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Review

A Brief Review of Hydrogen Production Methods and Their Challenges

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Abstract: Hydrogen is emerging as a new energy vector outside of its traditional role and gaining more recognition internationally as a viable fuel route. This review paper offers a crisp analysis of the most recent developments in hydrogen production techniques using conventional and renewable energy sources, in addition to key challenges in the production of Hydrogen. Among the most potential renewable energy sources for hydrogen production are solar and wind. The production of H_2 from renewable sources derived from agricultural or other waste streams increases the flexibility and improves the economics of distributed and semi-centralized reforming with little or no net greenhouse gas emissions. Water electrolysis equipment driven by off-grid solar or wind energy can also be employed in remote areas that are away from the grid. Each H_2 manufacturing technique has technological challenges. These challenges include feedstock type, conversion efficiency, and the need for the safe integration of H_2 production systems with H_2 purification and storage technologies.

Keywords: hydrogen; blue hydrogen; green hydrogen; grey hydrogen; electrolysis

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1. Introduction

The tremendous worldwide economic and demographic growth that is taking place is behind the rise in energy demand. Power generation plays a significant role in each country's industrial development. Fossil fuels provide for a sizable portion of the expanding energy demand; nevertheless, these conventional sources are in a very difficult situation because of their quick depletion. Increased global warming and CO_2 emissions are the main side effects of exploiting these traditional fossil fuel resources [1]. Renewable energy sources are the most likely candidate to replace these conventional fuels because of the escalating environmental problems. Due to increased greenhouse gas (GHG) emissions, environmental concerns and global warming, the globe must transition from conventional to renewable energy sources.

Renewable energy sources including solar, wind, hydro, geothermal, ocean thermal energy conversion (OTEC) and biomass are the leading candidates to replace fossil fuels [2]. Hydrogen can make the most of these resources and be utilised not just as fuel but also as an energy transporter and a storage medium because certain attractive renewable energy sources, such as solar and wind, are sporadic. In order to attain net-zero CO_2 emissions by 2050, it could also be crucial to decarbonize the main industries [3]. Hydrogen is becoming more known on a worldwide basis as a distinct energy source and possible fuel due to its carbon-free solutions.

The infrastructure for fuel storage and transportation that is now used for other chemical fuels is also considered as a potential option for hydrogen storage and delivery.

Clean hydrogen may be produced using a variety of home energy sources, including nuclear energy [4], natural gas [5], coal gasification [6], and renewable energy sources including solar [7], wind [8], biomass [9], geothermal [10], hydro [11] and OTEC [12].

Figure 1 depicts the proportion of the world's energy supply. A massive 35% of the world's energy supply comes from coal, followed by a 23% share from gas, 16% from hydropower and 10% from nuclear. Renewable energy sources contribute around 13%, which includes 7% from wind energy, 4% from solar, around 2% from Hydrogen and the rest from biomass and biogas. Annual CO_2 emissions from different types of fuels are shown in Figure 2.

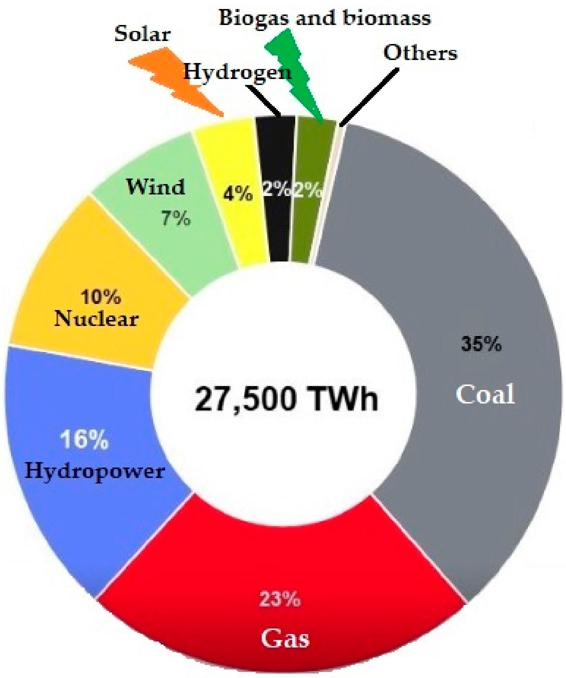

Figure 1. Global share of energy sources 2021 [13].

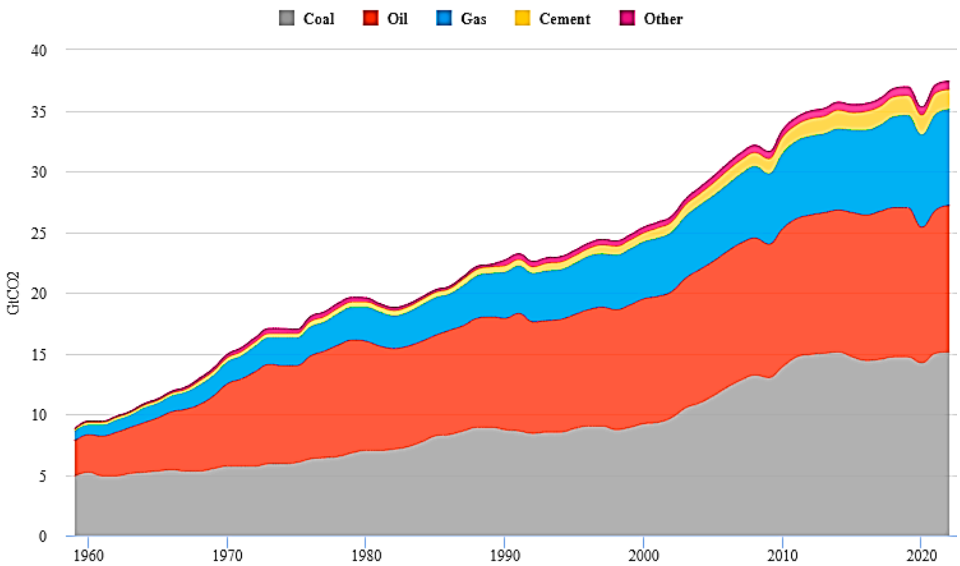

Figure 2. Annual CO_2 emissions from different types of fuels [14–16].

