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HYDROGEN HORIZONS: RENEWABLE AND NON-RENEWABLE ENERGY SYNERGIES FOR A GREENER ENVIRONMENT

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Abstract
The global energy crisis, together with rising greenhouse gas emissions, has intensified the search for clean, sustainable energy carriers. Hydrogen has emerged as a promising solution to decarbonise high emission industrial sectors and facilitate the integration of intermittent renewable energy sources into the grid. This review provides a systematic and comparative analysis of current and emerging hydrogen production methods, categorising them by energy source (renewable and non-renewable) and by technological pathway, including steam methane reforming (SMR), water electrolysis, biomass gasification, coal gasification, and thermochemical water splitting. From observations, while fossil fuel-based methods (primarily SMR) currently dominate global hydrogen supply due to lower production costs (0.9–3.2/kg H_2) and technological maturity, they are inherently carbon intensive, emitting ≈9 kg CO_2 per kg H_2 without carbon capture. On the other hand, renewable based routes, particularly electrolysis powered by solar and wind, offer near zero emission potential but face persistent challenges related to high capital costs, intermittent energy supply, and lower technology readiness levels. The review evaluates the trade-offs and scalability challenges of various hydrogen production methods, emphasizing the importance of novel materials for improving catalyst durability and electrolyzer efficiency. It also covers hydrogen purification techniques required for fuel cell standards. The analysis concludes that a combination of blue (fossil with carbon capture) and green (renewable) hydrogen is necessary, tailored to regional resources and infrastructure. The review also outlines key future research directions, including the advancement of methane pyrolysis, plasma reforming, process optimization, and the development of robust storage materials.

Keywords: Hydrogen, Renewable, Non-Renewable, Environment, Energy.

1. INTRODUCTION

The sustained increase in global greenhouse gas (GHG) emissions is primarily driven by population growth, rising energy demand, and the expansion of industrial activities. This trend has significantly accelerated global warming, necessitating an urgent transition toward environmentally benign and renewable energy systems. Among the various energy carriers proposed for a sustainable future, hydrogen (H_2) has emerged as one of the most promising candidates due to its high energy density, versatility, and zero-emission combustion profile. Despite the growing share of renewables, fossil fuels are projected to remain the dominant energy source at least until 2050 (Keshri et al., 2024). Consequently, bridging the gap between current fossil fuel-dependent infrastructure and a future low carbon economy requires strategic integration of both non-renewable and renewable hydrogen production pathways.

Globally, hydrogen production has grown substantially, approaching 100 million metric tonnes by 2024. However, nearly 95% of this hydrogen is classified as "grey hydrogen," derived primarily from fossil fuels, most commonly via steam methane reforming (SMR) of natural gas. SMR is currently the most mature and cost-effective method for large scale hydrogen production, but it is associated with significant CO_2 emissions, releasing approximately 9 kg CO_2 per kg H_2 produced (Ahad et al., 2023). In addition to SMR, other non-renewable routes include coal gasification, partial oxidation, and autothermal reforming. Coal gasification has seen a decline between 2021 and 2024 due to environmental concerns, while electrolysis-based production has gained momentum, driven by green hydrogen initiatives (LeValley et al., 2014; Nnabuife et al., 2022).

Emerging technologies such as biological processes (e.g., dark fermentation, photo fermentation) and photolytic methods remain at lower technology readiness levels but are gradually increasing in share. The carbon footprint of hydrogen production varies widely depending on the energy source and process used. Grey hydrogen, produced without carbon capture, carries a high environmental burden. Blue hydrogen, which incorporates carbon capture and storage (CCS), offers moderate emissions reduction but still relies on fossil feedstocks. Green hydrogen, produced via water electrolysis powered by renewable energy (solar, wind, hydro), achieves near zero GHG emissions and is widely considered the ultimate sustainable option (Bhawna & Sharma, 2023; Dash et al., 2023; Patel et al., 2024). The key green hydrogen technologies include: Alkaline water electrolysis (AEL); Proton exchange membrane (PEM) electrolysis; Solid oxide electrolysis (SOE); Anion exchange membrane (AEM) electrolysis; Other emerging low carbon routes, such as methane pyrolysis (turquoise hydrogen), cold plasma reforming, and photoelectrochemical (PEC) water splitting, are also under active investigation (Ahmad et al., 2024; Dash et al., 2023).

Despite its considerable potential as a clean energy vector, the large scale adoption is constrained by several interrelated technical and economic barriers. A primary limitation is the elevated cost of production via low emission routes; for instance, water electrolysis remains considerably more capital intensive than steam methane reforming, although this economic gap is progressively narrowing due to technological innovations and the falling levelized cost of renewable electricity. Furthermore, many hydrogen production methods, particularly electrolysis and thermochemical cycles, are highly energy intensive, requiring substantial and continuous inputs of carbon free electrical or thermal energy to achieve meaningful emission reductions. In addition to production side hurdles, the widespread deployment of hydrogen is hindered by significant infrastructure deficits, including insufficient networks for distribution, long distance transportation, and safe, high density storage when compared with established fossil fuel systems. Finally, several advanced production pathways, such as photoelectrochemical and solar thermochemical water splitting, remain at early stages of research and development, with low technology readiness levels that preclude near term commercial viability despite their long-term promise for sustainable hydrogen generation (Ahmad et al., 2024).

The present review aims to offer a systematic and comparative assessment of hydrogen production methods derived from both renewable and non-renewable sources. Table 1 shows the comparative analysis of unresolved limitations of the reviews conducted so far.

Table 1. Comparative analysis of the previous study

Method	Yield	Efficiency	Chemicals	Key Findings	Limitations	Research Gap	Ref
Proton Exchange Membrane (PEM) Water Electrolysis	High-purity hydrogen	High energy efficiency	Noble metal-based electrocatalysts (Pt for HER, Ir/Ru oxides for OER)	PEM electrolysis provides high efficiency, compact design and strong compatibility with renewable energy	High cost, durability issues of membrane and catalysts	Need for low-cost, non-noble metal catalysts, improved durability	(T. Wang et al., 2022)
Water Electrolysis (AWE, PEM, SOEC)	High-purity hydrogen	AWE: 62–82%, SOEC: up to 86%	Ni-based, Pt/Ir/Ru, Perovskites	Sustainable hydrogen production with high purity	High cost and water consumption	Need cost reduction and improved durability	(Arsad et al., 2023)
Water Electrolysis Technologies	Up to 99.999% purity	High efficiency	Pt (PEM), Ni (AWE), low-cost metals (AEM)	PEM highly efficient; AEM low-cost alternative; SOEC high	High energy demand, membrane degradation	Improve membrane stability and reduce energy consumption	(El-Shafie, 2023)

Method	Yield	Efficiency	Chemicals	Key Findings	Limitations	Research Gap	Ref
				conversion efficiency			
Seawater Water Electrolysis	Not fixed	Reduced due to side reactions	MnOx, LDH, protective coatings	Enables use of abundant seawater, reduces freshwater dependency	Corrosion, chlorine evolution, scaling issues	Need for selective catalysts and anti-corrosion systems	(Zhang et al., 2026)
Electrocatalytic Water Splitting	High-purity hydrogen	4.5–5.5 kWh/m^3 energy requirement	Transition metals	Clean hydrogen via renewable electricity integration	High electricity cost	Need cheaper energy	(Gao et al., 2024)
PEM Water Electrolysis	High-purity hydrogen	PEM systems considered highly efficient	Pt, Ir/Ru electrocatalysts, low-cost HER/OER catalysts	PEM electrolysis is a promising green hydrogen technology	High catalyst cost, membrane degradation	Development of durable and low-cost electrocatalysts and PEM components	(Shiva Kumar & Himabindu, 2019)
Hydrogen Production Technologies	System dependent	Thermochemical cycles: 38–42%, Electrolyzers >98% Faradaic efficiency	Noble metals, transition metals, ceramic catalysts	Compared thermochemical, electrolysis, photocatalytic, biological, and fossil-fuel hydrogen production technologies	High cost, durability issues, low photocatalytic efficiency	Need long-term durability, catalyst optimization, and cost reduction	(Zhao et al., 2026)
Steam Methane Reforming using Advanced Reactors	High hydrogen yield	Improved efficiency through membrane and sorption-enhanced reactors	Ru, Ni, Pd, Rh-based catalysts	Advanced reactors improve hydrogen production and conversion	Membrane fouling and scale-up limitations	Stable industrial-scale reactors with better membrane durability	(Ganguli & Bhatt, 2023)
Green Hydrogen and Electrolysis	High-purity green hydrogen	Efficiency governed by electrolysis thermodynamics and OER kinetics	LDH-based electrocatalysts, Pt/Ir catalysts	LDH catalysts improve OER performance	High cost and sluggish anodic kinetics	Development of efficient OER catalysts and scalable powered systems	(Subedi et al., 2026)

To achieve this overarching goal, the study pursues several specific objectives: first, to classify and describe the principal hydrogen production technologies according to their feedstock type and primary energy source; second, to evaluate each method using a consistent set of techno-economic and environmental metrics, including energy efficiency, production cost, carbon dioxide emissions, material requirements, and technological maturity; third, to critically contrast the relative advantages and limitations of renewable-based routes against conventional fossil fuel-based approaches; fourth, to

identify the key technical challenges and research gaps that must be addressed to enable a sustainable hydrogen economy; and fifth, to provide forward looking insights into emerging technologies, associated policy implications, and potential integration strategies.
The scope of this review encompasses a broad range of production pathways, including thermal processes (such as steam methane reforming and coal gasification), electrolytic methods (including alkaline, proton exchange membrane, and solid oxide electrolysis), biological routes (e.g., dark fermentation and photofermentation), and photolytic techniques (such as photoelectrochemical and solar thermochemical water splitting). Essential hydrogen purification methods, including S-I cycle and the water-gas shift reaction, are also addressed. Wherever applicable, quantitative metrics such as kilograms of CO_2 emitted per kilogram of hydrogen produced, cost per kilogram of hydrogen, and energy conversion efficiency are compared across different technologies. By synthesising current scientific knowledge and explicitly identifying barriers to scalability, this review aims to serve as a resource for researchers, industry practitioners, and policymakers working to establish hydrogen as a foundational element of global decarbonization strategies.

