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Review

Unlocking the potential of green hydrogen for a sustainable energy future: a review of production methods and challenges

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ABSTRACT

The buzz around green hydrogen is growing louder as a game-changer in the fight for a clean and sustainable energy future. This article dives into the coolest ways to create this eco-friendly fuel, exploring methods like splitting water with electricity, turning plant matter into gas, and even some cutting-edge techniques in the pipeline. This research dives deep into the latest breakthroughs in electrocatalyst and electrode materials, the secret ingredients that could supercharge hydrogen production, making it cleaner and cheaper. While good old water electrolysis using alkaline and PEM electrolyzers is the current champ, it's still a bit pricey and not as efficient as we'd like. Thankfully, innovative ways to design these "fuel-splitting champions" and integrate them with renewable energy sources are showing promise as solutions. But green hydrogen isn't just some cool science experiment; it's a potential game-changer for cleaning up our transportation, factories, and even the way we power our homes, all to fight climate change. The study also identifies areas where we need more research and ironing out of kinks before widespread use. It emphasizes the importance of keeping the innovation train rolling, smart investments in this technology, and government policies that give it a green light. By pushing green hydrogen forward, we can slash greenhouse gasses, become more energy-independent, and finally build that sustainable energy future we've all been dreaming of!

1. Introduction

Our planet's running on fumes! We desperately need to eliminate dirty fuels like coal and gas, and luckily, there are some awesome alternatives on the horizon. Sunshine, wind, heat from the Earth's core, and even the power of moving water- these renewable sources hold immense promise (but they're not without their quirks) [1-2]. Enter hydrogen: this champion packs a serious energy punch, way more than other contenders, making it a strong candidate for the future of clean energy. It is also essential in significant quantities for hydroprocessing in petroleum refineries, cleaning natural gas, and upgrading biofuels. However, hydrogen gas is not naturally available on Earth and must be extracted from various resources like fossil fuels, organic materials, and water. Extracting hydrogen from these sources remains a prevalent but challenging task. Currently, most of the hydrogen we use comes from revamping natural gas, particularly methane. This process, known as steam methane reforming (SMR), is like breaking down natural gas molecules to get the hydrogen out. It's the most popular and affordable way to do this, and it is responsible for around half of all hydrogen production globally. In the US, SMR is the champion, churning out a whopping 95% of the country's hydrogen from natural gas [3-4]. Pretty much everyone agrees: our CO2 emissions are climbing, fueled by a growing population and developing countries needing more energy. This is why there's a big push for sustainable energy sources, and guess what's getting a lot of buzz? Hydrogen. Some experts even think it could be the key to a future "hydrogen economy" [5]. The allure of hydrogen lies in its clean, burning nature- it creates no CO_2 when used for power. But here's the catch: to get that hydrogen, we currently rely heavily on fossil fuels, which pump out tons of CO_2 in the process. To cut these emissions, scientists are looking at ways to cook up hydrogen from renewable sources like plants and waste. They're experimenting with different methods, like superheating plant matter with water or turning plant-based fuels into hydrogen gas. This focus on bio-stuff for hydrogen production is a win-win. It not only cleans things up, but the variety of plant sources available also makes our energy supplies more secure and boosts the economy in developing countries, which is a big deal [6]. A method for producing hydrogen without using fossil fuels is essential [7–10]. Fossil-free methods include photocatalysis, thermochemical water splitting, and electrolysis. Of these methods, only electrolysis in alkaline electrolyzers at moderate temperatures around 75°C is commercially available. Although advanced in development, alkaline electrolysis requires an entirely electric energy input, which increases operating costs. Some of this electric energy can be replaced with cheaper thermal energy if electrolysis is conducted in solid oxide electrolyzers at temperatures between 500-1000°C. However, even at high temperatures, the proportion of energy that can be substituted with thermal energy is limited to less than 30%. Unlike electrolysis, thermochemical water-splitting processes use only thermal energy to split water and are theoretically highly efficient. Electrolyzers are classified into four main types: polymeric, alkaline, and solid oxide electrolyzers [11]. The process of direct water splitting by using sunlight is termed a photolytic process, which involves using light energy to separate water molecules into hydrogen and oxygen [12]. The replacement of fossil fuels with green hydrogen presents an effective means of alleviating the environmental impact attributed to energy-related industries, notably climate change, global warming, and acid rain. Green hydrogen is anticipated to exert a significant influence on forthcoming power and electricity systems and will be indispensable for cutting carbon emissions of energy-intensive domains like transportation and buildings. Producing green hydrogen from renewable resources is key to promoting sustainable energy production. It holds the potential to meet the hydrogen demand of these sectors while yielding markedly reduced environmental effects compared to fossil fuels [13]. Countries worldwide want to decarbonize by 2050 to combat climate change, with green hydrogen playing a critical part. Green hydrogen, produced through water electrolysis, is essential for renewable energy power plants as well as a variety of industrial and transportation applications. This paper examines water electrolysis technologies, pricing, and current advancements in electrode materials and identifies research gaps and commercial electrolyzer limits. It also investigates hydrogen synthesis from ammonia breakdown with mixed metal oxide catalysts, addressing the issues of hydrogen storage and distribution. The review focuses on recent developments in electrocatalysts and electrolyzers, such as seawater electrolysis, as well as innovations in biomass steam gasification for hydrogen production, emphasizing the importance of renewable electricity in these processes.