Coal, oil and gas combustion are the main sources of global emissions from fossil fuels. In 2022, coal will account for 40% of all global emissions from fossil fuels, more than any other fossil fuel. Gas production comes in third with a contribution of 21%, followed by cement production with a contribution of 4% and oil with a contribution of 32% of fossil CO_2. Presently the contribution of Hydrogen in the energy sector is negligible and when hydrogen is produced from renewable energy sources the net CO_2 emission is much lesser compared to other fuels. These percentages account for both the global use of each fossil fuel as well as variations in CO_2 intensity. Oil and gas are the next highest emitters of CO_2

per unit of heat or energy generated after coal. As depicted in Figures 1 and 2, oil, coal and natural gas are traditional energy sources that dominate the world's energy supply, power production and CO_2 emissions.

A modern and almost established energy source is Hydrogen [17–19]. Table 1 lists comparisons of the main technical parameters of hydrogen with other fuels.

Table 1. The main technical characteristics of hydrogen vs. other fuels [20–23].

Parameter	Hydrogen	Diesel	Methane
Density at STP (kg/m^3)	0.089	830.0	0.720
Volumetric energy at STP (MJ/m^3)	1.07×10	3.5×10^4	3.3×10
Net Lower Heating value (MJ/kg)	119.9	42.5	45.8
Boiling point (K)	20.0	453–633	111.0
Auto-ignition temperature (K)	853	~523	813
Minimum ignition energy in air at 1 bar & stoichiometry (mJ)	0.020	0.240	0.290
Stoichiometry air/fuel mass ratio	34.4	14.5	17.2
Quenching distance at NTP (mm)	0.64	-	2.1
Laminar flame speed in air at NTP (m/s)	1.85	0.37–0.43	0.38
Diffusion coefficient in air at STP (m^2/s)	85×10^{-7}	-	19×10^{-7}
Flammability limits in air (% vol)	4–76	0.6–5.5	5.3–15
Adiabatic flame temperature at NTP (K)	2480	~2300	2214

Among all other fuels, whether they be liquids or gases, hydrogen delivers the fastest burning rate. The hydrogen fuel cells provide a high-performance indication in terms of efficiency since they are not limited by the thermal Carnot cycle's thermal efficiency restrictions. In order to support hydrogen-powered fuel cell and fuel cell-based hybrid automobiles, it is anticipated that a significant quantity of H_2 refuelling stations will be built in 2022. Some of the key benefits of hydrogen include: effective conversion of energy; production through water splitting with no carbon emissions; synthesis of various intermediate fuels, including synthetic fuels and ammonia, followed by various chemical reactions; storage availability; ability to use in existing infrastructure for long-distance transportation; and a high LHV in comparison to other fuels.

Around the world, funding is already being considered for several hydrogen-based initiatives. To study offshore hydrogen generation, for instance, the OYSTER group was given 5 million euros [24]. Air Liquide [25] just put into operation the biggest green hydrogen generation facility in the world located in Quebec, Canada and generating up to 8.2 tonnes of green hydrogen a day (or around 3000 tonnes/annum). Although several green-hydrogen entrepreneurs have gigawatt-scale goals, the sector is still in its infancy. As a result, both the public and commercial sectors are making investments in the developing offshore wind hydrogen/ammonia industry.

Germany is planning a ground-breaking tender [26] for an offshore wind-hydrogen pilot in 2022 in order to achieve this. For experimental projects in the nation's exclusive economic zone in the North Sea, Berlin has contributed 58 M. 5 million euros, given to the EU-based OYSTER collaboration to study offshore hydrogen production [27]. To perform a feasibility study on the ship-to-ship bunkering of green ammonia at the Port of Singapore, Maersk has inked a contract with a number of other foreign businesses [28]. The Nordic Green Ammonia Powered Ships (NoGAPS) project [29], worth NOK 8 million, was developed by the Nordic maritime sector with the goal of decarbonizing the transport of people and goods at Nordic ports and between sea and land. This was carried out in order to bring shipping in line with the Paris Climate Agreement. To make green hydrogen commercially viable, the government has unveiled 38 policies [30].

Recent research [31] has provided a comparison of several methods for producing hydrogen using renewable energy. In order to provide an economic and environmental evaluation study for the production of hydrogen utilising various feedstocks, such as biomass, biogas, ethanol, and natural gas, a review study on the steam reforming method (SMR) for hydrogen generation was published [32]. A review of solar thermal methane reforming to create syngas and hydrogen was also published [33]. In order to deploy a transition path towards a solar powered hydrogen economy and for the decarbonization of fossil fuels, a solar-powered steam methane reforming process was proposed as a solution.