2. HYDROGEN PRODUCTION METHODS

Hydrogen is found abundantly within numerous naturally occurring chemical compounds. When deriving hydrogen from fossil fuel feedstocks, minimising adverse environmental impacts requires the complete capture and sequestration of all resultant emissions. The principal forms of energy harnessed for hydrogen generation include thermal, electrical, photonic, and biological sources. An overview of the various technologies employed in hydrogen production is presented in Fig. 1 and process parameters in Table 2.

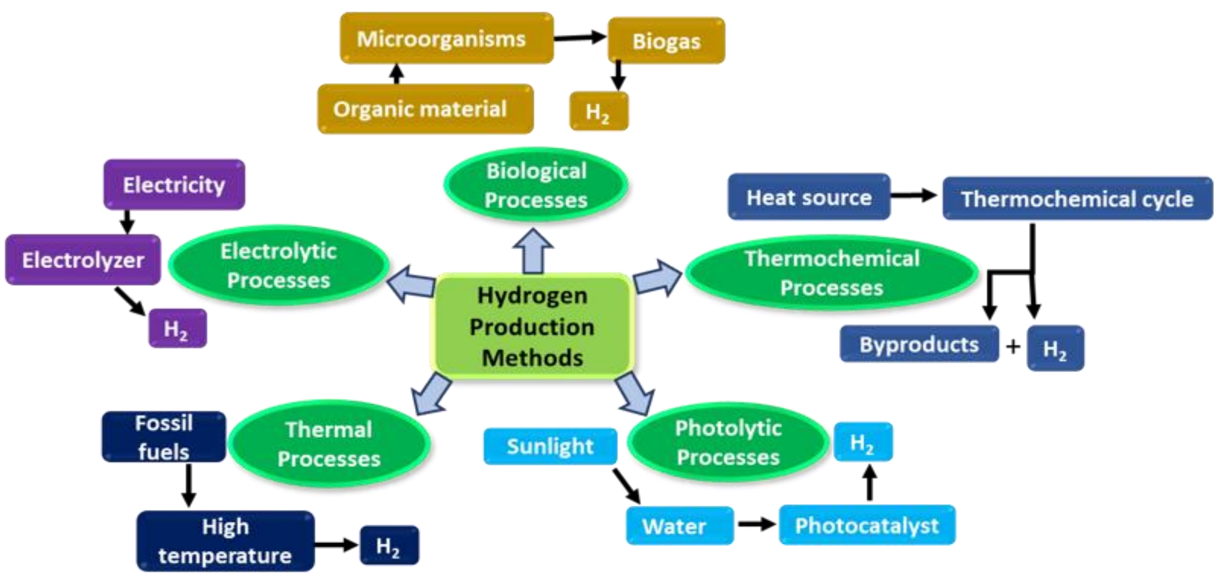

Fig.1. Hydrogen Production Technologies

2.1 Thermal Processes

Thermal hydrogen production encompasses several techniques, most notably thermochemical cycles and solar driven steam methane reforming. In thermochemical cycles, concentrated solar energy is harnessed to drive chemical reactions that dissociate water molecules, thereby releasing hydrogen gas. The efficiency of solar thermal steam reforming can be further enhanced by employing sustainable biomass as a feedstock. This approach utilizes high temperature solar heat to generate hydrogen from hydrocarbons or other fuel sources (Giaconia et al., 2022). However, several technical challenges must be addressed to improve the practical viability of solar thermal steam reforming, including cost reduction, process efficiency optimization, and enhancement of material resistance to thermal stress. High temperature electrolysis has also gained attention due to the accelerated chemical kinetics observed under elevated temperatures, which enable exceptional energy conversion efficiencies (Du et al., 2023; Y. Li et al., 2019). Overall, thermal production technologies offer an attractive pathway for large scales, carbon clean hydrogen generation, using only solar energy and water as inputs. Although significant obstacles remain, continued development of system

components and process integration is expected to yield considerable cost reductions.
Thermochemical hydrogen production extracts hydrogen from various feedstocks, such as hydrocarbons or water. The most common thermochemical method is steam methane reforming (SMR), although it is associated with substantial CO_2 emissions (Y. Chen et al., 2023; Katebah et al., 2022). Among thermochemical water splitting cycles, the UT-3 and sulfur-iodine (S-I) cycles are recognised as the most efficient. The S-I cycle splits water into hydrogen and oxygen through a sequence of three closed loop chemical reactions, beginning with the Bunsen reaction, which produces sulfuric acid and hydroiodic acid. The system forms two immiscible phases: sulfuric acid in the upper layer and hydroiodic acid in the lower layer. After filtration and concentration, each acid undergoes thermal decomposition. Sulfuric acid decomposes into oxygen and sulfur dioxide, while hydroiodic acid yields hydrogen and iodine (Mohd et al., 2024).

Table 2. Hydrogen production process and its parameters

S.No.	Parameters	Thermal Processes	Electrolytic Processes	Biological & Thermochemical Processes	Photolytic Processes	Ref
1.	Energy Source	Heat generated from fossil fuels, biomass, or solar	Electricity from renewable feedstock	Organic matter and sunlight	Solar	(Megía et al., 2021)
2.	Efficiency	Moderate to high	High	Moderate	Relatively low in the initial stages of study	(Martino et al., 2021)
3.	Environmental Impact	Fossil fuels - high, Biomass and solar energy - low	Low	Low	Very low	(Megía et al., 2021)
4.	Cost	Moderate to high	High	Low to moderate	Currently high	(Mio et al., 2024)
5.	Hydrogen Quality	High if the purification process is done	Very high	Moderate to high	Very pure	(Kim & Yang, 2025)

The key reactions of the S-I cycle are as follows:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (1)$$
$$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2O_2 \quad (2)$$
$$2HI \rightarrow I_2 + H_2 \quad (3)$$

A notable advantage of thermochemical cycles is that they can operate without external catalysts. In the S-I cycle, water is the only consumable resource, as all other reagents are recycled. Effective thermochemical hydrogen production depends critically on the integration of heat sources, the efficiency of product separation, and the number of reaction pathways employed (Q. Wang & Macián-Juan, 2022).
Another emerging thermal technique is pyrolysis, which converts organic compounds into valuable products, including hydrogen and other chemical derivatives. Pyrolysis is conducted at elevated temperatures and involves the thermal decomposition of organic matter, including biomass and various waste streams. Unlike biomass gasification, pyrolysis occurs in the complete absence of air or oxygen, making it a cleaner alternative for energy recovery. A comprehensive assessment of pyrolysis's future potential, however, requires systematic comparison with other hydrogen production technologies, as discussed in subsequent sections (Megía et al., 2021).

2.2 Electrolytic Processes

Water electrolysis represents the most commercially mature technology for producing high purity hydrogen. The process relies on electron transfer facilitated by an external electrical circuit. The principal techniques for electrochemical hydrogen generation include alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis (H. Li et al., 2023). In a typical electrolysis cell, a direct current is applied across two electrodes submerged in an aqueous solution, breaking the chemical bonds of

water molecules, yielding hydrogen and oxygen gases (Agyekum et al., 2022).
Beyond conventional electrical input, water molecules can also be dissociated using alternative energy sources such as biophotolysis, thermal energy, and photonic energy. The incorporation of catalysts significantly enhances current density and accelerates the electrolysis reaction rate. Both heterogeneous and homogeneous catalysts are employed, with homogeneous variants being more economical. Because the process emits no greenhouse gases and produces oxygen as a byproduct, valuable for industrial applications, water electrolysis is considered environmentally gentle. Common configurations use sulfuric acid as the electrolyte and platinum as the electrode material because sulfuric acid serves as an efficient proton rich electrolyte, while platinum is highly inert and conductive. Nevertheless, compared to steam methane reforming, water electrolysis remains a lesser known route for hydrogen generation (Grigoriev et al., 2020). Water quality is a critical parameter, particularly for PEM electrolysers, which are highly sensitive to impurities. Consequently, desalination and demineralisation must precede the electrolysis process. For instance, feeding seawater directly into an electrolyser favours chlorine evolution over oxygen production. One effective strategy to suppress such undesirable reactions is the use of ion-selective membranes for water pre-treatment (Fan et al., 2023).

