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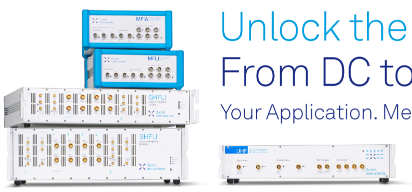

An Overview of Hydrogen Production Techniques: Challenges and Limiting Factors in Achieving Wide-scale Productivity

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Abstract. The growing population and human activities of the world have significantly increased the demand for energy worldwide. Currently, fossil fuels serve as the main source of energy, however, their use contributes to environmental pollution due to greenhouse gas emissions. Hydrogen, on the other hand, is an energy carrier that can be derived from both renewable and non-renewable sources. In this study, a comprehensive overview of various renewable methods for producing hydrogen, including thermal decomposition, electrical analysis, optical decomposition, vital mechanisms, and thermal and biological chemical processes, is presented. Limitations to the expansion of the hydrogen economy, such as the lack of a clean hydrogen value chain, storage and transfer issues, high production costs, lack of international standards, and investment risks, are also identified. To address these challenges and encourage governments to reduce investment risks, this study offers recommendations based on the latest research in this field. Improving the technical aspects of hydrogen production mechanisms, establishing a clean hydrogen value chain, developing standardized procedures for storage and transfer, and increasing investment in research and development are some of the proposed solutions. These actions can pave the way for a more sustainable and clean energy future.

Keywords. hydrogen production, biomass, electrolysis, thermochemical, plasma, dark fermentation**,** photolysis

INTRODUCTION

The use of hydrogen as a fuel gained significance in the 1950s, with the founding of national aeronautics and space administration (NASA), the United States space agency. Due to its high-energy and low-weight characteristics, NASA began using hydrogen as a fuel for its space vehicles. The high energy content per unit mass of hydrogen, as well as its combustion producing solely water vapor, made it an appealing fuel source for space travel. The successful utilization of hydrogen as a fuel for NASA's spacecraft has since stimulated additional research and development of hydrogen fuel cell technology for various applications in transportation, industry, and energy production.

Various industrial purposes are served by hydrogen, including its use in the production of methanol and ammonia, refining, and usage in the metal, electronic, pharmaceutical, and food sectors. The potential of hydrogen as a fuel to alleviate local air quality problems makes it an important resource for the future. Hydrogen's potential applications offer significant advantages to the automotive industry, and the current global production of hydrogen stands at around 50 million tons per year. The growth rate of hydrogen production has averaged 7% per year and is projected to increase to 10% [1]. The trend emphasizes the necessity of developing sustainable and cost-effective hydrogen production methods and infrastructure to meet the projected demand for hydrogen.

Hydrogen plays a critical role in the worldwide production of fossil fuels, and there is substantial research focused on developing its production methods from renewable sources like water and biomass [2]. As a result, hydrogen production is a topic of significant interest for numerous industrial companies worldwide.

Various sources can be used to obtain hydrogen, but the most effective method for its production in combination with other elements is through the crushing of raw materials [3]. Hydrogen is typically produced in industries based

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on steam reforming of hydrocarbons. However, other technologies exist in addition to this, such as thermolysis and electrolysis [4-6]. Hydrogen is considered one of the most accessible renewable energy sources due to its availability. In addition, the burning of hydrogen yields solely water vapor. It is regarded as the cleanest energy source [7]. Although water electrolysis is a simple method for producing hydrogen, it is energy-intensive and leads to high production costs, resulting in a higher price. The use of cheap electricity sources such as solar, wind, water, or nuclear facilities is necessary to reduce the costs associated with this method. Therefore, it is crucial to identify promising technologies and resources and evaluate the effectiveness of production methods while considering their environmental impact [8]. Hydrogen production from renewable resources offers another viable option for addressing environmental issues as a result of using fossil fuels as the primary energy source. The benefits of hydrogen include its high heating value, which ranges from 120 MJ/kg to 142 MJ/kg, and the fact that it emits no greenhouse gases when produced with renewable energy [9, 10]. The transformation of the global energy system from the past to the future is illustrated in Figure 1.