2. Water electrolysis

Electrolysis of water is an electrochemical method for producing green hydrogen that uses power and produces no emissions. The following equation shows the fundamental reaction for water electrolysis.

$$H_2O + \text{Electricity } (237.2 \text{ kJ mol}^{-1}) + \text{Heat } (48.6 \text{ kJ mol}^{-1}) = H_2 + 0.5O_2 \quad (1)$$

The concept of dividing water into oxygen and hydrogen fuel is quite intriguing: in theory, it shouldn't take much zap (around 1.23 volts) to do the trick at room temperature. But in the real world, things get a bit trickier – we actually need a little more juice (around 1.48 volts) to overcome some roadblocks and inefficiencies in the process [14]. While scientists have known about water splitting for hundreds of years, making it affordable hasn't been easy. That's why, even today, only a small fraction (around 4%, or 65 million tons) of the world's hydrogen comes from this eco-friendly method. Most of the hydrogen we use is actually a leftover from a different industrial process [15] . The evolution of water electrolysis technologies boasts a rich history, dating back to the 18th century [16]. This continuous development has been driven by various trends, leading to roughly five distinct generations of the technology. Notably, this journey has witnessed the emergence of four key types differentiated by their electrolytes, operating conditions, and ionic agents (hydroxyl (OH^-), proton (H^+), and oxide (O^{2-}):

- Alkaline Water Electrolysis
- AEM Water Electrolysis
- PEM Water Electrolysis
- Solid Oxide Water Electrolysis

Despite these variations in the underlying mechanisms, the fundamental principle of water splitting remains consistent across all types [17].

2.1 Alkaline water electrolysis

Alkaline water electrolysis (Figure 1), a long-established and mature technology, is widely used for industrial hydrogen production. It has been operational since the late 18th century, with significant advancements leading to the first large-scale plant in 1939. This process, which operates at temperatures between 30° and 80°C with a concentrated alkaline solution (5M KOH/NaOH), uses diaphragms made of asbestos and ZrO_2 and electrodes made of stainless steel coated with nickel. Alkaline water electrolysis is not only a well-established technique that can reach multiple megawatts, but it is also economically viable for large-scale operations. It costs USD 500-1000/kW and boasts a system lifespan of 90,000 hours, making it a practical choice for industrial applications [18]. Despite its advantages, the technology faces limitations, such as low current densities ($0.1–0.5$ A/cm^2) due to the moderate mobility of OH^- ions and the corrosive nature of KOH. The electrolyte's sensitivity to CO_2 results in the formation of K_2CO_3, which clogs the anode, impeding ion transfer and reducing hydrogen production. Additionally, the system yields gases of lower purity (99.9%) because the diaphragm fails to entirely obstruct gas crossed-over between the half-cells [18–22]. Many firms worldwide have successfully deployed and employed this technique for industrial applications. Nevertheless, there is a need for further advancements in this technology, including enhancing current density and minimizing gas crossover. New electrode materials and separators need to be developed to solve these problems. Additionally, integrating a renewable energy-powered electrolyzer for acidic water (e.g. solar, wind) helps save capital costs. Some research institutes and organizations are still attempting to improve efficiency and reduce hydrogen production costs. By development of low-cost and noble metal-free $MoS_2@Ni_{0.96}S$ as a heterojunction hybrid