2.3 Biological and Thermochemical Processes

Biological hydrogen production is controlled by microorganisms such as bacteria and algae, which generate hydrogen through metabolic pathways involving sunlight or organic substrates. Although these methods hold long term promise for carbon free hydrogen generation, they remain at the research and development stage, with ongoing experimental trials (Saqlain, 2023). Biological processes are attractive because they utilise renewable energy sources and typically operate at ambient temperature and pressure. Many microbes possess enzymes, particularly hydrogenase and nitrogenase—capable of producing hydrogen from water upon exposure to an external energy source (Mahidhara et al., 2019). Biological hydrogen production is broadly classified into microbial biomass conversion and photobiological processes. Microbial biomass conversion includes three main pathways: (i) biophotolysis using algae and cyanobacteria, (ii) photofermentation, and (iii) dark fermentation (Chandran & Mohan, 2023). These enzymes facilitate the utilization of metabolic byproducts derived from photosynthetic reactions in aqueous environments. Fig. 2 presents a classification of biological hydrogen production processes (Ahmed et al., 2021).

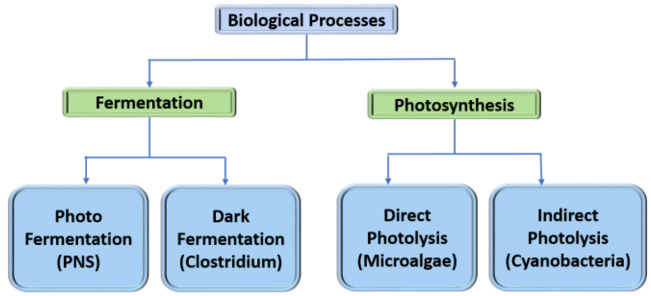

Fig. 2. Types of biological processes

Biophotolysis is a light-dependent mechanism wherein microbial systems absorb light energy, leading to the dissociation of water into molecular hydrogen and oxygen. This process is further divided into direct and indirect biophotolysis. Direct biophotolysis involves water oxidation and light driven electron transport, resulting in photosynthetic hydrogen release (Melitos et al., 2021). The two stage light-dependent reaction is represented by the following equations:

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2 \quad (4)$$
$$4H^+ + 4e^- \rightarrow 2H_2 \quad (5)$$

In indirect biophotolysis, green algae produce photosynthetic hydrogen under sulfur deprived conditions. Historically, research focused primarily on photosynthetic and photoautotrophic systems for microbial hydrogen production. However, advances in dark fermentation have enabled hydrogen generation in anaerobic environments via heterotrophic fermentation, which does not require light energy. Another innovative approach is the microbial electrolysis cell (MEC), which converts electrical energy into chemical energy to produce hydrogen from organic matter. MEC technology shares similarities with microbial fuel cells (MFCs) (Omidi et al., 2024). In MECs, microorganisms oxidize the substrate at the anode, generating electrons, protons, and carbon dioxide. Protons migrate to the cathode through an electrolyte, while electrons travel via an external circuit; their combination results in hydrogen evolution. Despite its promise, MEC technology faces several challenges, including complex reactor designs, high internal resistance, suboptimal electrode materials, and slow hydrogen production rates (Akroum-Amrouche et al., 2024).

2.4 Photolytic Processes

Photolytic hydrogen production utilizes light energy to split water into oxygen and hydrogen. Although still in early-stage research, these technologies offer the potential for sustainable hydrogen generation with minimal environmental impact. Two major categories are recognized: photoelectrochemical (PEC) processes, which employ photoelectrodes, and photobiological processes, which use living organisms such as algae or bacteria (Qureshi & Tahir, 2024). Photoelectrochemical water splitting uses photoelectrodes to separate water into hydrogen and oxygen. This technology is further subdivided into PEC-WS, where reaction components are physically separated, and PC-WS, in which all reactions occur within single particles. Photobiological processes, including direct and indirect biophotolysis, rely on photosynthetic organisms such as green algae or cyanobacteria to produce hydrogen via light driven reactions, with specific enzymes catalyzing the process (D. Liu & Kuang, 2024). Recent research has emphasized solar-driven hydrogen synthesis using particle photocatalysts, highlighting the need for efficient and environmentally benign technologies. One innovative development is a biphasic photocatalytic system that integrates photothermal and photocatalytic materials to enhance hydrogen evolution from water. Electrolysis driven by photovoltaic (PV) electricity referred to as PV electrolysis is another commercially available technique for hydrogen production. However, despite its commercial availability, PV electrolysis currently contributes only a minor fraction of global hydrogen supply. A comprehensive comparison of all major hydrogen production technologies is provided in Table 3.

Table 3. Different hydrogen production technologies

Technology	**Feedstock**	**Process**	**Efficiency (%)**	**Cost ($/kg H_2)**	**CO_2 Emissions** (kg CO_2/kg H_2)	**Advantages**	**Disadvantages**	**Ref**
Steam Methane Reforming (SMR)	Natural Gas	Steam Reforming	65-75	1-2	9-12	Low cost, established technology	High CO_2 emissions	(Jazani et al., 2024)
Coal Gasification	Coal	Gasification	45-55	1-3	19-20	Abundant feedstock	Very high CO_2 emissions	(Y. Liu et al., 2025)
Partial Oxidation	Crude Oil	Partial oxidation	55-65	2-3	10-12	Utilizes existing oil infrastructure	High CO_2 emissions	(Theofanidis et al., 2025)
Water Electrolysis	Water	Electrolysis	60-80	4-6	-	Low emissions, renewable energy source	High cost, dependent on the electricity source	(Dermühl & Riedel, 2023)
Biomass Gasification	Biomass	Gasification	40-60	3-5	1-3	Renewable feedstock	Lower efficiency, feedstock variability	(A. Alqahtani et al., 2026)
Photocatalysis	Water	Photocatalytic splitting	5-10	10-15	-	Direct solar energy use	Low efficiency, high cost	(Anwar et al., 2026)

3. HYDROGEN PRODUCTION FROM NON-RENEWABLE SOURCES

Fossil fuels currently govern global hydrogen supply due to their relatively low production costs and stable fuel prices. The most widely adopted technologies in this category include hydrocarbon reforming and pyrolysis. Collectively, hydrogen derived from conventional fossil sources such as natural gas, coal, and nuclear assisted processes accounts for most worldwide hydrogen production.

3.1 Natural Gas Reforming

Natural gas reforming has emerged as the dominant hydrogen production technology, particularly for large-scale applications, owing to its cost-effectiveness compared to alternative methods. Natural gas consists primarily of methane (CH_4), which is extracted from subsurface reservoirs often located near oil deposits, formed through the decomposition of organic matter. Steam methane reforming (SMR) is the most efficient technique for hydrogen extraction from natural gas. The process involves reacting to methane with high-temperature steam to produce carbon monoxide and hydrogen, thereby achieving high product yields. The SMR process is illustrated in Fig. 3.

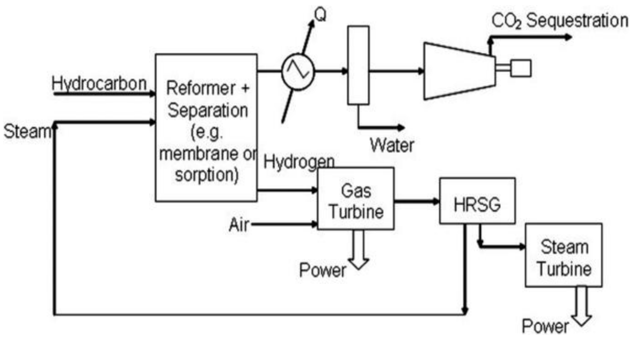

Fig. 3. Diagram of the SMR process (Jumah, 2024)

This widely adopted method generates synthesis gas—a mixture of carbon monoxide and hydrogen. However, the reaction is highly endothermic and requires expensive construction materials capable of withstanding severe operating conditions (Lee et al., 2021). High-performance catalysts, typically nickel based, are essential for maximizing hydrogen output. Combustion reactions between oxygen and methane can also convert methane into hydrogen-rich gas, despite producing moisture and carbon oxides, as shown in the following equations:

$$1/2\ O_2 + CH4 \rightarrow 2H_2 + CO \quad (6)$$
$$2O_2 + CH_4 \rightarrow CO_2 + 2H_2O \quad (7)$$
$$CH4 + H2O \rightarrow 3H2 + CO \quad (8)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad (9)$$

Partial oxidation (POX) represents an alternative reforming approach distinct from steam methane reforming. Unlike SMR, the POX process is exothermic, releasing heat that can be utilized for subsequent operations. POX is typically conducted at lower temperatures using heterogeneous catalysts, with nickel-based formulations remaining the most effective. Nevertheless, POX yields less hydrogen than SMR and generates additional byproducts, including carbon monoxide, carbon dioxide, and water vapour alongside hydrogen. The integration of SMR and POX has led to the development of autothermal reforming (ATR). This process combines exothermic partial oxidation using pure oxygen to supply the energy required for the endothermic steam reforming reaction. Given the global imperative for sustainable and environmentally friendly energy sources, natural gas-based reforming technologies continue to play a vital role in hydrogen generation (Schneider et al., 2020). ATR offers distinct advantages over both standalone steam reforming and partial oxidation: it eliminates the need for external heat input, reducing costs, and produces more hydrogen than POX alone. However, ATR is highly sensitive to temperature variations, presenting challenges in achieving optimal yields compared to SMR and POX (Schneider et al., 2020). A significant drawback of natural gas-based hydrogen production is the substantial CO_2 emissions released, necessitating the development of mitigation technologies.

3.2 Coal Gasification

Gasification is a well-established technique for converting various hydrocarbons into usable synthetic gas using oxidizing agents such as oxygen. Coal gasification is commonly applied to diverse feedstocks, including plastic waste, plant matter, and coal tar derivatives, which can subsequently be transformed into valuable products. The coal gasification reaction scheme is presented in Fig. 4.