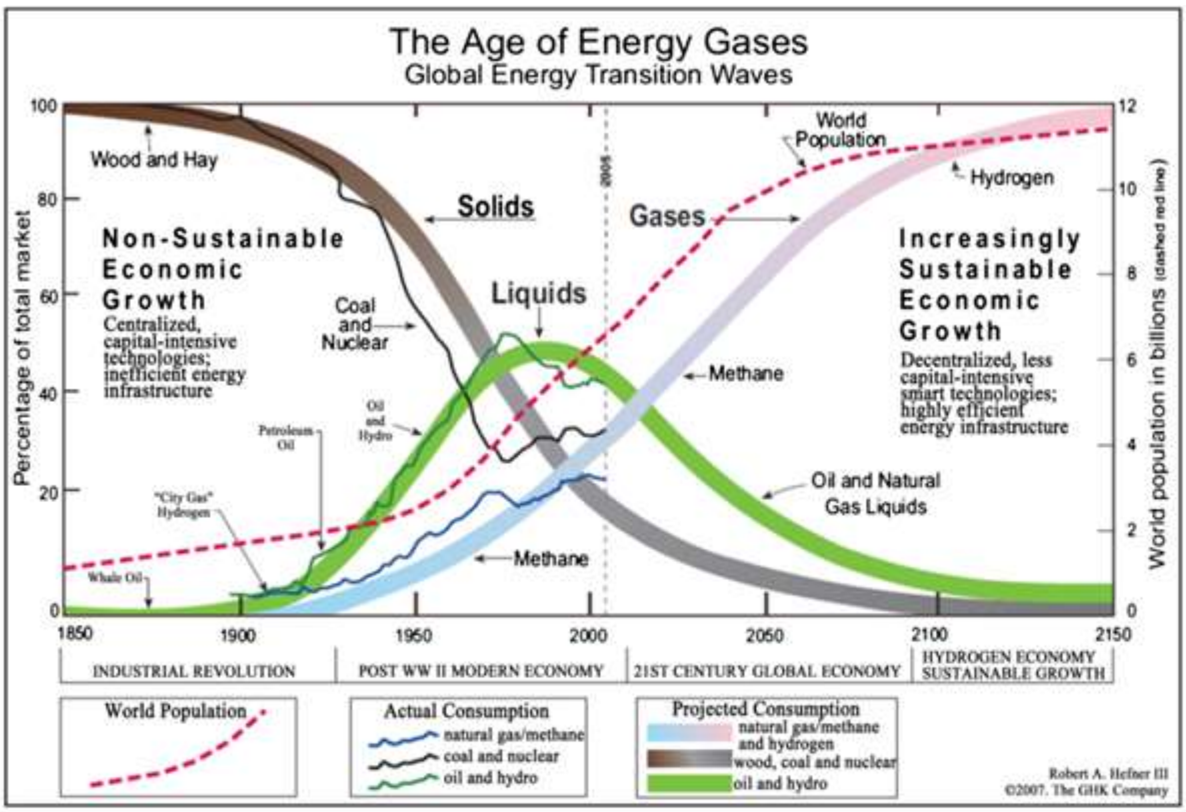

FIGURE 1. From the past to the future: The evolution of the global energy system

This research highlights the previous work on hydrogen production methods and their environmental impacts. The importance of improving the efficiency of hydrogen production methods to reduce resource depletion and increase productivity is considered. Utilizing renewable energy sources for hydrogen production, such as solar or wind power, is recommended to reduce energy consumption, greenhouse gas emissions, and environmental effects. The modern advancement in hydrogen production using various augmentation techniques is reported in the literature. Furthermore, finding the approaches to lower water usage in hydrogen production that can aid in mitigating the environmental consequences of water depletion is discussed. This study will address the research gap in the most recent hydrogen generation strategies to assist future researchers. The main significant critical insights from this review research are (i) the new ways to boost fuel supplies in the future, (ii) paths of producing hydrogen, (iii) a critical comparison of hydrogen production paths, and (iv) the environmental impact of hydrogen production.

TYPES OF HYDROGEN

Figure 2 illustrates the six distinct types of hydrogen that are identified by various color codes or nicknames used in the energy industry for differentiation purposes.

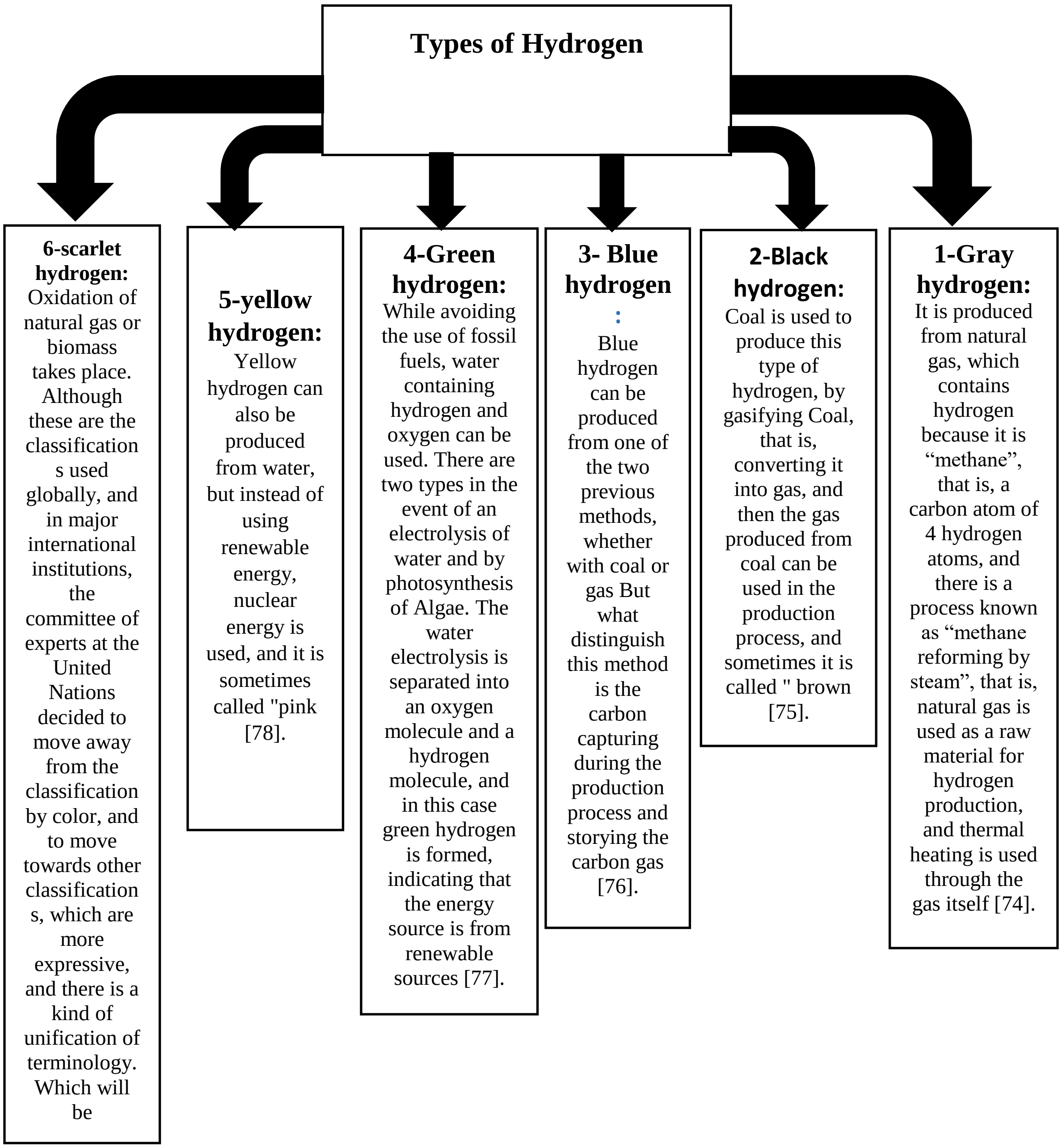

FIGURE 2. The six distinct types of hydrogen

NEW WAYS TO BOOST FUEL SUPPLIES OF THE FUTURE

There are various methods of producing hydrogen, including gasification of coal, biomass, electrolysis of water, photolysis, and nuclear energy. These methods differ in terms of efficiency, sustainability, and cost, with natural gas currently being the dominant source. However, the push towards the energy transition and advancements in technology suggest that more sustainable hydrogen production methods will play a vital role in future decarbonization efforts. The International Energy Forum has recently highlighted several new technologies for hydrogen production aimed at enhancing its role in carbon-intensive industries [12].