Electrodes designed for the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) in alkaline surroundings. $MoS_2@Ni_{0.96}S$-1. The electrocatalyst demonstrated the most significant response, with a considerably lower overpotential of 104 mV at 10 mAcm^{-2}, in contrast to the overpotential of 182 mV for both the HER and OER at the same temperature. Additionally, obtained a lower cell voltage of 1.86V to separate water in the aggregate and displayed greater stability during 15 hours of nonstop operation [23]. The improvement of this material is attributed to the numerous heterojunction interfaces present within it, the increased exposure of active sites, and the strong integration between ultrathin MoS_2 nanosheets and non-stoichiometric $Ni_{0.96}S$ nanocrystals $MoS_2@Ni_{0.96}S$-1h [24]. Researchers have created a bifunctional electrocatalyst in nanostructure, NiCo-$NiCoO_2@Cu_2O$@CF, designed for overall water splitting and evaluated its performance in a 1M KOH mixture. This electrocatalyst exhibited enhanced electrochemical performance for both the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) in alkaline media, with low overpotentials of 133 mV and 327 mV, respectively, to achieve a current density of 10 mA cm^2. It also showed small Tafel slopes of 119 mV dec^{-1} for HER and 118 mV dec^{-1} for OER. The electrocatalyst's effectiveness was further confirmed through single-cell electrolysis, where it achieved a cell voltage of 1.69 V at a current density of ≥10 mA cm^{-2}. It remained stable for 12 hours of continuous electrolysis within a very acidic solution due to the strong physical cling of NiCo-$NiCoO_2$ nanoparticles. The enhanced efficiency is attributed to the compact dimensions and even spread of the nano heterostructures across the surface of the copper foam after oxidation. This facilitated optimal utilization of active sites during electrochemical reactions [25]. Researchers created a very effective bifunctional electrocatalyst using NiCoP nanoflakes ($NiCo_{(nf)}$-P) derived from the 2D metal-organic framework (MOF) for overall water splitting in alkaline conditions. They assessed its functionality by employing a three-electrode cell configuration and conducting linear sweep voltammetry (LSV) with a cycling rate of 2 mV s^{-1} in a 1M KOH solution. The electrocatalyst $NiCo_{(nf)}$-P exhibited excellent electrocatalytic performance, with a lower onset mili-voltage of 37 mV for the hydrogen evolution reaction and 1.435 V for the oxygen evolution reaction at a current density of 100 mA cm^{-2}, outperforming the commercial 5% Pt/C (43 mV) and IrO_2 (1.504V). Furthermore, $NiCo_{(nf)}$-P had low overpotentials of 0.119V for HER and 0.315V for OER, compared to 291 mV for Pt/C and 400 mV for IrO_2, to achieve a current density of 100 mA cm^{-2}. The Tafel slopes were also much lesser for $NiCo_{(nf)}$-P (0.112V dec^{-1} for HER and 0.066V dec^{-1} for OER) than for Pt/C (164 mV dec^{-1}) and IrO_2 (88 mV dec^{-1}), indicating efficient Electric current flow at the surfaces of electrocatalytic materials. Furthermore, the stability of the developed $NiCo_{(nf)}$-P electrocatalyst was tested at various current densities (100, 500, and 1000 mA cm^{-2}) for both. Through chronopotentiometric (V-t) measurements of continuous operation, the data indicated consistent electrochemical performance over a 30-hour period for both HER and OER, as depicted in Figure 2. This study involved the synthesis of a carbon-supported Ni-Mo-O/Ni_4Mo electrocatalyst having nanointerface doped-up with N (Ni-Mo-O/Ni_4Mo@NC) using calcination and electrodeposition methods. The electrocatalysis performance of this catalyst for an evolutionary process using hydrogen in a 1M KOH alkaline solution was thoroughly evaluated. The Ni-Mo-O/Ni_4Mo@NC electrocatalyst unequivocally demonstrated remarkable electrocatalytic activity, exhibiting a significantly lower over-potential of 61(mV) at a current density of 10 mA cm^{-2}. This astounding performance, 50% lower than that of Ni-Mo-O (0.120V), can be attributed to the N-doped layers of Carbon. Under neutral conditions in a 1M PBS solution, Ni-Mo-O/Ni_4Mo@NC exhibited an overpotential of less than 60 mV, while Ni-Mo-O showed an overpotential of around 100 mV.