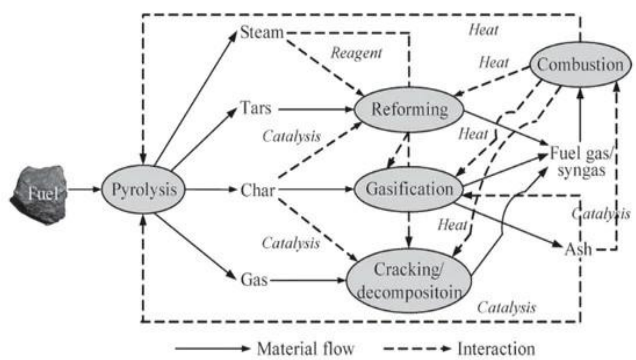

Fig. 4. Reaction process in the coal gasification (Dai et al., 2023)

As a thermochemical process, coal gasification converts solid coal into gaseous products, primarily hydrogen and carbon monoxide. This approach aims to reduce hazardous emissions while increasing the energy density of the fuel (Khlifi et al., 2024). Under elevated temperatures and pressures, coal reacts with steam and air to produce synthesis gas (syngas). The resulting hydrogen-rich syngas serves as a valuable energy source for both combined cycle and conventional power plants. The purity and quality of the feedstock coal significantly influence the quality of the hydrogen produced. The fundamental reactions of coal gasification involve the interaction of carbon with high temperature steam, yielding carbon monoxide and hydrogen, which subsequently react with moisture to generate additional hydrogen (Szima & Cormos, 2021):

$$C + H_2O \rightarrow CO + H_2 \quad (10)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad (11)$$

Beyond these primary reactions, secondary processes may occur in which carbon reacts with carbon dioxide rather than oxygen, producing additional carbon monoxide. Many industrial facilities employ coal gasification for ammonia production, a valuable hydrogen derived product. However, the process also generates various byproducts, including hydrogen cyanide, hydrogen chloride, ammonia, carbon monoxide, ash, and tar, necessitating thorough gas cleaning (Gezerman, 2022). The gasification process utilizes four coal types—lignite, bituminous, sub-bituminous, and anthracite with feedstocks typically gasified at temperatures exceeding 900°C. Compared to alternative hydrogen production methods, coal gasification results in higher CO_2 emissions due to the variety of feedstocks employed. When coupled with carbon capture technology, however, coal gasification can yield low-carbon hydrogen with substantially reduced emissions (Bargiacchi et al., 2020). An alternative approach is co-gasification, which combines low quality coal with organic materials such as biomass and hydrocarbons to enhance hydrogen generation. Another emerging method involves underground extraction of coal bed methane, using coal as a feedstock (J. Liu et al., 2021). Combustion reactions between oxygen and methane can also convert methane into hydrogen-rich gas, despite producing moisture and carbon oxides, as shown in the following equations:

Pressure swing adsorption (PSA) provides a cost-effective and environmentally friendly method for hydrogen separation and purification. When charcoal powder is processed with microwave plasma in the presence of steam, substantial hydrogen yields can be achieved, although cold gas efficiency remains relatively low (Chen et al., 2020).

3.3 Nuclear Energy

Nuclear power can serve as a primary energy source for hydrogen production, with integrated systems potentially increasing hydrogen output capacity by more than 95% (Song et al., 2022). The heat and electricity generated by nuclear reactors can be harnessed for electrochemical, thermochemical, or conventional water electrolysis processes to obtain hydrogen gas. Efficient thermal to hydrogen and thermal to electrical conversion rates generally require higher operating temperatures (Kim & Yang, 2025). Thermochemical water splitting offers a consistent and long-lasting hydrogen supply. Radiolysis—the dissociation of water molecules by high energy radiation such as X-rays, gamma rays, or ionizing particles also produces hydrogen gas. Thermal reactors capable of achieving moderate to high temperatures for thermochemical reactions include the Modular Helium Reactor (MHR), the Advanced High-Temperature Reactor (ATHR), and the Advanced Gas Reactor (AGR) [Safari et al., 2024]. The electrochemical route for nuclear assisted hydrogen synthesis involves water or steam electrolysis. Although effective, this process requires substantial electrical power, increasing system costs. High temperature steam electrolysis (HTSE) is the preferred method for nuclear-based hydrogen generation, as electrolyzing steam at elevated temperatures reduces electricity demand (Mrzljak et al., 2023). For medium to high temperature energy conversion, two systems have been proposed: helium gas turbines and supercritical CO_2 gas turbines.

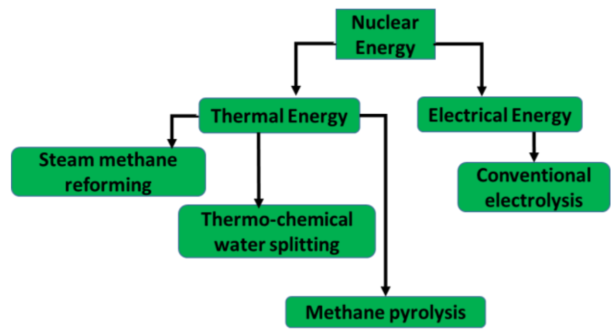

Fig. 5. Nuclear hydrogen generation routes

Fig. 5 illustrates potential nuclear hydrogen production pathways. Since hydrogen and other hazardous gases may be released during manufacturing, safety systems including shutoff devices and breach detectors are essential to prevent explosions that could damage reactor foundations (Venizelou & Poullikkas, 2024). The most significant challenge associated with nuclear waste is its long-term radiotoxicity, persisting for millions of years due to dangerous nuclides and fission products. This creates risks related to proliferation, waste storage, and operational safety. While nuclear based hydrogen production shows promise for reducing carbon emissions, radioactive waste management raises substantial environmental and health concerns (Majumdar et al., 2021).

3.4 In-situ Hydrogen Generation from Petroleum Reservoirs

Hydrogen generation from petroleum and oil reservoirs employs in-situ combustion and gasification techniques, relying on high-temperature interactions between reservoir rocks, water, and hydrocarbons to produce hydrogen. Down hole hydrogen selective membranes separate hydrogen from other gases, enabling high-purity extraction while trapping unwanted gases and solid combustion by products within the reservoir—a configuration described as carbon zero technology. This approach leverages existing upstream petroleum infrastructure, potentially offering a cost-effective and environmentally beneficial route to large-scale hydrogen production (Ifticene et al., 2023). Fig. 6 shows the Process flow diagram of the in-situ hydrogen production process from petroleum reserves. Reservoir heating facilitates access to both primary and secondary in-situ hydrogen generation processes. When a hydrogen permeable membrane is installed at the production well, only hydrogen reaches the surface, isolated from synthesis gas. This method optimally utilizes resources by continuously generating additional hydrogen through subsequent reactions (Worku et al., 2024).

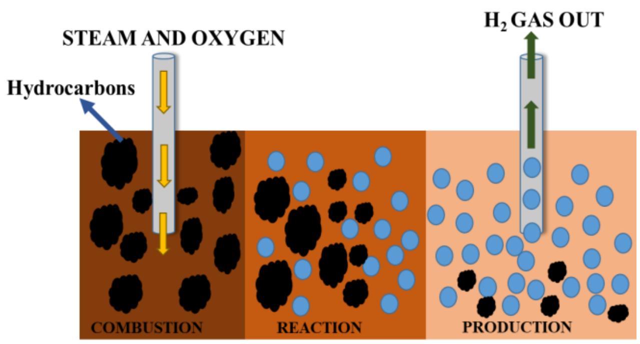

Fig. 6. Process flow diagram of the in-situ hydrogen production process from petroleum reserves (Okere & Sheng, 2023)

Nevertheless, several disadvantages exist, including the need for field scale feasibility assessments, technological challenges in membrane development, environmental risk mitigation, and economic viability improvements. Optimizing hydrogen production through various reactions coke gasification, water gas shift, pyrolysis, and aqua thermolysis presents multiple obstacles (Worku et al., 2024). Although the technical objective is gas sequestration, associated hazards include habitat loss, ecosystem disruption, water resource depletion, and CO_2 leakage. Research implications span both economic and technical aspects of clean hydrogen production from petroleum sources (You et al., 2020). Pilot studies and environmental impact analyses are critical for successful implementation (Shumiya Alam et al., 2023).

3.5 Hydrocarbon Gas and Liquid fuels

Hydrogen generation from liquids hydrocarbons like gasoline and diesel involves fuel delivery, reforming, and purification methods. An innovative approach incorporates pre-reforming to prevent undesirable gas-phase reactions, autothermal reforming with a distributed air supply to maintain optimal temperatures, and hydrogen enrichment via palladium membranes with concentration polarisation. This method shows potential for small scale hydrogen synthesis in distributed power generation using fuel cells (Lakhtaria et al., 2022). Catalytic pyrolysis processes can also generate hydrogen from liquid and light hydrocarbon fuels. Using metal oxide or carbon-based catalysts, these processes decompose fuels into hydrogen-rich gas. Adding unsaturated hydrocarbons like acetylene to methane enhances hydrogen concentration in the effluent gas—a CO_2 free production method suitable for on-site hydrogen generation and fuel cell applications. Liquid fuels, including gasoline and diesel, can be similarly converted into hydrogen-rich gases (Martín-Lara et al., 2025).