Natural Gas

Natural gas, mainly methane, is the most widely available, efficient, and cost-effective method for hydrogen production, accounting for approximately 70% of the world's hydrogen production and 95% of the total in the United States. Furthermore, taking advantage of the existing gas infrastructure makes it a favorable production method [13]. Hydrogen can be produced from hydrocarbon (mainly known as natural gas) by three techniques of chemical reactions such as; (i) partial oxidation, (ii) steam methane reforming, and (iii) autothermalre reforming [14]. The partial oxidation technique converts oxygen, steam, and hydrocarbon to yield hydrogen. Both catalytic and non-catalytic versions of this technique are possible. Hydrogen production with a high efficiency of roughly 74% was achieved using the steam methane reforming approach at an estimated cost of about $1.8/kg [15]. Furthermore, hydrogen production is considered a priceless commercial product [16]. The autothermalre reforming approach combines partial oxidation and steam methane reforming methods, where the partial oxidation method produces heat and the steam reforming method increases hydrogen production [17].

According to the report [18], hydrogen is typically produced by the steam reforming of methane. This process involves heating the gas at high temperatures in the presence of steam and a catalyst, causing methane molecules to decompose and form carbon monoxide and hydrogen. However, this method produces a significant amount of carbon dioxide, typically between 9 and 12 tons for every ton of hydrogen produced. As a result, this type of hydrogen is commonly referred to as gray hydrogen. New technologies are emerging to reduce emissions from hydrogen production, such as carbon capture and storage. Carbon can also be removed from steam methane reforming by utilizing heat from nuclear reactors instead of fossil fuels. Additionally, a new method involves the conversion of plastic waste to produce hydrogen. According to a recent study in Nature Catalysis, this method can extract over 97% of the mass of hydrogen from plastics through a simplified process [19].

Biomass

Gasification is a less sophisticated technology for producing hydrogen, which involves converting any carbon source or biomass into a gas using a high-temperature gasifier. Energy can be produced from various biomass resources, including energy crops, wood processing residues, agricultural crop residue, forestry residues, and industrial waste [20]. However, essential factors, including biomass type, steam/biomass ratio, temperature ranges, particle size, and catalyst types, influence the hydrogen production rate [21]. To produce hydrogen, energy production methods based on biomass are primarily divided into two categories: (i) thermochemical and (ii) biological. Thermochemical processes are divided into four categories: combustion, pyrolysis, liquefaction, gasification, and liquefaction [22, 23]. Generally, there are five categories for biological processes: photo fermentation, dark fermentation, direct biophotolysis, indirect biophotolysis, and biological water-gas shift reaction [24]. This gas then reacts with steam to extract the hydrogen. This method has proven to be very interesting for governments due to its potential to reduce the carbon intensity of hydrogen production. The US Department of Energy expects biomass gasification to be implemented soon. Liquids produced from biomass, such as ethanol and bio-oil, can also be utilized to generate hydrogen. This method has the advantage of being easier to transport than solid biomass feedstocks. Since biomass is a non-fossil resource and does not harm the environment, it is a promising alternative for hydrogen production [25].

Water Electrolysis

Hydrogen production through electrolysis, which involves splitting water molecules into hydrogen and oxygen, is gaining popularity as a means to reduce carbon emissions, particularly because most of these projects rely on renewable energy sources [26]. Typically, there are three categories of water electrolysis that can be performed under identical operating parameters depending on their ionic agents, electrolytes, and working conditions. The three types of water electrolysis methods include polymer electrolyte membrane water electrolysis [29, 30], solid oxide electrolysis [27, 28], and alkaline water electrolysis [31-33]. Although the current electrolysis technology used in hydrogen production is costly and ineffective, it is expected to become more affordable due to the implementation of policies that support the global energy transition. The International Energy Forum states that there are other technical methods for extracting hydrogen from water in the long term, but they require more work to improve and market. One such method is the thermal chemical cracking of water molecules using high temperatures. Another promising method is photoelectrochemical water splitting, which uses sunlight and semiconductors to extract hydrogen from water molecules [34].

The Contribution of Clean Hydrogen to the Energy Sector by 2050

With the urgent need to address the climate crisis and the increasing economic feasibility of renewable energy sources, clean hydrogen has received as a significant area of global interest. Fossil fuel exporting nations view blue hydrogen as an appealing opportunity to diversify their economies during the energy transition, whereas countries with ample renewable energy resources are advocating for green hydrogen production.

The International Renewable Energy Agency (IRENA) has estimated that clean hydrogen can play a significant role in reducing global carbon emissions by about 10% by 2050, and it will be a major contributor in transforming the energy sector. The agency has projected that hydrogen and its derivatives could account for up to 12% of final energy consumption by mid-century, based on the agency's 1.5°C temperature reduction scenario. These projections are similar to the International Energy Agency's scenario for achieving carbon neutrality by 2050. However, they are lower than the Hydrogen Council's estimates, which suggest that hydrogen will represent 22% of final energy use [35]. However, IRENA expects that the production of green hydrogen and its derivatives will represent 30% of the total electricity demand by the middle of this century [38]. The demand for electricity to produce hydrogen could reach 21,000 terawatt-hours in 2050, which is roughly equivalent to global electricity consumption at present. As for the green hydrogen market, IRENA estimates a potential market of $50-60 billion across the value chain of hydrogen electrolysis by 2050. According to the Najjar [36], the hydrogen fuel cell market is expected to be valued at around $21-25 billion by the middle of the century.