For the first time, a straightforward and affordable approach for $NaBH_4$ regeneration without hydrides as starting materials for the reduction process has been created. Instead of using dehydrated sodium metaborate ($NaBO_2$), the actual hydrolysis by-products ($NaBO_{22}H_2O$ and $NaBO_{24}H_2O$) can be used to regenerate $NaBH_4$ with magnesium at ambient temperature and atmospheric pressure. The $NaBH_3(OH)$ intermediate chemical is effectively detected, and the regeneration process of $NaBH_4$ is made clear for hydrogen storage, as reported in [34].

Because the hydroxylation process can produce high-purity H_2 at room temperature with predictable kinetics, sodium borohydride ($NaBH_4$) is one of the most researched hydrogen storage materials. However, it has proven difficult to regenerate $NaBH_4$ from the hydrolytic product [34]. There is now information on a simple process that produces high yields of $NaBH_4$ at little cost. Under ambient circumstances, the hydrolytic product $NaBO_2$ in aqueous solution combines with CO_2 to produce $Na_2B_4O_{710}$ H_2O and Na_2CO_3, both of which are ball-milled with Mg to produce $NaBH_4$ in a high yield (near to 80%) [35].

We provide a simple and inexpensive process for the regeneration of $LiBH_4$ by ball milling $LiBO_{22}H_2O$, the hydrolysis by-product and Mg in ambient settings, where expensive H held in LiBH4 is completely converted from inexpensive H+ in coordinated water. This scenario, which does not use hydrides as hydrogen sources for the reduction process, is described for the first time. Furthermore, this approach may produce yields of up to 40% for $LiBH_4$ synthesis. Compared to prior research utilizing $NaBH_4$ as the raw material, the cost of $LiBH_4$ regeneration has been reduced by five times. The as-purified product, which is significant, has even better physicochemical characteristics than commercial $LiBH_4$, such as improved hydrolysis kinetics. Overall, a closed cycle that combines hydrogen synthesis and storage in one phase has been reported in [36].

Different methods of Hydrogen generation are available in different studies, but to understand the different methods of Hydrogen generation and its hurdles at a glance, a brief literature review is required. This paper provides a thorough analysis of the generation methods as well as the main hurdles in the generation of Hydrogen. Due to its versatility as a fuel, energy storage medium, catalyst for the synthesis of methanol and ammonia, and energy carrier, among other things, hydrogen is the leading contender to meet the fluctuating nature of solar and wind renewable energy sources. Due to increased interest in hydrogen applications, a detailed examination of hydrogen generation is necessary. This evaluation must also include the key factors concerning renewable energy-powered hydrogen generation devices. This review study is presented using a strategy that starts with currently available resources (both renewable and conventional), particular techniques (such as hydrogen production by thermochemical cycles, water electrolysis, and coal and natural gas reforming) and technical advances of Hydrogen generation. Additionally, this research review offers a helpful and comprehensive source for research, scientific advancement, and innovation in the fields of hydrogen generation utilizing conventional and renewable energy sources and commercialization hurdles.

2. Methodology

Based on particular keywords, the evaluated literature was chosen. A thorough strategy was used to analyse and compile the most reliable and pertinent papers for the study. This is because a good literature review creates the foundation for knowledge and theory development. On content delivery, a thorough assessment of the literature was conducted.

As shown in Figure 3, the process included five major searches on hydrogen production, including blue hydrogen, purple hydrogen, turquoise hydrogen, grey hydrogen, and green hydrogen.

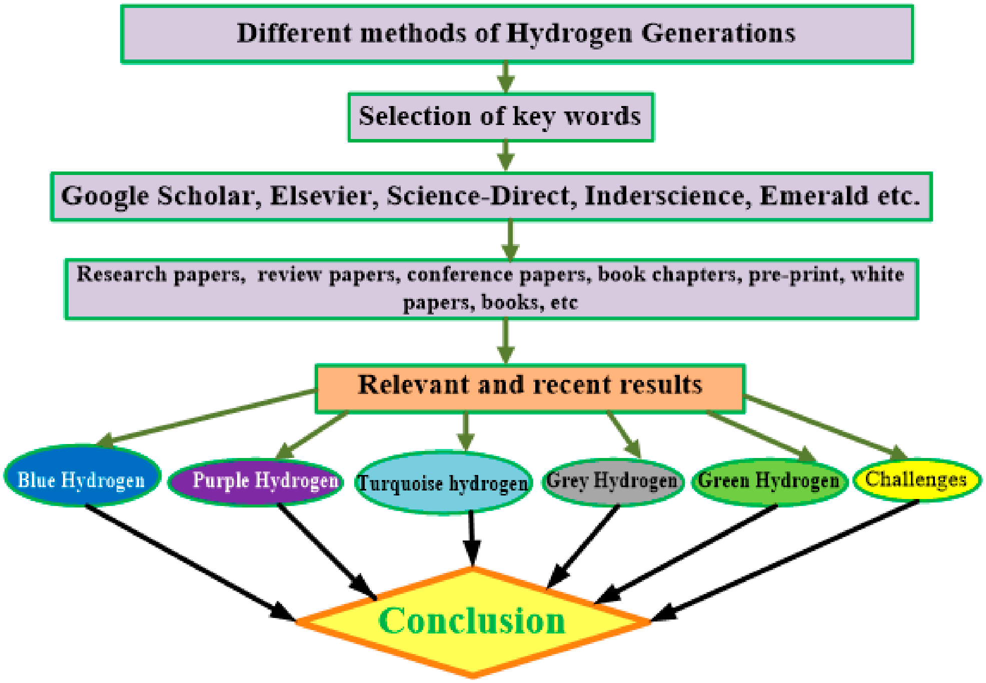

Figure 3. Schematic methodology of the review.