Technologies such as catalytic reforming and reformate cleaning ensure hydrogen purity, improving fuel cell system efficiency and reliability. Researchers continue developing advanced methods for converting liquid fuels into hydrogen to support widespread fuel cell adoption (H. Li et al., 2021). However, most hydrocarbon-based processes release greenhouse gases, even when striving for CO_2 free operation. Petroleum derived liquid fuels also cause concerns about resource depletion and long term sustainability. Additionally, the toxic and combustible nature of these fuels poses risks to both environmental and human health (Blohm & Dettner, 2023). Table 4 summarises current global hydrogen production statistics (International Energy Agency, 2021).

4. HYDROGEN PRODUCTION FROM RENEWABLE SOURCES

Renewable energy sources have significant potential to reduce global energy consumption, though further development is needed to improve affordability. Renewables emit substantially less CO_2 than non-renewable sources, thereby reducing greenhouse gases and mitigating climate change. In contrast, fossil fuels such as natural gas and coal release massive volumes of CO_2 and other greenhouse gases, contributing significantly to global warming. Contemporary research increasingly focuses on hydrogen generation from sustainable sources, including biofuels, solar, and wind, to improve fuel production efficiency.

4.1 Biomass Energy

Addressing the global challenge of rising CO_2 emissions requires increased utilization of renewable sources, including biomass. Biomass encompasses algae, forest residues, municipal solid waste, and various plant and animal materials natural energy source convertible into fuels and chemical products [Sahoo et al., 2021]. Hydrogen derived from biomass finds applications across industrial, power generation, transportation, and fuel sectors. H_2 production from biomass can be achieved through pyrolysis, char steam gasification, and volatile steam reforming, with outcomes strongly influenced by process parameters. Gasification offers a cost-effective renewable hydrogen production method with approximately 50% efficiency. Research on lignocellulosic biomass has focused primarily on gasification and pyrolysis conversion techniques (H. Song et al., 2022).

Table 4. Present global hydrogen production

Country	Source	Percentage of Total Production	Main Production Technology	Ref
United States	Natural Gas	95%	SMR	(Victor & Nichols, 2024)
China	Coal	60%	Coal Gasification	(J. Li et al., 2025)
European Union	Natural Gas	96%	SMR	(Graczyk et al., 2025)
Japan	Natural Gas	95%	SMR	(Konovalov et al., 2025)
India	Natural Gas, Biomass	99%	SMR, Biomass Gasification	(Nuttall et al., 2026)

Hydrogen can be produced from biomass via anaerobic digestion (microbial breakdown into biogas), fermentation, and thermochemical gasification. The latter, like coal gasification, converts biomass into CO, CO_2, H_2, and methane. Thermochemical biomass conversion encompassing gasification, liquefaction, and pyrolysis is technologically advanced with broad applications (B.Dou et al., 2019).

Biomass steam gasification is an endothermic process producing CO_2 and H_2, subsequently purified via pressure swing adsorption. However, product compositions are complex. Plasma-assisted biomass gasification at high temperatures addresses some of these challenges. Supercritical water gasification (SWG) transforms large molecules into alcohol and sugars through complex reaction pathways. Biomass gasification provides a clean, cost-effective method for recovering energy from household and agricultural waste, lowering net CO_2 emissions by capturing and fixing carbon released during oxidation (Dossow et al., 2024). Concerns regarding biomass gasification include land requirements and competition for natural resources when cultivating fuel crops. Technical challenges include low carbon conversion rates and tar management. Beyond biomass-based techniques, solar driven thermochemical processes including water-splitting cycles and solar thermal reforming represent additional pathways toward sustainable, carbon-free hydrogen synthesis (Boretti et al., 2021). Fig. 7 illustrates biomass conversion via pyrolysis and the resulting reactions for hydrogen and other gas production (Aboelela et al., 2023).

Algae represent an abundant and renewable feedstock, with numerous methods demonstrating potential for large scale hydrogen production. According to the International Agriculture Organization, global fresh algae yield ranges from 150 to 600 tonnes per hectare annually, totaling approximately 12 million tonnes of dry algal matter. Algal biomass has been proposed as a substitute feedstock for industrial hydrogen production via gasification or similar methods (Saeed et al., 2021).

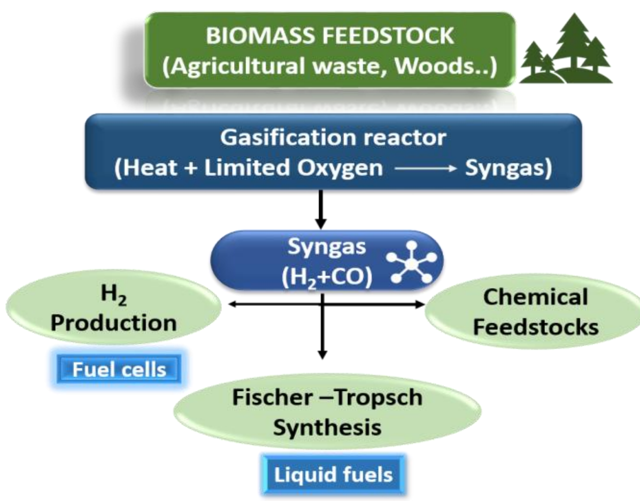

Fig. 7. Biomass Gasification

Recent research highlights algae's advantages as a fuel source, including higher photosynthetic activity and faster growth rates compared to terrestrial plants. Unlike hydrocarbon-based fuels, algae absorb excess atmospheric CO_2, meaning their use does not cause net CO_2 emission increases contributing instead to climate mitigation (Jha et al., 2024). Biohydrogen is a renewable, environmentally friendly fuel capable of replacing fossil fuel-based hydrogen. Algal biomass conversion is among the most promising bio hydrogen sources. Biohydrogen synthesis requires less energy as it occurs at ambient temperature and pressure. Microalgae and cyanobacteria are key bio hydrogen producers. Table 5 presents various biological hydrogen production processes and associated microbial benefits (Limongi et al., 2021).

Table 5. Various biological hydrogen production methods and advantages

Microorganisms	Biological hydrogen production methods	Benefits	Ref
Algae	Direct biophotolysis and Photo-fermentation	• Hydrogen Production from water and sunlight • Efficiency in Solar conversion • Reduction in CO_2 emissions	(Owolabi et al., 2026)
Cyanobacteria	Direct biophotolysis and Indirect biophotolysis	• Hydrogen Production from water and sunlight • Reduction in CO_2 emissions	(Krishna Prasad, 2025)
Photosynthetic bacteria	Photo-fermentation	• Use of a broad range of light	(Sharma et al., 2026)
Fermentative bacteria	Dark -fermentation	• Continuous production of hydrogen in dark conditions in an anaerobic process.	(Bozieva et al., 2025)

Fig. 8 depicts hydrogen production from algae. Nitrogen, phosphorus, and potassium (NPK) fertilizers accelerate algal growth; higher sugar content in the liquid phase enables further hydrogen treatment using ultrasound and microwaves. Oxygen is particularly sensitive in bioconversion processes—its removal may enhance hydrogen generation. Substrate removal during alkaline processing can reduce biohydrogen yields (Mtaki et al., 2021).

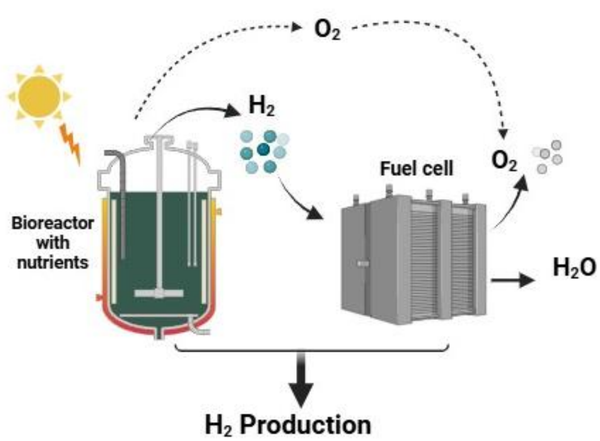

Fig. 8. Hydrogen production from algae biomass

Numerous studies have demonstrated the feasibility of hydrogen production from algal biomass via conventional routes such as fermentation or thermochemical conversion. Fermentation has emerged as a common approach for converting microalgal carbohydrate content into hydrogen. Engineering photosynthetic organisms to enhance hydrogen production remains an active research area.

4.2 Solar Energy

Solar energy is a major renewable source providing low-cost electricity and is considered the most promising option for meeting future global energy demand. Renewable energy has become increasingly affordable in recent years, while natural gas and oil prices remain volatile. Converting solar energy into hydrogen offers a sustainable and cost-effective alternative (Qadir et al., 2021). A feasible solar to hydrogen transition uses solar energy to generate hydrogen without releasing greenhouse gases. Solar power technologies fall into three categories: photovoltaic (PV) power generation, direct solar power generation, and photothermal power generation (Khan et al., 2021). Water electrolysis powered by solar energy can be accomplished using solid oxide electrolysis cells (SOEC), alkaline water electrolysis (AEL), and proton exchange membrane electrolysis (PEM). Alkaline and PEM electrolysis are currently the most commercially promising on-demand hydrogen generation technologies. In a PEM electrolyzer, a pure water filled cell contains anode and cathode chambers with electrodes; applying voltage drives current flow, producing hydrogen at the cathode and oxygen at the anode (Okonkwo & Otor, 2021).