According to IRENA, green hydrogen production is expected to make up at least 66% of the supply, with the remaining 34% coming from blue hydrogen. The agency also anticipates that two-thirds of green hydrogen production will be consumed domestically by 2050, with the remaining one-third used in commerce. Additionally, there are various obstacles that must be overcome to ensure the widespread adoption of clean hydrogen. IRENA has identified several obstacles that hinder the widespread adoption of clean hydrogen in the energy transition. The primary hurdle is the high cost of producing hydrogen compared to carbon-intensive fossil fuels. Additionally, there is a lack of necessary technology to maximize the potential of clean hydrogen in the energy sector, and the process of producing and converting hydrogen results in significant energy losses at every stage. Furthermore, the shortage of renewable electricity and regulatory uncertainties are significant barriers to the development and adoption of hydrogen [37].

Paths of Producing Hydrogen

Hydrogen can be produced through various pathways, including the splitting of water using methods such as electrolysis, thermolysis, and photolysis, as well as through biomass processes such as biological and thermochemical operations. These methods are illustrated in Figure 3.

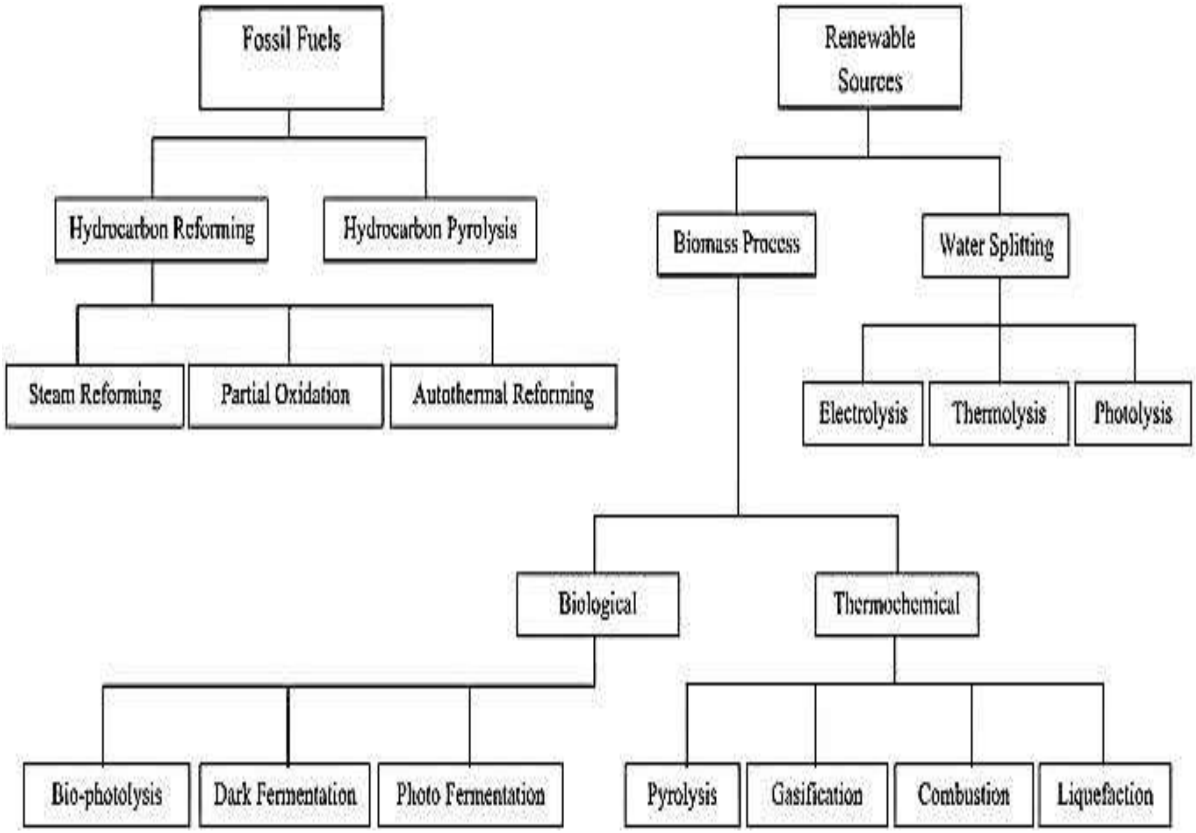

FIGURE 3. Methods for producing hydrogen

Hydrogen Production Mechanism by Electrolysis

Electrolysis of water has been a well-established technology for almost a century, with various applications in industries. It is a fundamental process that can be used to understand the mechanism of producing hydrogen through electrolysis of water and other methods. In the near future, it is expected that hydrogen production through electrolysis will continue to gain importance, with the use of hydroelectric converters on the rise [2]. One sustainable and established method for water electrolysis is low-cost alkaline electrolysis, which utilizes renewable energy inputs. However, preventing hydrogen/oxygen mixing and effectively utilizing unstable renewable energy sources pose significant challenges [40]. Figure 4 demonstrates the electrolysis mechanism for hydrogen production. The mechanism for producing hydrogen through electrolysis of alkaline water using nickel hydroxide as a redox intermediate involves the use of renewable energy. The process occurs at the cathode through water reduction, while $Ni(OH)_2$ at the anode is oxidized to NiOOH. The subsequent oxygen production involves the cathodic reduction of NiOOH, as shown by the equation: NiOOH → $Ni(OH)_2$ +H. NiOOH. During hydrogen production through electrolysis, NiOOH production can be coupled with a zinc anode to form a zinc battery with NiOOH-Zn. The discharge product, nickel (II) hydroxide ($Ni(OH)_2$), can be utilized again in the electrolysis mechanism. The electrolysis of water can be carried out under acidic or alkaline conditions at room temperatureThe procedure is carried out in an electrolyzer using a proton exchange membrane (PEM) under acidic circumstances. However, despite its benefits, such as great energy effectiveness and an elevated level of electrolytic production of hydrogen, the PEM faces difficulties because of the expensive cost of its membranes and catalyst[41]. The impact of pressure on water electrolysis has been studied [42]. The speed at which pressure is applied to water molecules determines the amount of energy required. An increase in pressure results in the need for more energy. However, by increasing the electric current, the same amount of voltage can be used. This is dependent on the amount of electrolyte used at the anode/cathode in the electricity generator. If a medium environment can be created, like in a car battery, for instance, the electric current will remain constant with respect to the medium, but not the atmosphere. Water molecules can cause refraction and/or reflex refraction, which can make the lightning energy more exciting than it is, leading to a slight increase in the electric current as it passes through the water molecule in the air and then bounces back. The strength of lightning is related to the number of times the energy of the bolt is magnified in the many series of reflections down the path of the electron. The higher the moisture, the greater the energy [43].