In the initial phase of the information gathering process, research articles, abstracts and unpublished materials were acquired from Google Scholar, Elsevier, Science-Direct, IEEE, Springer, Taylor Francis, Wiley, Inderscience and Emerald. A sizable amount of material was found by searching for the terms “hydrogen production”, “hydrogen generation”, “hydrogen from renewable energy sources” and “hydrogen from biomass”. To discover the most pertinent material from well-known sources, the second stage was designed. Only appropriate items were selected for additional processing at the conclusion of the second round. Academic publications and peer-reviewed articles were taken into account. Abstracts and unpublished articles were not considered. The year of publication was utilized to reduce the number, and the majority of the literature taken into consideration is from the last three years (2019–2022). Since they featured the most recent data, the most recent publications were chosen for the inquiry. The content, methodology and the appropriate keywords used to choose the best papers for the study were additional selection criteria. Since they ensured a complete assessment of the literature and offered more information on the study issue, systematic reviews and meta-analyses were recommended. The third stage involved looking over and classifying the information based on the type of paper, the year of publication and its application to different parts of the article.

3. Hydrogen Production

Hydrogen production may be categorised into three main groups: green (based on renewable energy), blue (based on coal gasification and natural gas, along with CCS hydrogen generating systems) and red (based on fossil fuels alone) (based on conventional fossil fuels). Green hydrogen may also be created utilising renewable energy sources, despite the fact that the majority of it is currently produced via the CO_2-intensive steam methane reforming process. Electrolysis is a typical method that uses an electrical current to separate water into oxygen and hydrogen and creates green hydrogen without any direct emissions of carbon dioxide. Renewable energy sources may be used to produce the necessary electricity. The expense of producing hydrogen, particularly for green hydrogen, is a significant hurdle. The cost of manufacturing hydrogen using steam reforming is around three times greater than the cost of producing one unit of energy using natural gas. Hydrogen will cost almost twice as much to produce using electrolysis with 5 cents/kWh of energy compared to hydrogen produced using natural gas. Lower hydrogen concentrations may be transported via the existing natural gas pipeline infrastructure, which will also assist in reducing CO_2 emissions from the existing natural gas reforming plants.

There are a number of factors drawing attention to hydrogen fuel, but the following are the most important ones:

- Different energy sources can be used to produce hydrogen.
- Since hydrogen is the least polluting, using hydrogen in fuel cells or combustion processes results in the production of water.
- All energy needs may be met by hydrogen, which is also utilised in residential applications, hydrogen fuel cell automobiles, energy carriers, and integrated heating and power generation systems. Hydrogen also covers all requirements for energy

By using off-grid offshore wind energy to generate clean fuel (hydrogen/ammonia), hydrogen may significantly contribute to the decarbonization of the marine sector. Energy may be transported and potentially stored by hydrogen, which is the best substance for both. Some important hydrogen generation techniques include: landfill gas dry reformation; coal gasification; H_2S methane reformation; naphtha reformation; methane/natural gas pyrolysis; steam-iron process; steam reforming of waste oil; partial oxidation of heavy oil and coal; grid electrolysis of water; high-temperature water electrolysis; chloralkali electrolysis; solar and PV water electrolysis; photolysis of water; and biomass gasification.

According to the literature and study reports [34,35], there are three main forms of hydrogen generation based on the use of various technologies and proposed sources. The idea of colour has been developed as a result of the use of important sources in the generation of hydrogen. The production of hydrogen from fossil fuels results in the release of CO_2 and other greenhouse gases. Grey hydrogen is the term used to describe this method of producing hydrogen and its used source [36]. Blue hydrogen came into being as a result of the use of grey hydrogen with carbon capture technology to lower the quantity of greenhouse gas emissions [37,38]. In order to produce hydrogen for sustainable transportation, fossil fuels including industrial gas, by-product gas and natural gas typically release pollutants and greenhouse gases into the atmosphere [39–41]. A variety of technical advancements for hydrogen generation have been documented in the literature as a means of reducing the pollutants released into the environment. Therefore, recent literature [42–44] has reported on the use of renewable energy resources for hydrogen production. Green hydrogen is another by-product of electrolysers made from renewable energy sources. It has also been noted that bioenergy sources such as the burning of biomass and biomethane can also create green hydrogen. Researchers and businesses are paying increasing attention to the improvement of green hydrogen generation, since green hydrogen produced using diverse approaches has net zero gas emissions [45,46].

3.1. Blue Hydrogen Production Methods

Current conventional hydrogen production facilities integrate carbon capture and storage (CCS) or carbon capture and utilisation (CCU) systems to collect the discharged CO_2 emissions. Alternately, to fulfil the worldwide need for hydrogen, which is currently being satisfied by renewable energy sources, conventional hydrogen production pathways are employed. These approaches provide a sizable part of hydrogen. The majority of conventional hydrogen is produced from fossil fuels, mainly by partially oxidizing methane and reforming natural gas. Unprocessed natural gas contains gaseous hydrogen sulphide (H_2S), which is removed from the gas during the first stage of processing by desulfurization. The Claus procedure is used to extract sulphur from gaseous H_2S. In Claus plants, the gaseous hydrogen sulphide generated interacts with oxygen gas to extract sulphur. Another common technique for producing hydrogen is coal gasification. Air separation is the initial phase, which extracts oxygen from the air and delivers the same to the gasifier. One of the three frequently used methods for air separation: membrane separation, cryogenic air separation, or pressure swing adsorption, is employed. Coal pyrolysis follows the air separation process. In order to gasify coal, the pyrolysis stage needs two inputs: steam and oxygen. Coal is broken down into volatile and char in this process. The process of quenching, which applies fast cooling, comes after the gasification stage [47]. The next step is a cooling unit for the syngas, where heat is collected for syngas and may be utilised for a variety of things including electricity generation, hot water production, and space heating. The watergas shift reaction comes after the syngas cooling unit, which converts CO into CO_2, the component that prior to the water gas shift process separates hydrogen sulphide (H_2S) and carbon dioxide (CO_2). After the hydrogen purification unit, there is an acid gas removal step where hydrogen is frequently separated from other gases using the pressure swing adsorption technique. The blue hydrogen production method is depicted in Figure 4.

