH_2.

1.2 Hydrogen production via PV electrolysis

The LCA method to study the comprehensive benefits of PV power generation systems for hydrogen production; their evaluation results showed that the GHG emission equivalent for such systems is 2412 gCO_2 /kgH_2. The life cycle effects of various hydrogen production systems, and concluded that the life cycle energy consumption of PV power generation for hydrogen production was 77.864 MJ/kgH_2 with a GHG emission rate of 6674 gCO_2 /kgH_2 [55].

1.3 Nuclear-assisted hydrogen production via thermochemical cycle and water thermolysis

GHG equivalent of 860 gCO_2 /kgH_2 was released using nuclear thermal hydrogen production technology based on the S-I cycle. Analysis of a similar system, but their system was based on the Leontief matrix model; their results show that the life cycle GHG emission equivalent of the system is 412 gCO_2 /kgH_2. Furthermore, an LCA of one of the proposed methods for hydrogen production-the high temperature electrolysis of water vapor is presented; the results of this analysis are presented in terms of the global warming potential (GWP) and acidification potential (AP) of the system. In particular, the GWP for the system is 2000 gCO_2 /kgH_2 [56].

1.4 Hydrogen production via gasification of biomass

It has long been recognized that the clean and effective method of generating hydrogen is biomass gasification, an appealing technology for converting different kinds of biowastes into energy. Given that biomass gasification is (a) quick, (b) effective, (c) ecologically friendly, and (d) renewable, these factors make it a highly interesting process [57].

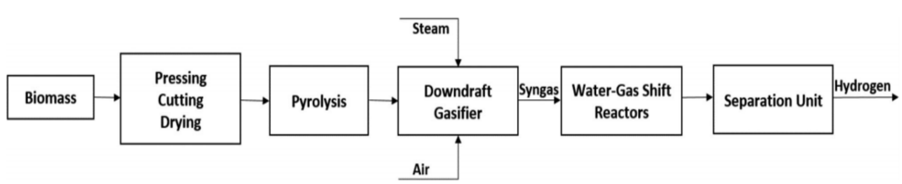


Figure 19. Structure of the biomass gasification-hydrogen production process [57].

Table 5. Hydrogen production method with its GHG emission

Types of Hydrogen production methods	GHG emission range (g CO_2 /KgH_2)
Wind driven electrolysis	600-970
Nuclear-thermochemical cycle/Water	
Thermolysis	412-860
Gasification of biomass PV electrolysis	2412-6674

Table 5, provides an overview of the environmental impact of various hydrogen production systems over a spectrum of greenhouse gas emissions [58]. The approaches that have the least impact on the environment include gasification of biomass and the nuclear-thermochemical cycle/water thermolysis hydrogen production methods; in contrast, the PV electrolysis approach has a comparatively greater impact [59]. On the other hand, the creation of hydrogen using wind-powered electrolysis has negligible environmental impact. It is obvious that any method of producing hydrogen based on renewable energy is more ecologically benign than hydrogen creation based on fossil fuels [60].

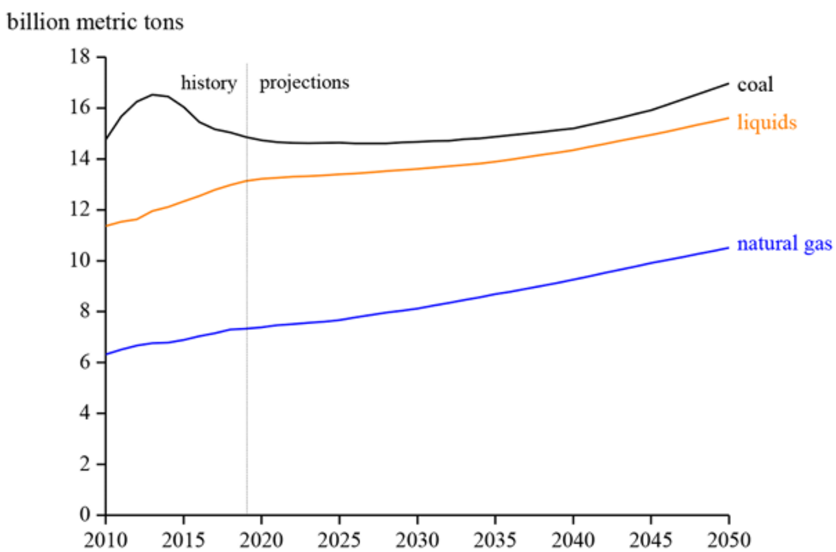


Figure 20. Energy-related carbon dioxide emissions

1.5 Hydrogen production via biomass electrolysis

The research object is a hydrogen production system that uses wheat straw as a raw material. The creation of system equipment, the recovery of production equipment, the recycling and reuse of pollutants generated at different stages in the process, and the energy consumption and environmental emissions during these activities were not taken into consideration [61]. The current study uses four techniques to estimate the boundary of hydrogen production from biomass [62]. The processes involved in acquiring biomass are as follows: (1) transportation of biomass; (2) processing of biomass; and (4) electrolysis of hydrogen [63]. The data for the earliest steps of biomass collection and transportation is derived from the gasification of biomass, as this method of producing hydrogen has not yet been scaled up for use in biomass electrolysis [64].