Solar to hydrogen conversion efficiency is the most critical performance metric. Solar PV systems achieve up to 12% efficiency, while concentrated solar photovoltaic (CSPV) systems reach up to 25%.

Current research focuses on replacing first generation PV cells with third generation multi junction solar cells (MJSC) to capture more energy. Reflective mirrors are also incorporated to increase the intensity of solar radiation. The two step water electrolysis reduction process has been commercially adopted for hydrogen production, yielding pure, emission free hydrogen (Khouya, 2021). Solar thermolysis requires extremely high temperatures to dissociate water, posing material challenges. However, thermochemical solar to hydrogen processes operate at milder temperatures by combining metal and metal oxide reactions in the reactor. Solar based decarbonization of fossil fuels and electrolysis methods (PEM and alkaline) remain under active research. Compared to wind or nuclear high-temperature electrolysis, solar based electrolysis currently underperforms due to higher production costs and lower energy efficiency. Nevertheless, continued process and component development is expected to yield significant cost reductions (Hosseini & Wahid, 2020). Fig. 9 depicts hydrogen production using solar panels (Preethi, 2023).

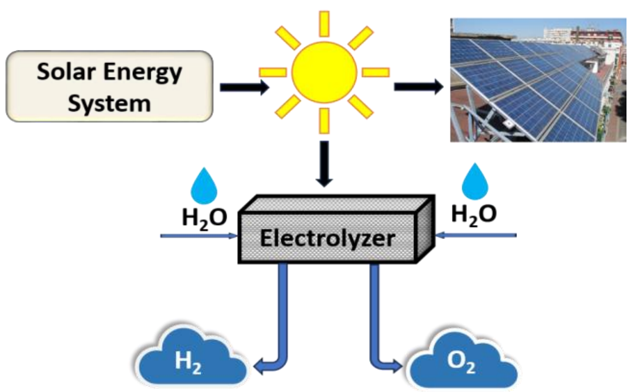

Fig. 9. Hydrogen Production using Solar Energy

4.3 Wind Energy

Wind energy has gained increasing attention as a sustainable electricity generation method and is considered optimal for hybrid power systems relying on multiple clean energy sources (F. Wang et al., 2021). To maximize utility and minimize waste, storage systems are commonly integrated with wind generation. However, wind energy presents intermittency and uncertainty challenges, making energy storage systems preferable (Reilly et al., 2022). Among hydrogen production methods, water electrolysis is the most proven and advanced technology. Studies examining hydrogen generation systems driven by hybrid energy production (including wind) have found that wind power produces the highest hydrogen yield. Since renewable hydrogen cannot be obtained directly, a hybrid approach is required for wind-based hydrogen extraction. Fig. 10 illustrates how wind turbines and electrolyzers are used to generate green hydrogen (Maka & Mehmood, 2024).

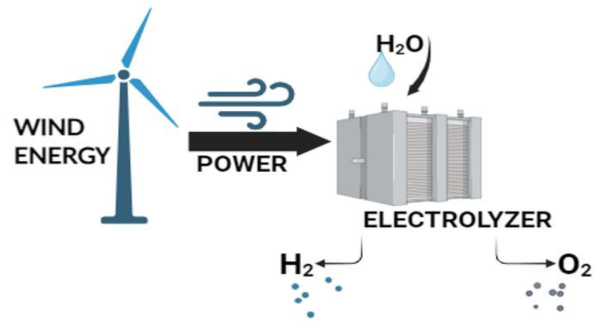

Fig. 10. Hydrogen production from wind energy

A typical system comprises a wind farm, an AC/DC converter, a power controller, and electrolyzer. The electrolyzer uses wind generated electricity to split water into hydrogen and oxygen. Hydrogen output depends on electrolyzer energy consumption (typically 5–6 kWh/Nm^3) and rectifier efficiency (85–95%). Performance can be enhanced by adjusting wind turbine power output (Terlouw et al., 2022). This method significantly reduces greenhouse gas emissions compared to fossil fuel-based hydrogen production. Overall efficacy depends on wind speed, turbine characteristics, and system location. Wind energy exhibits the lowest GHG emissions among all current hydrogen pathways. Primary challenges include wind intermittency, hydrogen storage, and fuel production logistics (J. Li et al., 2022).

4.4 Geothermal Energy

Geothermal energy has long been recognized as one of the most reliable and consistent renewable sources. Extracted from heat stored in subsurface geological layers, it presents a promising solution to rising global energy demands (Aliouane & Ouadfeul, 2023; Gutiérrez-Negrín, 2024). Despite widespread use in countries with accessible reservoirs, geothermal resources remain underutilized in many resource rich areas where extraction costs are low. Heat transfer carriers are required to bring geothermal energy to the surface. Extraction occurs in two stages: first, heat transfers between rocks; second, hot water flows to the surface (Gutiérrez-Negrín, 2024). Geothermal energy is also considered a potential answer to escalating environmental concerns and is compatible with hydrogen production. High temperature electrolysis studies indicate superior energy efficiency with geothermal integration. Proton exchange membranes split water into hydrogen and oxygen, with water temperature significantly influencing system cost, energy requirements, and hydrogen output. Elevated reaction temperatures reduce energy consumption and overall production expenses (Franco & Giovannini, 2024; Ren et al., 2024).

Geothermal hydrogen production occurs via two primary routes: geothermal power plants using geothermal fluids and waste heat for water heating and electricity generation, and flash splitter systems separating water and steam. Steam drives turbines for electricity, while recovered heat energy supports hydrogen generation. Catalysts improve oxygen dissociation, and higher water temperatures enhance process efficiency. Hydrogen is produced using alkaline and high temperature solid oxide electrolyzers powered by electricity from low and high temperature geothermal sources. High temperature sources also supply necessary heat. As shown in Fig. 11, produced hydrogen serves geothermal sectors. Recent investigations indicate that electrolyzers operating above 100°C achieve high efficiency. However, challenges persist in handling impurities particularly hydrogen sulfide and other hazardous gases at electrode terminals during geothermal hydrogen generation (Karayel et al., 2022).

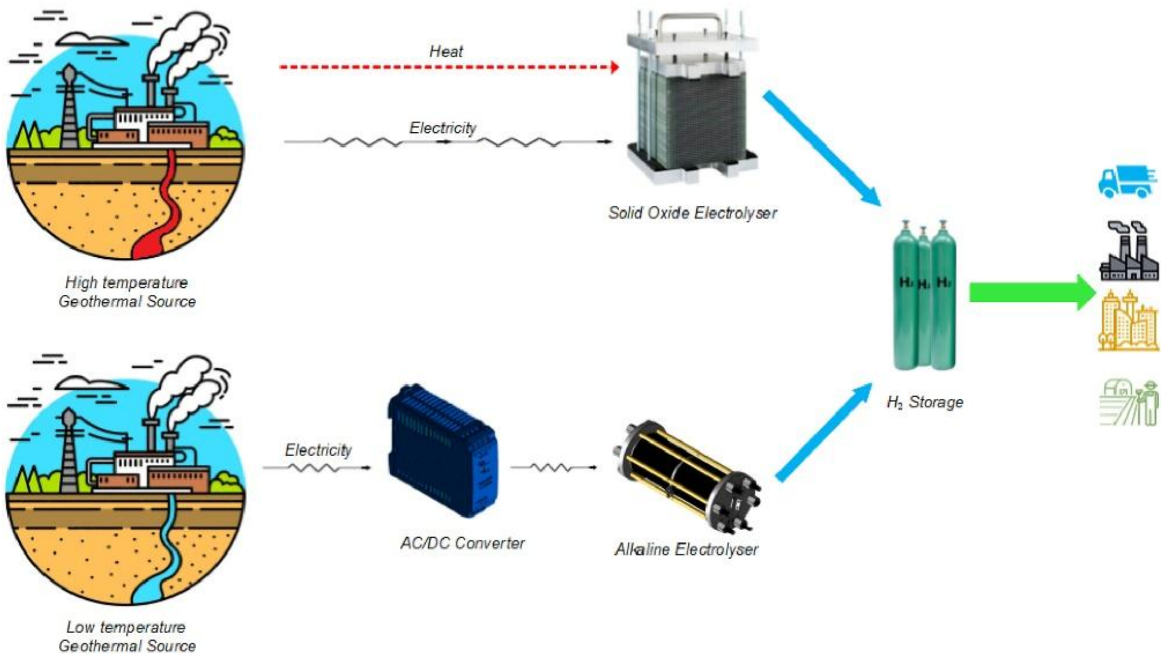

Fig. 11. Representation of hydrogen production from geothermal energy (Karayel et al., 2022)

5. HYDROGEN PROCESSING AND UTILIZATION TECHNOLOGIES

5.1 Purification Techniques

Hydrogen purification is a post-production process used to remove impurities and contaminants from crude hydrogen to produce high quality product meeting application specifications. Contaminants include water vapor, carbon monoxide, and other gases. Crude hydrogen is generated from processes like coal gasification, natural gas reforming, byproduct streams, and water electrolysis and subsequently requires purification. Fuel cell power systems require high purity hydrogen; therefore, purification must meet established standards before utilization in fuel cell vehicles (Nicita et al., 2020). Hydrogen purity depends on the generation source. Gas composition analysis employs techniques such as gas chromatography (separating gases by chemical properties) and mass spectrometry (detecting ion masses). Gas analyzers with electrochemical sensors test hydrogen purity. Several purification approaches exist, selected based on contaminant profile and required purity level (Chuah et al., 2020). Common techniques include distillation, membrane separation, electrochemical separation, pressure swing adsorption (PSA), and metal hydride separation. Membrane separation uses selectively permeable membranes; PSA employs vessels filled with adsorptive materials; distillation separates impurities by boiling point, collecting pure gas at the top and contaminants at the bottom. Cryogenic distillation effectively separates hydrogen from hydrocarbons, carbon monoxide, nitrogen, and other gases, offering high hydrogen recovery rates. However, contaminants like CO_2 and H_2O must be removed to prevent equipment blockage at low temperatures (Król et al., 2024). Recent PSA advances aim to increase H_2 purity and recovery. Conventional adsorbents—silica gel, activated carbon, zeolite molecular sieves, and alumina are commonly used. Enhancements to these materials have improved purification efficiency, particularly for CO_2 removal. Alternative PSA configurations, including two and four bed systems, have been investigated to optimize H_2 purification from sources such as synthetic ammonia tail gas and methane steam reforming (Moghadam et al., 2020).