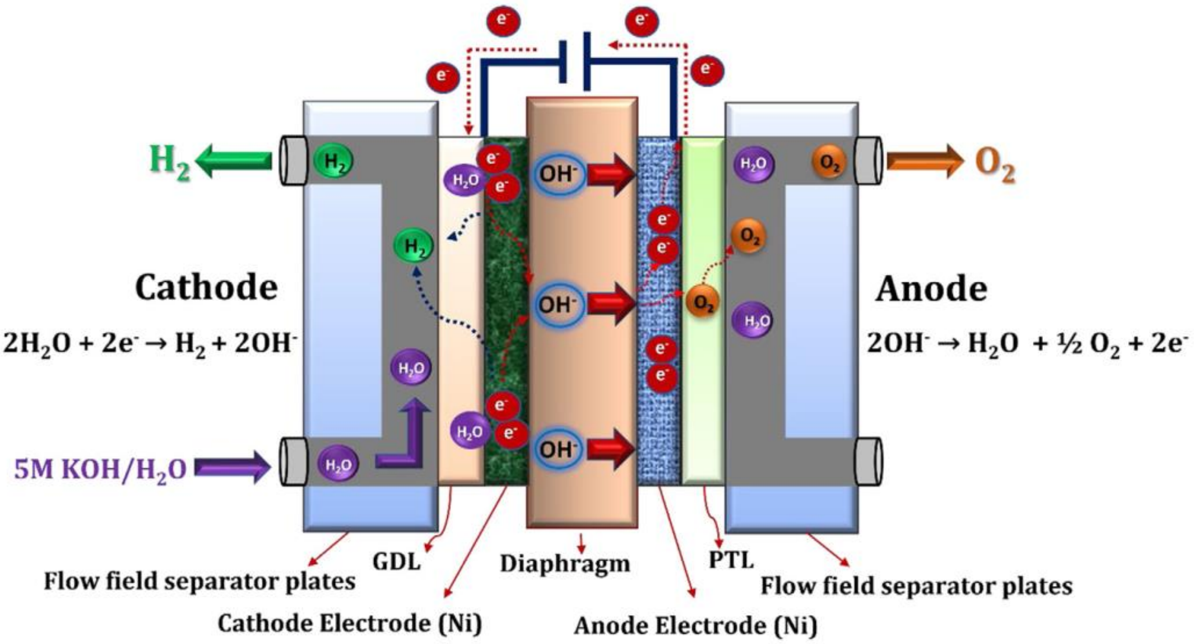


Figure 1. Diagram depicting the working principle of alkaline water electrolysis [24]