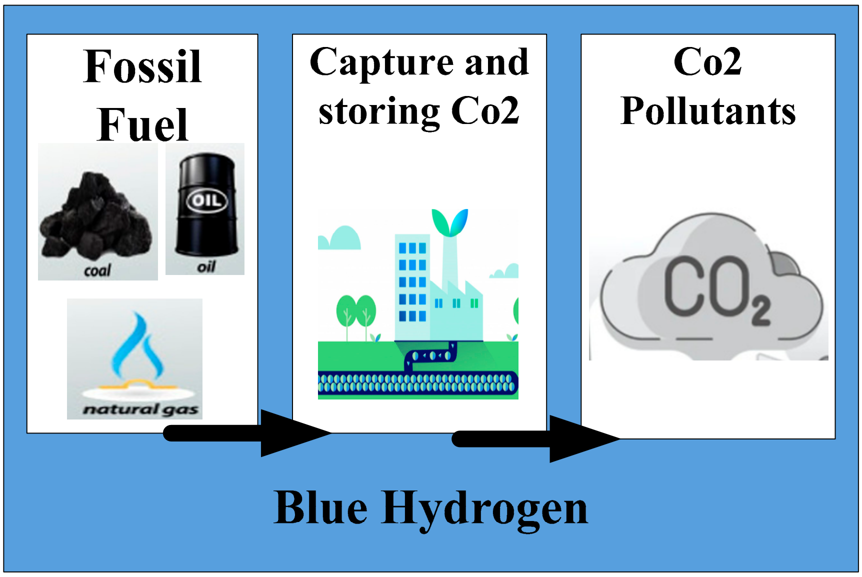

Figure 4. Schematic of Blue hydrogen production.

3.2. Purple Hydrogen Production Method

Purple hydrogen is produced using nuclear energy, and other forms of hydrogen may be produced using thermochemical processes thanks to the high temperatures of the nuclear reactor. The fission of uranium atoms produces nuclear energy. Heat from nuclear energy is used to create steam, which is then used in turbines to create electricity [48,49].

Nuclear power plants do not directly burn fuel; thus, they do not emit any greenhouse gases in that way. Because it can be controlled in the reactors used in nuclear power facilities, fission reaction is utilised. The fission process in the nuclear reactor serves as the heat source for the thermal energy in a nuclear power plant [50–54]. Nuclear reactor heat is used to make steam, which is subsequently utilised in a turbine to produce electricity using a generator similar to conventional stations that produce thermal energy. Nuclear energy is created by the nuclear reactor's atoms splitting process, which transforms water into steam and drives a turbine to generate electricity. The most popular way to use this thermal energy is to turn a turbine to generate electricity, which may then be used to power fuel cells to create hydrogen [55,56]. Other ways to use this thermal energy include steam reforming techniques, water electrolysis for the creation of hydrogen, and thermochemical water splitting cycles.

3.3. Turquoise Hydrogen

Hydrocarbons split to generate turquoise hydrogen. This may be accomplished using a variety of methods. The approach that has advanced the most in research and is most likely to be commercialised is the plasma process for producing carbon black and hydrogen.

Other techniques include cold plasma, methane catalytic conversion and molten metal pyrolysis via thermal splitting [57,58]. Hydrocarbons such as natural gas are utilised as feedstock and process energy for all of these operations, and electricity is the source of both. Methane splitting potentially requires 38 kJ/mol H_2, while water electrolysis requires 285 kJ/mol H_2 and steam-methane reforming requires 252 kJ/mol H_2. Methane splitting requires high temperatures and heat losses [59,60].

3.4. Production of Grey Hydrogen

Grey hydrogen is the result of the steam reformation of coal or natural gas without the addition, usage, or storage of carbon. A by-product of other chemical processes produces more than 40% of grey hydrogen [61].

White hydrogen has also been unofficially coined by the North American Council for Freight Efficiency [62]. Grey hydrogen is mostly used in the petrochemical industry and in the production of ammonia [63]. The main disadvantage of grey hydrogen is due to the significant CO_2 emissions that are generated during hydrogen synthesis, which are estimated to be around 830 Mt of CO_2 yearly [64]. However, a tried-and-true technique that generates hydrogen at a fair price is natural gas steam reforming (SMR) without CCUS. During the procedure, the water is heated and natural gas is pre-treated. The methane is subsequently broken down into syngas in the reformer with steam.

Another important method of producing grey hydrogen is coal gasification, which is sometimes referred to as brown hydrogen in the literature. Since coal has the largest reserves of any fossil fuel in the world, this production method is also frequently used. China, in particular, generates a substantial quantity of hydrogen by coal gasification due to the high cost of natural gas and the abundance of coal reserves [59]. Four main types of coal, including lignite (low rank), sub-bituminous coal (low rank), bituminous coals (middle rank), and anthracites, are widely used as gasification feedstock (high rank) [61–63]. Figure 5 shows grey hydrogen production.