Environmental impact of the chosen hydrogen generating system's life cycle in terms of greenhouse gas emissions (kg/H_2). Our estimates show that the system's GWP under the same conditions is 0.3779 mPET2000 and its energy consumption is 96.4324 MJ/kgH_2 [65]. On the other hand, the gasification of biomass results in a GWP of 2.7 mPET2000 and an energy consumption of 128.72 MJ/kgH_2. This approach has a tremendous deal of potential as a hydrogen generation technology because it uses less energy and emits less greenhouse gases than other systems [60].

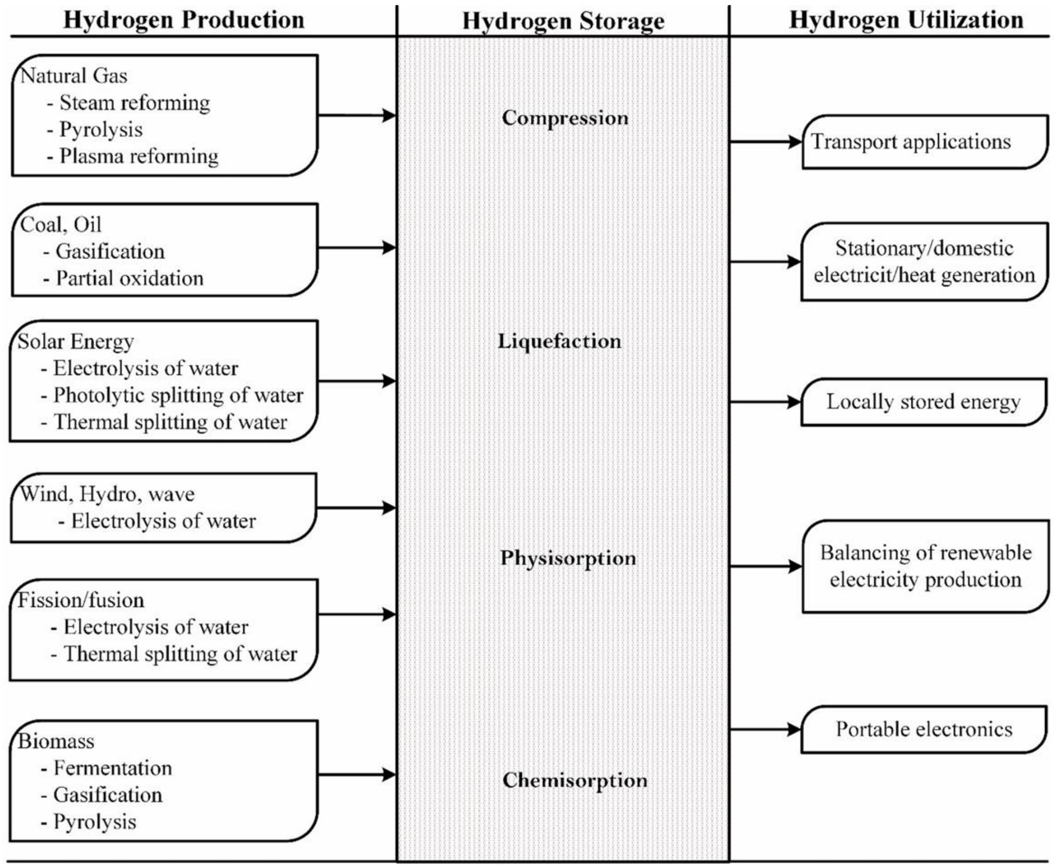


Figure 21. Hydrogen vector: sources, generation options, storage options and end-uses [66].

5. Conclusion

A clean energy source like hydrogen has the potential to significantly contribute to the world's ecologically friendly future energy needs. Therefore, a great deal of study has been done to determine the viability and cost-effectiveness of contemporary ecologically friendly methods for producing hydrogen that can facilitate a seamless shift to a hydrogen economy in comparison to methods that rely on dirty fossil fuels. All renewable energy-based methods of producing hydrogen are clearly more environmentally benign than fossil fuel-based methods, according to the findings of numerous research reported in the literature. Nevertheless, in order to be implemented widely, the cost of producing hydrogen from renewable energy must be substantially decreased. Hydrogen production technique based on biomass has some advantages over other renewable energy-based hydrogen production systems, both in terms of economics and environmental impact. Specifically, when subjected to the same evaluation parameters as previous research, biomass electrolysis produces hydrogen with a lower environmental impact than the other methods. This suggests that biomass electrolysis could be a viable option for an energy-efficient, environmentally friendly method of producing hydrogen.

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