Membrane separation offers environmental sustainability, low energy consumption, and operational flexibility. Membrane material efficacy including metal, polymer, carbon, MOF, and nanomaterial membranes is critical for efficient hydrogen separation. Metal hydride separation employs reversible H_2 absorption and desorption in storage alloys, providing a promising solution for hydrogen purification and storage applications. These technologies remove CO, CO_2, and other pollutants to meet application standards. According to the literature, grey hydrogen may contain higher contaminant levels (particularly CO_2) than green hydrogen due to its SMR production pathway and absence of advanced filtration (Katebah et al., 2022; Patel et al., 2024).

5.2 Methane Pyrolysis

Methane pyrolysis is a cost-effective, low-emission technology producing hydrogen and solid carbon. Process efficiency depends on catalysts, temperature, and reactor design. Methane pyrolysis yields CO_2-free hydrogen and crystalline carbon, resulting in substantially lower CO_2 emissions compared to conventional methods, making it more environmentally friendly (Patlolla et al., 2023). Catalytic methane pyrolysis uses metal and non-metal catalysts (including carbon materials) with reaction mechanisms including molecular and dissociative adsorption to reduce operating temperatures and increase hydrogen output. Approaches include (i) molten metal and salt pyrolysis, (ii) microwave and plasma-assisted catalytic pyrolysis, and (iii) molten metal pyrolysis (Wen et al., 2024). Catalysts such as iron, nickel, cobalt, and carbon lower reaction temperatures and increase methane conversion rates. While high temperatures are typically required, iron oxide catalysts enable lower processing temperatures while improving hydrogen and carbon generation rates. Liquid metal media prevent carbon deposition, achieving high methane conversion at elevated temperatures (Korányi et al., 2022). Thermochemical modelling optimises reaction kinetics. Future research may focus on mass transfer and methane solubility in liquid metals. Methane pyrolysis offers a carbon-free alternative to steam reforming, which generates residual CO_2. Catalytic decomposition of methane (CDM) is a promising method for producing viable hydrogen with various catalyst types and reactor designs. The technology aims to produce carbon-free hydrogen for diverse applications while generating valuable carbon byproducts with controlled morphology (Sánchez-Bastardo et al., 2021).

5.3 Plasma Reforming

Plasma reforming combines plasma discharge with thermal catalysis to enhance hydrogen production. Plasma pre-processing has proven highly effective, with two stage plasma catalysis systems demonstrating particular success (Budhraja et al., 2023). Plasma catalyst interactions offer additional research and development opportunities. Plasma reforming generates hydrogen from methane and ethanol-water mixtures by accelerating electrons in a plasma zone to break down organic matter into hydrogen and carbon syngas (N. Wang et al., 2024). Several plasma reactor types exist, each with advantages and disadvantages. Dielectric barrier discharge produces stable discharge at atmospheric pressure but consumes substantial energy. Pulsed plasma degrades pollutants efficiently but may generate secondary contamination. Gliding arc plasma processes organic molecules effectively but requires complex, high maintenance equipment. Microwave plasma generates high temperatures for contaminant breakdown but is energy intensive and may damage equipment over time. Despite its promise, plasma assisted hydrogen generation must overcome challenges including low process efficiency, high capital and operating costs, and the need for further optimization (Hrycak et al., 2023).

5.4 Fuel Cells

Cost-effective energy conversion using hydrogen has long been a concern, and fuel cell technology offers a viable solution. Hydrogen can be produced from both renewable and non-renewable energy carriers, with fuel cells enabling more efficient hydrogen utilization particularly in the transportation sector (Pistidda, 2021). Hydrogen powered fuel cells are electrochemical devices that convert hydrogen's chemical energy into electricity via redox reactions, producing only water as a byproduct. This makes fuel cells a clean, sustainable transportation solution, enabling zero-carbon vehicle operation. Fuel cell technology offers significant environmental advantages over conventional internal combustion engines (Ma et al., 2021). Current hydrogen production techniques primarily address short term needs, often relying on non-renewable resources. The energy sector requires more dependable, innovative approaches to facilitate the transition to greener energy while maintaining economic viability (Baum et al., 2022). One transportation application involves hybrid fuel systems combining H_2 with conventional fuels. Fuel cells achieve maximum electrical efficiency in combined heat and power (CHP) systems, which simultaneously produce heat and electricity from a single energy source. CHP systems include a prime mover and thermal recovery system, capable of operating on sustainable fuels including solar and biomass. Waste heat recovery further improves energy efficiency (Erixno et al., 2022).

Several fuel cell types exist, including alkaline water electrolysis (AWE), proton exchange membrane (PEM), and PEM fuel cells (PEMFCs). Alkaline water electrolysis is a well-developed, cost-effective method used in chemical industries for over a century. Anion exchange membranes (AEMs)—polymers with anionic conductivity represent a promising new approach in alkaline electrolysis research (Mehrtash, 2022). Fig. 12 illustrates polygeneration systems based on solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). The diagram shows how gas turbines and steam power plants can be coupled with high-temperature fuel cells to generate multiple byproducts and excess energy. Drawbacks include limited energy usage range, narrow operating pressure, low current density, and low hydrogen purity. PEM electrolysis cells have gained prominence due to high efficiency and hydrogen purity, offering more compact designs than alternatives. SOFCs and MCFCs are high-temperature fuel cells suitable for large-scale industrial applications, though high temperature requirements limit their use (Arifin et al., 2020).

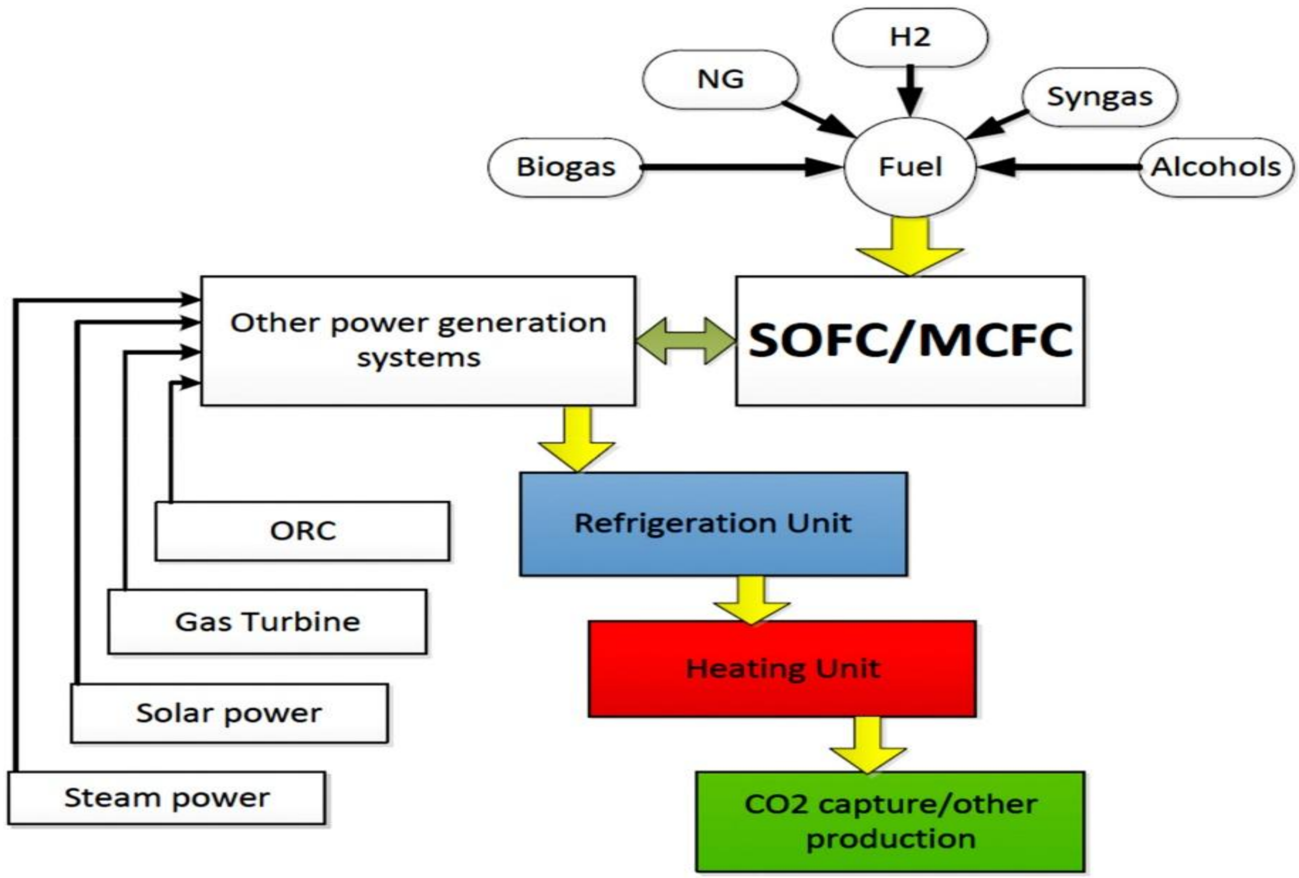

Fig. 12. Overview of polygeneration systems based on high-temperature fuel cells (Mehr et al., 2021)

Challenges in internal reforming include CO generation, chemical toxicity, low purity, and reduced biogas energy value. Microbial electrolysis using glucose as primary feedstock exhibits lower performance, but viability improves by linking liquid catalyst fuel to a fuel cell. Glucose thermally degrades into hydrogen (collected at the cathode) and carbon dioxide (collected at the anode) (Y. Li et al., 2019). Table 6 summarizes various hydrogen generation methods from renewable and non-renewable sources, with SMR remaining the most common (Nnabuife et al., 2023).