$$H_2O(g) + 2e- \rightarrow H_2\,(g) + O\,_2-$$

$$O\,_2- \rightarrow 1\ 2\ O_2\,(g) + 2e-$$

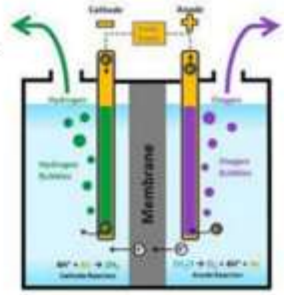

FIGURE 4. Hydrogen production mechanism by electrolysis

Thermochemical

The production of hydrogen through chemical reactions involves the interaction of certain chemicals with water. Through a series of reactions, the water is eventually converted into oxygen and hydrogen, while the chemical compounds involved return to their original state. There are various chemical compounds that can be utilized in the chain of reactions involved in hydrogen production [45]. Various thermal cycles, including those utilizing natural gas and coal, play a significant role in hydrogen production. Certain thermal processes involve closed chemical cycles that use heat to produce hydrogen from primary resources like sulfur iodine and iron chlorine. However, even after the production of hydrogen via these reactions, the series of interactions does not come to an end, and it becomes necessary to complete the series of reactions [46]. The sulfur iodine cycle is a thermal chemical cycle used to produce hydrogen. Sulfur is decomposed into oxygen, water, and sulfur dioxide at a high temperature of around 850°C. The oxygen and sulfur dioxide are then separated, and the sulfur dioxide is reacted with iodine water to produce sulfuric acid and hydrogen. The sulfuric acid is separated and removed, and the remaining hydrogen is heated to around 300°C to break the bonds between hydrogen and iodine, resulting in the production of oxygen and hydrogen from water. This process is repeated by recycling the sulfuric acid and iodine used in the reaction [47]. Steam reformation is a commonly used thermal process for hydrogen production as displayed in Figure 5, which involves the reaction of steam with a hydrocarbon fuel at high temperatures. Hydrogen is able to be produced from a variety of fuels made from hydrocarbons, including petroleum, natural gasoline, diesel, sustainable liquid fuels, charcoal, or invasive flora. Presently, 95% of all thermal hydrogen generation comes from the steam reformation of natural gas. [48].

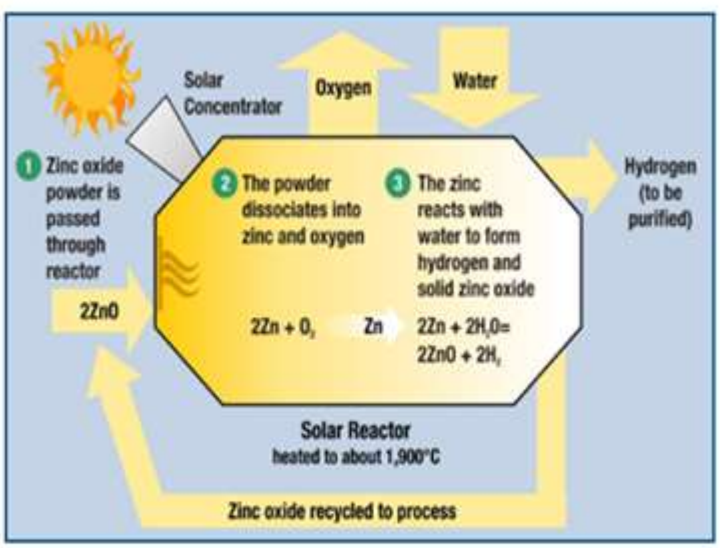

FIGURE 5. Thermal processes of hydrogen production

Hydrogen Production by Exploiting the Sources of Renewable Energies

There are several common methods of hydrogen production and that use renewable and exploitable energies as displayed in Figure 6. The wind and solar energy are the sources of renewable energies that are most exploited and can be used as vital transfers for energy supplies, and that development in techniques to generate electric energy from these two sources [50]. The Rural-Hydrogen System is a symbolic scheme that illustrates the use of wind energy to produce electricity and hydrogen. This system utilizes electrolysis to split water molecules into oxygen and hydrogen. The excess electrical energy generated by wind turbines is used to power the electrolysis process, producing hydrogen gas that can be stored for later use. This method is considered environmentally friendly as it does not produce any emissions or contaminated gases [51]. The analysis of water using solar energy is a widely used method for hydrogen production, as it is a cost-effective and environmentally friendly approach. Solar energy is utilized in the electrolysis process, making it one of the most efficient methods for hydrogen production. Moreover, this method is considered one of the simplest ways to generate hydrogen [51].