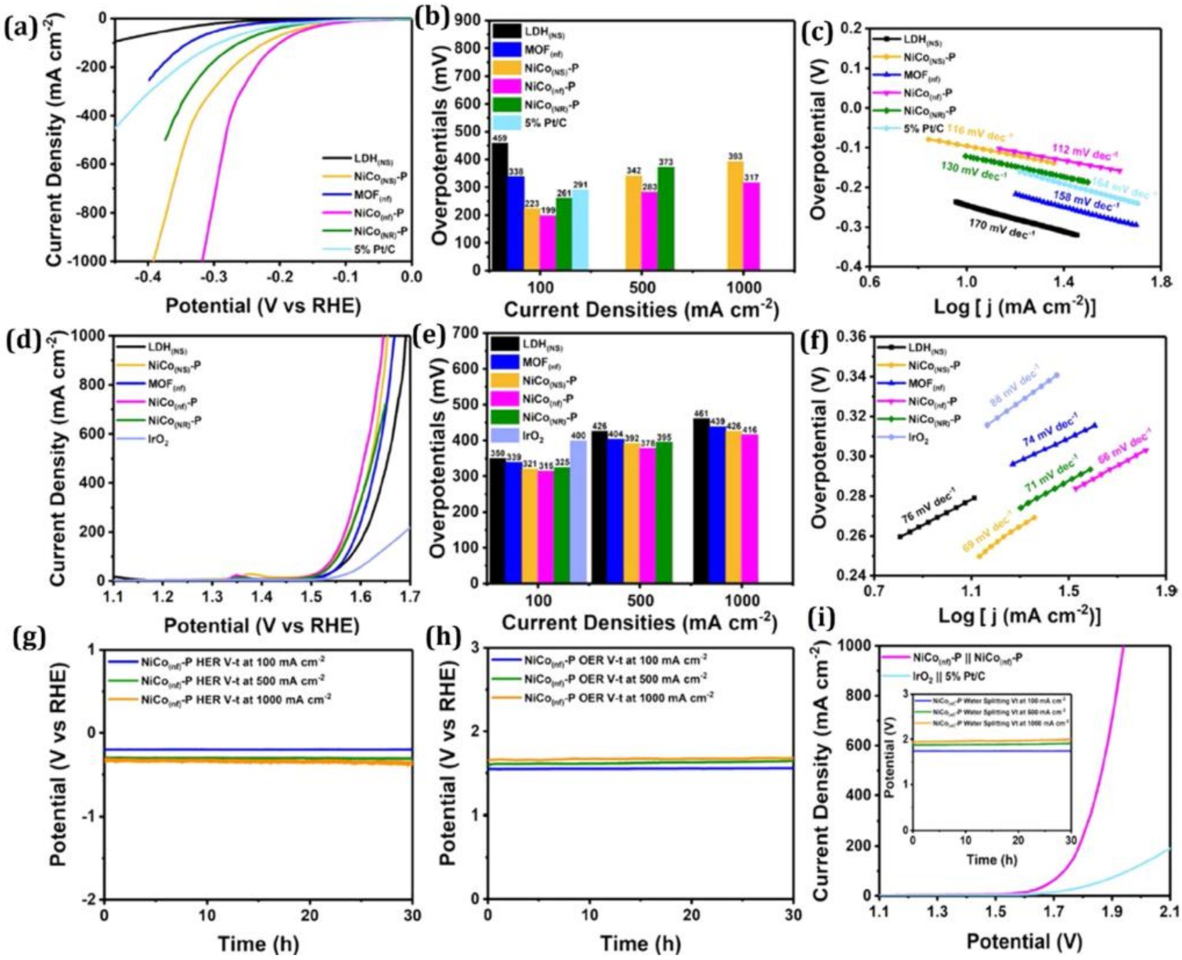


Figure 2. The electrocatalytic activity of the following synthesized electrocatalysts will be evaluated: LDH(NS), NiCo(NS)-P, MOF(nf), NiCo(nf)-P, NiCo(NR)-P, as well as the commercial 5% Pt/C and IrO2.(a) Polarization curves for the hydrogen evolution reaction (HER), (b) HER potential failures at varying current densities of 100, 500, and 1000 mAcm−2, (c) Tafel slopes for the HER, (d) Polarization curves for the oxygen evolution reaction (OER), (e) Different current densities of 100, 500, and 1000 mA cm−2 used to measure OER overpotentials.(f) Tafel incline for the OER, (g, h) Stability studies (V-t curves) of the NiCo(nf)-P electrocatalyst for both HER and OER at current densities of 100, 500, and 1000 mA cm−2,(i) Polarization curves of NiCo(nf)-P and NiCo(nf)-P; Commercial IrO2 and 5% Pt/C for overall water splitting. The inset shows the V-t curves of NiCo(nf)-P at the specified current densities for the overall water splitting process [25].