Table 6. Renewable vs. non-renewable hydrogen production

Source	Production Method	Cost ($/kg H_2)	Efficiency (%)	Impact	Examples	Ref
Renewable	Water Electrolysis	3.5-6	60-80	Low emissions	Solar, Wind, Hydropower	(A. Lima et al., 2025)
Non-renewable	Steam Methane Reforming	1-2	65-75	High CO_2 emissions	Natural Gas	(Usman et al., 2026)
Non-renewable	Coal Gasification	1-3	45-55	High CO_2 emissions	Coal	(Burchart et al., 2022)
Non-renewable	Partial Oxidation	2-3	55-65	High CO_2 emissions	Crude oil	(T. M. Lima et al., 2024)

6. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

Hydrogen is a critical component of an environmentally sustainable future, offering the ability to reduce greenhouse gas emissions and fossil fuel dependence. This section discusses the environmental and economic implications of various hydrogen generation technologies, including green, blue, and grey hydrogen, while highlighting future technologies that may reduce costs and improve access to green hydrogen. Ongoing innovation and global collaboration remain essential (Aboelela et al., 2023). Grey hydrogen, produced from fossil fuels, is inexpensive and moderately efficient but emits large quantities of CO_2. Blue hydrogen, incorporating carbon capture and sequestration (CCS), minimizes emissions but is more expensive and less efficient. Environmental impacts vary considerably, with fossil fuel-based processes generating substantial GHG emissions. CO_2 is regarded as the primary greenhouse gas due to its detrimental environmental effects; therefore, future energy carriers must focus on CO_2 emission reduction. Mitigation techniques include CCS and repurposing CO_2 as a resource (Tripathi et al., 2021).

LCA evaluates environmental effects using global warming and acidification potentials [104]. Findings indicate that biomass gasification has the highest acidification potential, mainly due to agricultural activities like fertilizer use and farming operations while, fossil fuel-based hydrogen generation is the most ecologically damaging (Osman et al., 2024). Hydrogen exists in multiple color classifications, each with distinct features. Grey hydrogen (SMR from natural gas) has high carbon emissions, making it unsustainable. Blue hydrogen incorporates CCS for emission capture. Green hydrogen, produced from renewable sources (wind, solar), is the most environmentally friendly but requires substantial infrastructure investment. Purple hydrogen combines nuclear power with electrolysis. Turquoise and yellow hydrogen are emerging variants that capture and repurpose carbon emissions. A rapid transition to renewable sources is essential for a sustainable hydrogen economy (Wei et al., 2024).

Cost-efficiency correlations for renewable and non-renewable technologies vary: natural gas costs 0.9–3.2/kg H_2 with 70–83% energy efficiency; other non-renewable sources (nuclear, thermochemical, coal) show different ranges; renewable sources have well documented conversion efficiencies. These correlations highlight economic and efficiency considerations across hydrogen synthesis pathways. Hydrogen is predicted to play a crucial role in the global transition to a greener economy (Schrotenboer et al., 2022). Hydrogen generation approaches carry important policy implications regarding energy security, economic factors, and environmental impacts. Governments can promote greener hydrogen through subsidies, tax benefits, increased research funding, regulations with specific requirements, and infrastructure development. Fostering global collaboration is also essential. Supportive government policies can create optimal conditions for green hydrogen adoption by promoting sustainability and reducing emissions (Sarmah et al., 2023).

7. TECHNOLOGICAL ADVANCEMENTS AND FUTURE PROSPECTS

Renewable hydrogen generation technologies are generally superior to non-renewable methods due to their environmental friendliness, sustainability, and low ecological impact. Renewable sources (biomass, geothermal, wind, hydropower, solar) provide cleaner alternatives to fossil fuels (Deshmukh et al., 2023). Recent advances in hydrogen generation, particularly fuel cell and electrolysis systems, emphasize cost reduction and efficiency improvement. These advancements enhance scalability and economic feasibility of hydrogen energy systems, including infrastructure

and storage materials. Transitioning to renewable hydrogen production is critical for lowering GHG emissions and mitigating environmental damage from non-renewable sources (Reigstad et al., 2022). Investment in renewable hydrogen technologies promotes innovation and technical development, leading to more efficient and cost-effective solutions. Green hydrogen has already seen transportation deployment through Germany's H_2 Mobility, which successfully operates over 90 refueling stations through corporate partnerships. The UK's HyNet Northwest project aims to reduce GHG emissions by 10 million tonnes annually by 2030. Japan's Fukushima Hydrogen Energy Research Field produces green hydrogen using solar energy, demonstrating large scale feasibility. The Port of Rotterdam is developing a comprehensive hydrogen infrastructure to become a major European hub, integrating hydrogen into industrial ecosystems for decarbonization (Blohm & Dettner, 2023).
Future research opportunities include novel production methods such as purple and biohydrogen, along with enhanced storage technologies to optimize hydrogen utilization across industries.

Table 7. Prospects for hydrogen demand

Year	Estimated Global Demand (million tonnes)	Major Demand Sectors	Growth Rate (%)	Ref
2025	100	Industry, Transport, Power	5	(Qazi, 2022)
2030	150-180	Industry, Transport, Power, Heating	7.5	(Rolo et al., 2023)
2035	220-250	Industry, Transport, Power, Heating	8.5	(Vechkinzova et al., 2022)
2040	320-380	Industry, Transport, Power, Heating	9	(Ammar et al., 2025)
2045	450-510	Industry, Transport, Power, Heating	10	(Guan et al., 2023)
2050	585-615	Industry, Transport, Power, Heating	11.5	(Benbouzid et al., 2025)

Table 7 presents global hydrogen demand projections from 2025 to 2050 (International Energy Agency, 2023)]. Improved electrolysis techniques (particularly water electrolysis) offer a renewable pathway with zero carbon emissions. Storage efficiency and safety have improved through innovations, including solid state materials and subterranean formations. The hydrogen electrolyzer market is predicted to expand dramatically, with a 1000-fold increase by 2050, driven by the shift toward a hydrogen economy and demand for sustainable energy solutions (J. Li et al., 2021; Miller et al., 2020).

8. CONCLUSION

Hydrogen as a key energy carrier: Hydrogen is a versatile, pure energy carrier derivable from diverse sources, offering a viable alternative to carbon intensive fuels and significant potential for reducing greenhouse gas emissions. Despite the industrialization of fossil fuel-based hydrogen, environmental concerns are driving a shift toward alternative sources. However, green hydrogen commercialization is limited by storage and transportation difficulties

1. Biohydrogen production via enzymatic reactions, photobiological processes, and microbial biomass conversion remains in early research stages; deeper fundamental understanding is required for future scale up.
2. Electrolysis is one of the most advanced green hydrogen methods, benefitting from technological maturity and cross-sector applications; improving process efficiency is a priority.
3. Thermal processes using solar and geothermal energy, along with emerging methods such as thermochemical cycles and biomass gasification, hold great promise for affordable, environmentally friendly hydrogen generation.
4. Alkaline and polymer membrane electrolysis can produce near pure hydrogen, while biological processes also contribute to sustainable production.
5. Supercritical water gasification of biomass faces issues related to hydrocarbon generation,

energy consumption, and material degradation, requiring intensive study for optimization.

6. Hydrogen production is driven by electrical, thermal, biological, and photonic energy, which can be derived from nuclear, renewable, and other sources via various conversion pathways.
7. Each production approach has distinct advantages and disadvantages; optimal technology choice depends on specific application requirements.
8. Using cost-effective polymeric materials for membrane synthesis can make water-splitting economically feasible. Appropriate process design can reduce capital and operating costs, achieving competitive H_2 prices.

Further research can increase the efficiency of ecologically beneficial hydrogen production techniques, especially when powered by renewable energy sources. Renewable energy is essential for a green economy, as it significantly reduces GHG emissions and mitigates climate change effects. All hydrogen production technologies require ongoing development and enhancement to meet economic and environmental demands. Through process improvement, hydrogen can be realized as a major energy carrier, enabling a sustainable energy future and a green economy.

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