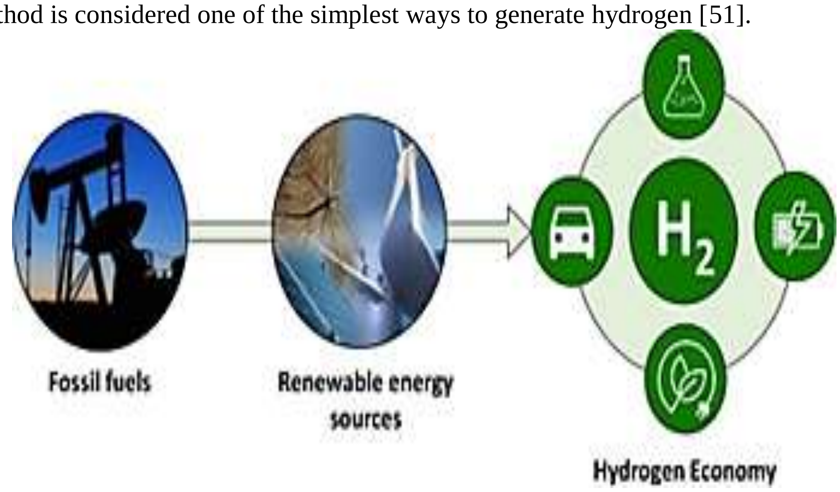

FIGURE 6. Hydrogen production by exploiting

Biological

Biomass can be used as a source of hydrogen production since its conversion to hydrogen results in emissions of 2CO. Figure 7 displays the hydrogen production by biological method. It can be produced in several ways such as supplying 2CO and H, and after purification, hydrogen is obtained. Currently, more than 50 stations worldwide are using biomass to produce hydrogen, even though it is not the primary method of hydrogen production [53]. The utilization of certain microalgae or cyanobacteria in the analysis of their organic compounds can result in hydrogen production. This hydrogen can then be utilized or transferred through a pipeline network. Scientists and developers are encouraging efforts to further explore this field [54]. Biomotopia represents a significant portion of global hydrogen production, with coal being a primary material used in the process. This method involves mixing charcoal in either solid or clay form with air oxidation or pure oxygen and water vapor to produce hydrogen, which is equivalent in energy to the coal used [55]. While, the Biomocopting involves two phases for hydrogen production: optical composition and hydrogen stimulation using microalgae and blue bacteria. If successful, it can result in renewable hydrogen production. It is crucial to understand the natural genetic systems involved in hydrogen production and to use genetic science to validate this method. Another option is to repeat the two steps using optical composition [56].

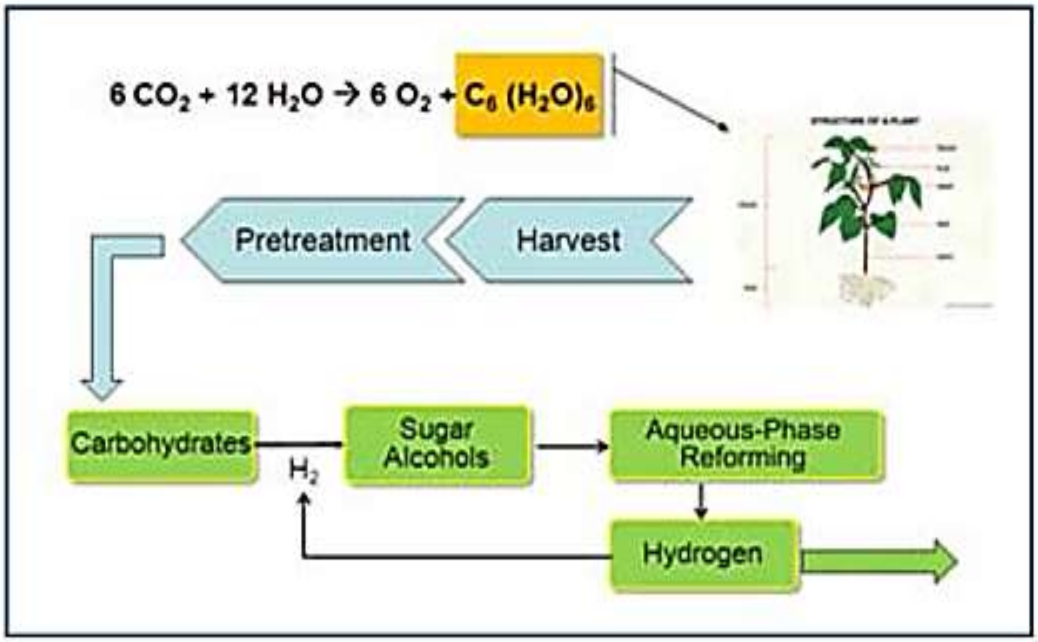

FIGURE 7. Hydrogen production by biological method

Nuclear Energy

In recent years, researchers have been studying a method called nuclear reaction to produce hydrogen without emitting greenhouse gases, as depicted in Figure 8. This method requires an increase in heat flows and consumes less electricity. Although hydrogen production through electrolysis of water using electricity is not as efficient, it is a more environmentally friendly and sustainable long-term solution. However, traditional electrolysis methods require about 850°C and limited reserves of electricity, making it important to develop nuclear energy technology in terms of cost and sustainability [57].