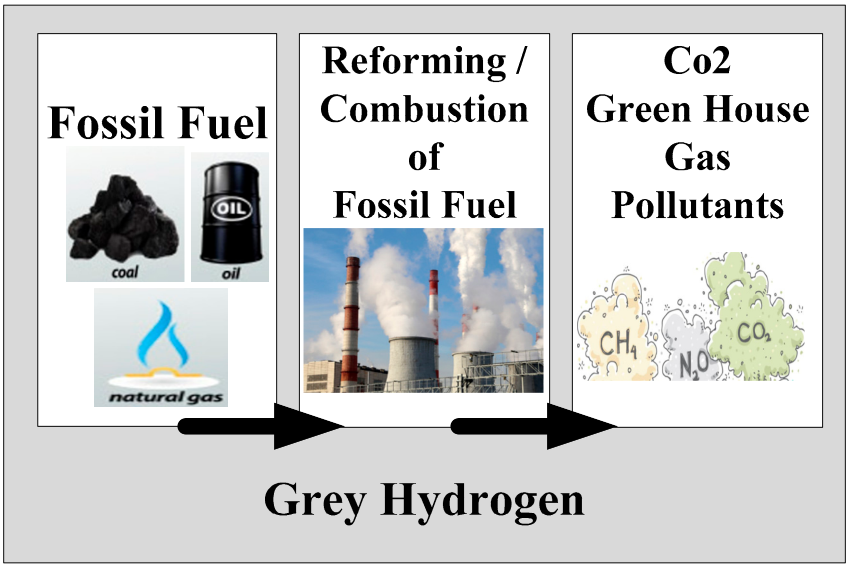

Figure 5. Schematic of Grey hydrogen production.

3.5. Green Hydrogen

Green hydrogen is the term used to describe hydrogen generation based on renewable energy. Green hydrogen is produced when water is electrolyzed with electricity produced by renewable energy sources or low-carbon power sources. The electrolysis process is thoroughly discussed before moving on to the specifics of various green hydrogen generation techniques.

Currently, electrolysis is the most established commercially accessible process for producing hydrogen from water. Water electrolysis is the process of dissolving water into its component elements, hydrogen and oxygen, using an electric current. Positive ions (H+) are drawn to the cathode by the electric potential, whereas negative ions (OH-) are drawn to the anode. Alkaline water electrolysis (AEL), proton exchange membrane (PEM) water electrolysis, solid oxide water electrolysis (SOE), and alkaline anion exchange membrane (AEM) water electrolysis are some of the water electrolysis methods depicted in Figure 6 [65].

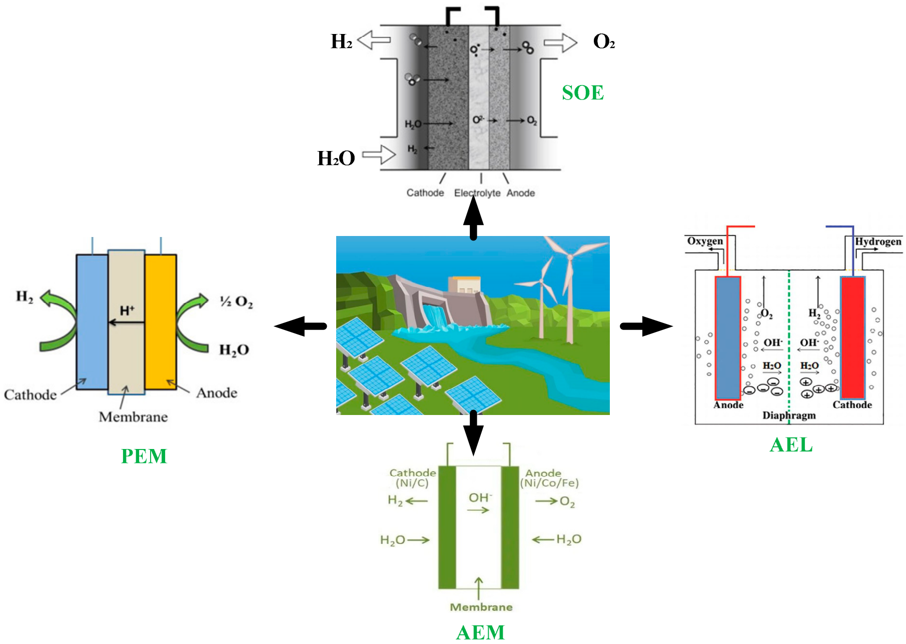

Figure 6. Water electrolysis processes to generate hydrogen.

By using AEM water electrolysis, conventional noble metal electrocatalysts might be swapped out for less costly transition metals. AEM electrolysis has garnered interest despite being a relatively new technology thanks to its superior power efficiency, membrane stability, robustness, ease of handling, and low-cost hydrogen generation method [66]. In addition to the increase in electrolysis voltage brought on by the bubbles created during the electrolysis process, high energy consumption is a barrier to the production of hydrogen from water [67]. To consume less energy, hydrocarbons can be employed in water electrolysis. The expected trajectory for electrodes in the future should be toward inexpensive metals or nonmetal composite materials such as Ni. The major renewable energy sources used in the electrolysis process are discussed below:

It is well knowledge that solar energy is the main significant renewable energy source that can be used to produce clean, sustainable hydrogen. Solar-powered energy systems have the potential to be a significant contributor to the transition from fossil fuels to renewable energy sources. Solar power is one of the crucial basic energy sources that may be utilised to create pure hydrogen. Figure 7 classifies the many solar energy sources that can be utilised to create hydrogen. Solar thermal, solar photovoltaic, and photo electrochemical energy are the three primary forms of solar energy [68]. Utilizing the concentrated sun's thermal energy, hydrogen may be produced in a variety of methods, such as solar thermolysis, the solar thermochemical cycle, mechanical energy to electrical energy conversion, solar gasification, solar cracking, and electrolysis. Direct hydrogen synthesis is possible through photoelectrolysis as well as bio-photolysis.