The Tafel slope for Ni-Mo-O/Ni_4Mo@NC was 0.099V dec^{-1}, which is less than the Tafel slope of Ni-Mo-O, which was 135 mV dec^{-1} [26]. Creating an efficient HER electrocatalyst, $Co_2P/N@Ti_3C_2T_x@NF$, with 3-dimensional porous architectures and interactions between heterostructures. They utilized a process that included nitriding and electrodeposition in two steps on MXene-modified NF. This electrocatalyst performed well in 1M KOH solution, with an excessive potential of 15 mV at 10 mA cm^{-2} and a Tafel incline of 0.030V dec^{-1}. It also remained stable after 3000 CV cycles. DFT simulations revealed significant binding energy (−0.822 eV) and ideal hydrogen adsorption energy, showing its potential as an effective electrocatalyst for HER [27].

2.2 Anion exchange membrane (AEM) water electrolysis

AEM water electrolysis is an emerging method for producing green hydrogen. AEMWE is gaining popularity among research organizations and institutions due to its low cost and superior performance compared to traditional electrolysis technologies.

We and Scott published the first scholarly article on AEMWE in 2011. Since then, several researchers have contributed to its advancement [28]. AEM water electrolysis technology is comparable to traditional alkaline water electrolysis [29]. Alkaline water electrolysis differs from AEM water electrolysis in that it replaces traditional asbestos diaphragms with quaternary ammonium ion exchange membranes. AEM water electrolysis has various advantages, including using cost-effective transition metal catalysts instead of noble metal catalysts and using purified water or a low-concentration alkaline solution (1M KOH) as the electrolyte instead of a high-concentration solution (5 KOH Solution) [30]. AEM water electrolysis utilizes an anion exchange membrane and electricity to split water through electrochemical reactions. The process involves two main reactions: the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER). At the cathode, water molecules are reduced to produce hydrogen gas (H_2) and hydroxyl ions (OH^-) by gaining electrons. Hydrogen is released at the cathode, while OH^- ions move across the membrane towards the anode, attracted by its positive charge. Simultaneously, electrons flow through an external circuit to the anode. At the anode, OH^- ions recombine to form water and oxygen gas (O_2), which is released. This describes the fundamental operation and half-cell reactions involved in AEM water electrolysis Figure 3.

Significant advances and challenges characterize the field of AEM water electrolysis. The technology is currently in the developmental stage, steadily progressing towards kW-scale applications. Many international research organizations and institutions are currently engaged in the advancement of AEM water electrolyzers, as outlined in Table 1. However, substantial advancements and enhancements are necessary to expand the utilization of this technology for business purposes. Key challenges include achieving sufficient stability, with current targets aiming for operational lifetimes of up to 100,000 hours, and reducing the high cost of hydrogen production. As of 2020, the production cost was approximately USD 1279 per kW/H_2, with a target of reducing this cost to USD ≤ 300 per kW/H_2 by 2050. Recent progress has been achieved in tackling these obstacles, including the creation of a 3D electrode for producing oxygen using non-crystalline NiFeOOH on activated carbon fiber paper. This electrode showed excellent electrochemical performance in a 1M KOH solution, with an overpotential of just 170 mV at 10 mA cm^{-2}, a low Tafel slope of 39 mV dec^{-1}, and exceptional stability over 240 hours of continuous operation. Synthesis report of Cu-Co-P on carbon paper via electrodeposition techniques optimized for HER in alkaline solutions and enhancement of electrochemical performance through surface modification and copper (Cu) incorporation. The modified Cu-Co-P1200/CP electrode demonstrated significant enhancements, having an excessive potential of 59 mV at 0.010A cm^{-2} and a Tafel incline of 0.038V dec^{-1} presented in Figure 4. This electrode also demonstrated promising performance in a single-cell AEM water electrolyzer setup. Additionally, the development of a non-noble metal Electrocatalyst $Cu_{0.5}Co_{2.5}O_2$ anodes by means of co-precipitation techniques showed improved performance with an overpotential of 285 mV at 10 mA cm^{-2} in 1M KOH solution.