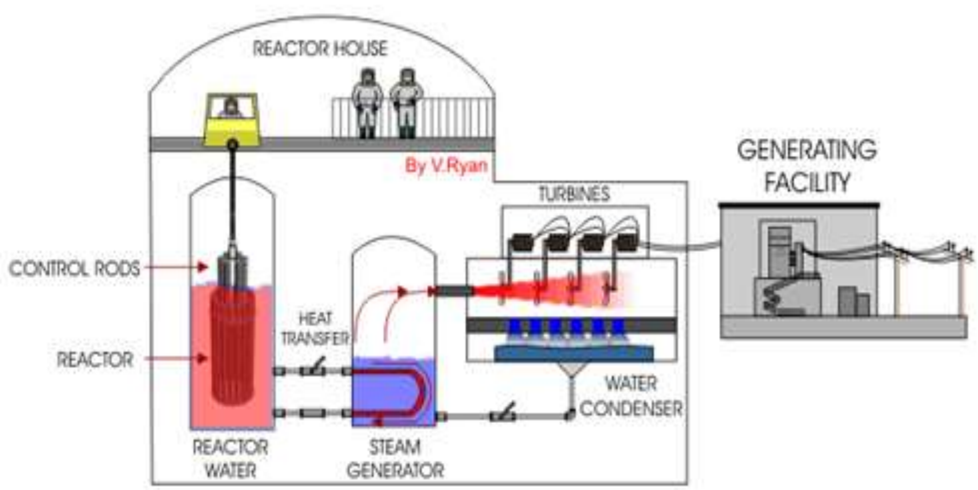

FIGURE 8. Hydrogen production by nuclear energy

Thermal Method

This method of hydrogen production involves the thermal disassembly of water, which can be achieved in two ways. The first method involves heating water to a very high temperature, over 2500 degrees, causing it to disintegrate into oxygen and hydrogen. However, producing a significant amount of hydrogen using this method requires high temperatures and materials that can withstand such heat, making it costly and difficult to implement. As a result, this process is often not considered desirable [55]. The water is heated at a temperature of about 5,000 ℃ using the plasma arc process, causing it to be disintegrated into its products, and the percentage of hydrogen production of the mixture is estimated to be about 50% of its size. This process is considered very expensive compared to other methods of hydrogen production [58].

A Critical Comparison of Hydrogen Production Paths

The production of hydrogen can be categorized based on various factors such as production conditions, type of sources used (renewable or fossil), logistical factors, and variable costs. Tables 1 and 2 illustrate the different production methods and their associated costs, while Figure (8) provides a clear picture of the production efficiency and cost for each method, taking into account the use of alternatives in the production processes.

TABLE 1. Various generation of hydrogen techniques and their benefits, , costs, as well as effectiveness

Hydrogen production Method	Benefits	Drawbacks
Steam Repair	Technology advancements and current structures	Production CO, CO_2 Unsettled supply
Partial Oxidation	Reliable technology	Manufactured coke from petroleum and heavy-oil products alongside H2 Manufacturing.
Auto thermal Repairing	Current infrastructure and technology that is long-standing	Produced CO_2 as a byproduct,
Bio photolysis	Consumed CO_2, Produced O_2 as a byproduct, working under mild conditions.	Poor H2 productivity, dependence on sunshine, demand for big reactors, sensitivity to O2, and expensive materials.
Dark Fermentation	Simple approach, H_2 produced no light, no determination O_2, CO_2-neutral, include to trash recycling	Fatty acids elimination, Poor H2 production, poor effectiveness, and the need for a large reactor capacity
Photo Fermentation	Include to trash water recycling, utilize various organic waste waters, CO_2-neutral.	sunshine is necessary for poor efficiency and poor H2 generation level.
Gasification	Plentiful, affordable feedstock, and neutral CO2.	Fluctuating H_2 yields because of contaminants in the fuel, seasonality accessibility, and tar production.
Pyrolysis	Abundant, cheap feedstock and CO_2-neutral.	Tar production and varying H2 levels as a result of substrate impurity
Thermolysis	Clean and sustainable, O_2-byproduct, copious feedstock	Large expenditures on capital, hazardous elements, and corrosion issues.
Photolysis	O_2 as byproduct, abundant feedstock, No emissions.	Needs sunshine; low performance; ineffective photo catalytic substance.
Electrolysis	Dependable technology 0 emissions the result of current infrastructure is O2	Issues with storage and shipping.

TABLE 2. Chosen hydrogen generation techniques, together with their prices and output competences

Manufacturing Process	Cost, $/kg	Operational effectiveness, %
Electrolysis	10.3	70
Thermolysis	7.8	35
Photolysis	9	0.1
Dark fermentation	2.5	70
Gasification	2	35
Photo fermentation	2.8	0.1
Steam reforming	2.2	85
Pyrolysis	1.6	45
indirect bio photolysis	1.4	0.1
Direct bio photolysis	2.1	1
Solar thermal electrolysis	7	1
Solar thermolysis	7.5	1
Wind electrolysis	5.9	1
Photo-electrolysis	10.4	0.1

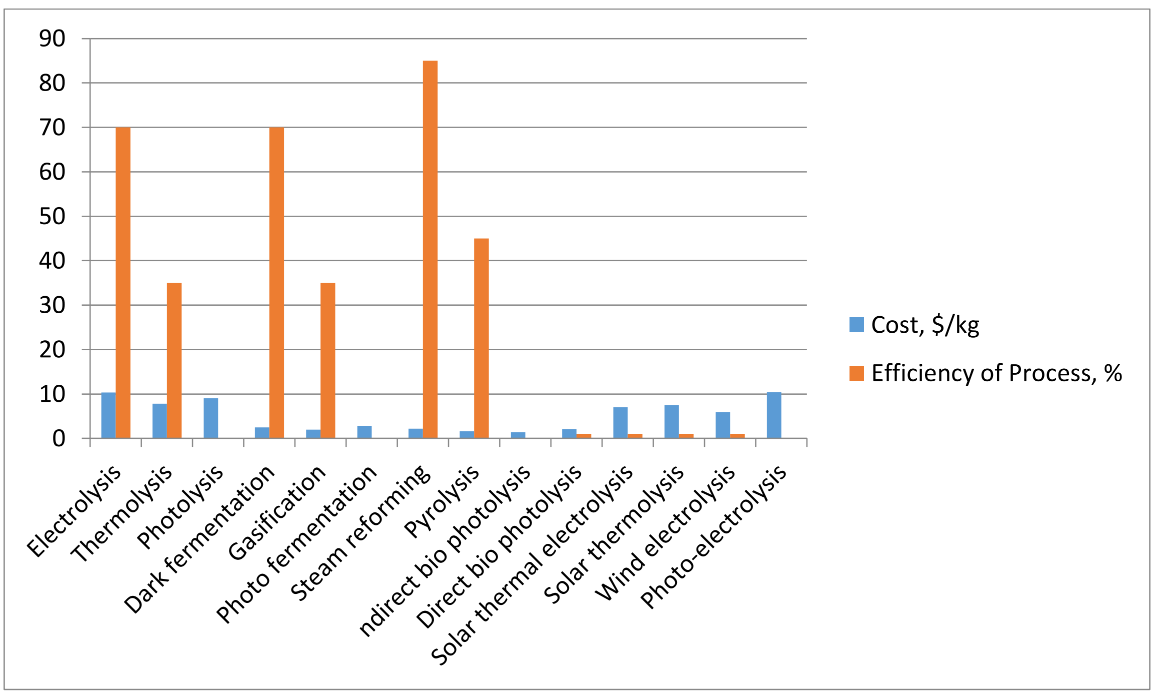

FIGURE 9. Price and manufacturing capabilities of various hydrogen manufacturing techniques