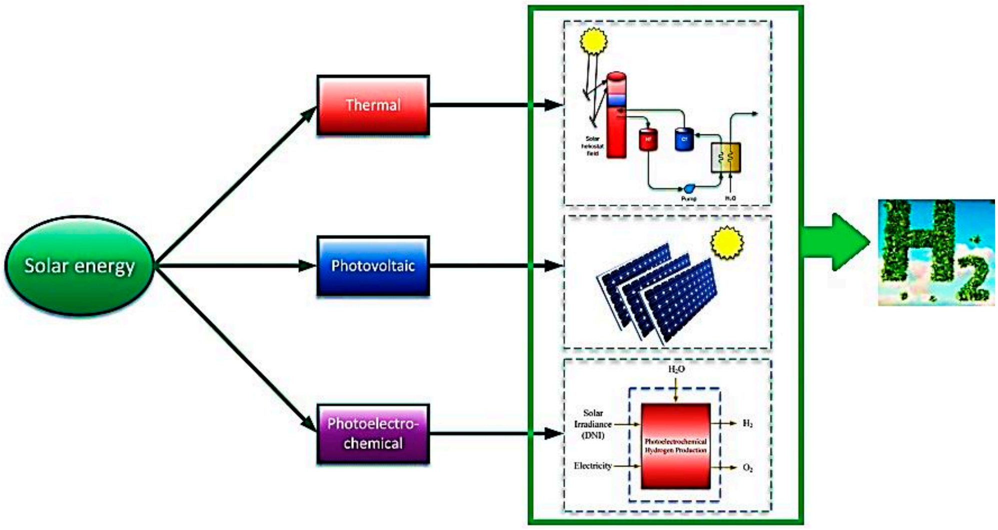

Figure 7. The classification of solar energy to produce hydrogen.

Electricity generated by the photovoltaic source is utilised to make hydrogen through electrolysis. Solar gasification and sun ammonia reforming methods both employ the thermal energy produced by concentrated solar thermal energy to make hydrogen.

The electrolyser, which separates water into oxygen and hydrogen, uses the electrical energy generated through the wind energy resource after being converted from an alternating current to a direct current [69–71]. The electrolyser can use wind-based power to make hydrogen, and the resulting hydrogen may be used in stationary applications or in fuel cells to produce electricity. In order to satisfy the load requirement during periods of comparatively lesser wind speed, hydrogen can also be stored. Utilizing wind power to create hydrogen is a reliable, sustainable, and cost-effective method of energy production.

There are several ways that geothermal energy can be utilized to generate hydrogen, including geothermal power fed to water electrolysis [72], geothermal energy used to heat water to increase the efficiency of water electrolysis [73–75].

Biomass is burnt in a small quantity of air to generate hydrogen, carbon dioxide, methane, carbon monoxide, nitrogen, steam and compounds including char, tars, and ash particles that contain flammable gas [76]. Gasification, as opposed to combustion, produces fuel in the form of syngas rather than burning it, preventing the release of many pollutants such as oxides of nitrogen and sulphide, as well as other particles that occur at temperatures higher than common for gasification [77].

A summary of the hydrogen production method is presented in Figure 8.

Some further research findings on different types of hydrogen production have been tabulated in Table 2:

Table 2. Some significant research on different types of hydrogen production.

Literature	Significance	Approach	Remarks
[78]	Solar powered hydrogen production	Thermodynamic and sustainable aspect	Environmental impact of solar-based hydrogen production
[79,80]	Water electrolysis-based hydrogen production	Thermodynamic aspect	Proton exchange-based electrolysis for hydrogen production
[81–83]	Analysis and assessment of solar energy powered natural gas reforming system	Cost assessment carbon emission analysis	improved energy and energy efficiencies

Table 2. *Cont.*

Literature	Significance	Approach	Remarks
[84–86]	Geothermal energy-based hydrogen production	Thermodynamic modelling	geothermal heat is used to preheat the water and the high-temperature water is used in the electrolyser. It improves the system efficiency
[11,87,88]	Production of hydrogen at hydropower plants	Thermodynamic aspect	The hydrogen production efficiency improves
[89–91]	Production of hydrogen from renewable resources	Comparative assessment of renewable energy resources	hydrogen was found to be produced at high pressure, employing small amount of consumption of energy
[92–95]	biomass gasification-based hydrogen production	biomass gasification-based hydrogen production	The proposed biomass gasification study offered improvement in efficiency
[91,96,97]	Analysis and assessment of geothermal energy	Energy and exergy assessment along with study on specific energy consumption	Geothermal energy-powered clean hydrogen liquefaction process
[98,99]	future hydrogen infrastructure	Hydrogen infrastructure	energy security issues posed by current fuels are discussed and technical, societal, economic and infrastructure challenges in adopting new technology are analysed in detail
[100,101]	Future hydrogen markets for production and industry	Hydrogen Production	In the initial phase, low-cost, long-term storage and better-quality refuelling station utilization makes the best impression