Environmental Impact of Hydrogen Production

This research highlights the previous work on hydrogen production methods and their environmental impacts. The importance of improving the efficiency of hydrogen production methods to reduce resource depletion and increase productivity is considered. To cut down on energy use, emissions of greenhouse gases, and impact on the environment, hydrogen manufacturing should use sustainable energy sources like wind and solar power. The modern advancement in hydrogen production using various augmentation techniques is reported in the literature. Furthermore, finding the approaches to lower water usage in hydrogen production that can aid in mitigating the environmental consequences of water depletion is discussed. This study will address the research gap in the most recent hydrogen generation strategies to assist future researchers. The main significant critical insights from this review research are (i) the new ways to boost fuel supplies in the future, (ii) paths of producing hydrogen, (iii) a critical comparison of hydrogen production paths, and (iv) the environmental impact of hydrogen production.

The environmental impact of hydrogen production methods must be carefully evaluated before selecting a production method. There are several common methods for producing hydrogen, each with its own set of environmental impacts. Table 3 displays the environmental impact of different methods of hydrogen production. It is worth noting that the environmental impact of each method can vary depending on the specific details of the process, such as the type of feedstock or energy source used, as well as the location and management of the production facilities.

TABLE 3. Comparing the environmental impact of different methods of hydrogen production

Production Method	Environmental Impact
Steam Methane Reforming (SMR) [62][63]	• Significant greenhouse gas emissions, including carbon dioxide • Depletion of natural resources, such as water and natural gas • Negative impacts on local ecosystems and communities • Generation of air pollutants, such as nitrogen oxides
Electrolysis using Renewable Energy [64] [65][66]	• Low greenhouse gas emissions • Renewable energy sources (e.g. wind, solar) do not deplete natural resources • Minimal negative impacts on local ecosystems and communities • No generation of air pollutants
Biomass Gasification [67] [68]	• Lower greenhouse gas emissions compared to SMR • Use of biomass as a renewable feedstock • Minimal negative impacts on local ecosystems and communities • Generation of air pollutants, such as nitrogen oxides and particulate matter
Nuclear Hydrogen Production [69][70]	• Low greenhouse gas emissions • Depletion of uranium resources • Nuclear waste management concerns • Potential negative impacts on local ecosystems and communities
Photoelectrochemical Water Splitting [71][72][73]	• Low greenhouse gas emissions • Use of renewable energy sources, such as solar energy • Minimal negative impacts on local ecosystems and communities • High cost and low efficiency compared to other methods

CONCLUSIONS AND FUTURE PERSPECTIVE

The potential of hydrogen as an energy carrier is well-known for reducing greenhouse gas emissions from fossil fuels used in power generation. A comprehensive study was conducted to review modern technologies and methods for producing clean hydrogen, as well as challenges that hinder the growth of the hydrogen economy. Hydrogen production offers several benefits, including its clean nature and the possibility of creating a distributed hydrogen supply network model. However, there are obstacles that need to be addressed to promote the expansion of the hydrogen economy, such as the lack of infrastructure for hydrogen cleaning, transportation, and storage, as well as investment risks and production costs. Researchers are encouraged to explore the use of minerals and catalysts to reduce the electrical potential required in water electrolysis cells, thereby reducing the cost of hydrogen production.

Future studies should prioritize evaluating the efficiency of various clean hydrogen technologies, For instance, the application of acoustic and pulsing fields of electricity to enhance production efficiency. It is also important to investigate the use of different materials such as polyamides, polyether ketone, and polyethylene to improve hydrogen production processes. Additionally, research can focus on commercializing hydrogen production based on renewable energy sources and understanding the complex phases of bio hydrogen production to enable large-scale implementation. Governments can assist in managing these projects by co-financing them. It is advised to carry out additional research on the mechanics and reaction processes of the generation of hydrogen in order to choose the best strategy.There is also a need for the development and enhancement of biological processes to produce hydrogen in larger quantities.

RECOMMENDATIONS

Based on the literature, there are several recommendations that should be considered.

1. Encourage the use of renewable energy sources for hydrogen production, such as solar or wind power, to reduce greenhouse gas emissions and environmental impact.
2. Highlight the importance of improving the efficiency of hydrogen production methods to reduce resource depletion and increase productivity. Many hydrogen production methods are currently not very efficient, meaning they require large amounts of energy to produce relatively small amounts of hydrogen. Improving the efficiency of these methods could help reduce energy consumption and associated environmental impacts.
3. Minimize water consumption, as many hydrogen production methods demand significant amounts of water, which may be scarce in certain regions. Identifying approaches to lower water usage in hydrogen production can aid in mitigating the environmental consequences of water depletion.
4. Reducing greenhouse gas emissions is crucial in hydrogen production methods that rely on fossil fuels, like SMR, as they generate significant amounts of such emissions. To lessen the generation of hydrogen's harmful effects on the natural world, it is recommended to minimize these emissions through carbon capture and storage or alternative production methods.
5. Discuss the need for further research and development in hydrogen production technologies to identify more sustainable and environmentally friendly methods.
6. Advocate for the implementation of government policies and incentives to promote the adoption of sustainable hydrogen production methods.

Encourage the collaboration between researchers, industries, and policymakers to develop and implement more sustainable hydrogen production methods.

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