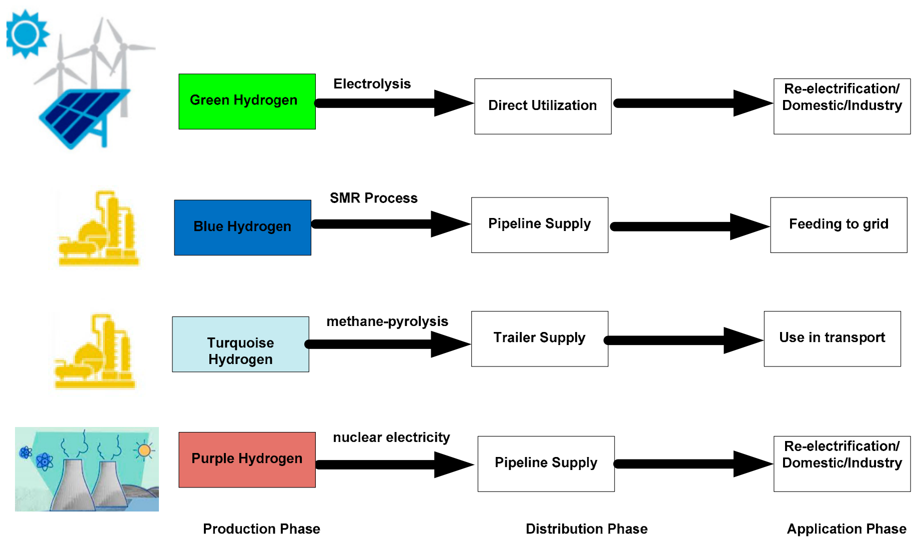

Figure 8. Summarized Hydrogen production methods.

4. Challenges in Hydrogen Production Methods

Both renewable energy sources and fossil fuels may be used to make hydrogen; however, there are several ways to make hydrogen from fossil fuels, including gasification, steam reforming, partial oxidation and auto thermal oxidation. Hydrogen may be produced from renewable energy sources by solar or wind energy splitting water and gasifying biomass/biofuels [101,102]. The most hydrogen is extracted from coal at a rate of around 21.5 billion tonnes per year, and this has to be replaced by renewable energy sources.

In addition to the anticipated need for H_2 as a transportation fuel and portable electricity, there will be an enormous demand for H_2 due to the upgrading of heavy oil, desulfurization and upgrading of ordinary petroleum, and the manufacturing of ammonium. As a result of increased H_2 production with present technology, more traditional hydrocarbons (mainly natural gas) will be used, increasing greenhouse gas emissions. With little or no net greenhouse gas emissions (without the use of carbon sequestration technologies), the generation of H_2 from renewable sources derived from agricultural or other waste streams increases the flexibility and boosts the economics of distributed and semi-centralized reforming [103].

It is simple to convert electrolysis, thermocatalytic and biological production to on-site decentralised H_2 generation, doing away with the requirement to set up a significant and expensive distribution infrastructure. However, there are technical difficulties with each of these H_2 production methods [104–106]. These difficulties include conversion efficiencies, feedstock types, and the requirement to securely combine H_2 production systems with H_2 purification and storage technologies.

5. Recommendation and Conclusions

The commercialization of hydrogen manufacturing processes powered by renewable energy, as well as market development and infrastructure, all require further study.

For distant places that are far from the grid, water electrolysis devices powered by off-grid solar PV or wind turbines can also be used. Hydrogen may also play a significant part in the decarbonization of the marine industry through the use of off-shore wind energy to provide clean fuel. Blue hydrogen may be transported internationally in the form of ammonia, which can also be readily broken on-site to create hydrogen. The commercial deployment of carbon dioxide removal technologies can also aid in reaching net-zero CO_2 emissions and to reduce global warming by 1.5 °C.

In addition to its traditional use as an industrial raw material for the manufacture of ammonia and methanol, hydrogen is now being developed as a new energy vector. The technologies used to produce hydrogen from conventional and renewable energy sources, as well as the major difficulties encountered in the practical implementation of such systems, are all covered in this study. Solar, wind, geothermal, hydro, biomass and other renewable energy sources are all taken into account for producing hydrogen. Since intermittent renewable energy sources such as the sun and wind are among the most promising, hydrogen seems to be the greatest choice for use as fuel, an energy transporter and a storage medium. Because of the benefits associated with its use and the availability of carbon-free alternatives, hydrogen is gaining increasing attention as a possible fuel and a unique energy carrier option internationally. This review article provides a brief analysis of various conventional and renewable energy-based hydrogen production methods. It also describes each method of producing hydrogen using renewable energy while taking into account the efforts that have been made thus far. The main focuses of the paper are listed as below:

- Selection of hydrogen energy for various applications can be useful due to its low emissions or zero emissions released into the environment. Therefore, various methods of hydrogen production and utilization based on their sources of production have been analysed.
- The actual production methods for hydrogen and its related challenges have been discussed in this paper.
- The utilization of hydrogen as a source of energy can be helpful to protect the environment from harmful emissions, which has been the main focus of the manuscript.

In the future, hydrogen energy could become a sustainable energy which can be utilized in every type of application due to its clean nature towards the environment. However, the generation of hydrogen from sources such as fossil fuel will be hazardous to the environment. Therefore, from this review article, it can be recommended that for hydrogen production, renewable energy and nuclear energy should be focused on to protect the environment from emissions. It can also be suggested that in the future, various methods of producing hydrogen from different renewable sources should be taken into account to analyse its efficiency.

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