This electrode maintained high stability during extended operation, including achieving a current density of 1.3 A cm^{-2} at 1.8 V and demonstrating durability over 2000 hours at 10 mA cm^{-2}. Furthermore, advancements in poly (fluorenyl-co-aryl piperidinium) (PFAP)-based anion exchange materials as electrolytes and binders have contributed to achieving high ionic conductivity and durability under alkaline conditions. Combined with platinum group metal (PGM) catalysts, these materials achieved impressive cell performances and durability, highlighting their potential for practical applications in AEM water electrolysis. Overall, while significant progress has been made in improving the performance and durability of AEM water electrolysis technologies, ongoing research and development efforts are essential to overcome remaining challenges and commercialize this technology effectively [32–35].

2.3 PEM water electrolysis

In PEM water electrolysis, water undergoes electrochemical splitting into hydrogen and oxygen. Initially, at the anode, water molecules decompose to produce oxygen (O_2), protons (H^+), and electrons (e^-). Oxygen is released from the anode surface, while protons migrate through the proton-conducting membrane to the cathode. Simultaneously, electrons flow through an external circuit to the cathode. At the cathode, protons and electrons combine to form hydrogen gas (H_2). This process outlines the fundamental principle of PEM water electrolysis, as depicted in Figure 5. PEM water electrolysis technology has achieved a high level of technical maturity and is currently available for industrial and transportation applications on the megawatt (MW) scale. This is facilitated by several prominent manufacturers, as indicated in Table 1. Further enhancements are required to effectively lower the cost of hydrogen production, which currently ranges from USD 700 to 1400 per kW/H_2 (2020), with a targeted reduction to USD ≤ 200 per kW/H_2 by 2050. Challenges include replacing or reducing platinum group metals, minimizing costs associated with bipolar plate coatings, and optimizing membrane thickness to enhance cell efficiency (Figure 6).

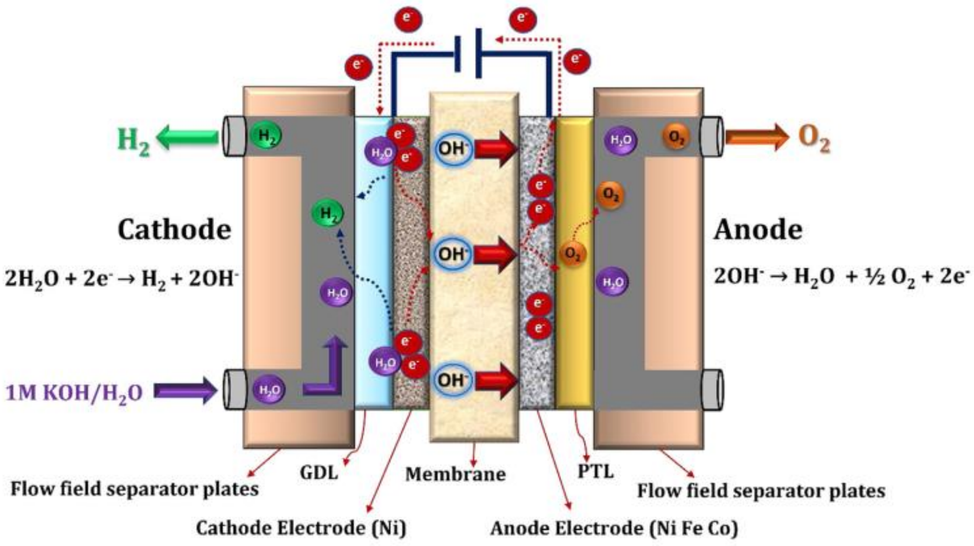


Figure 3. Schematic representation of the working principle of AEM water electrolysis electrolysis [31]

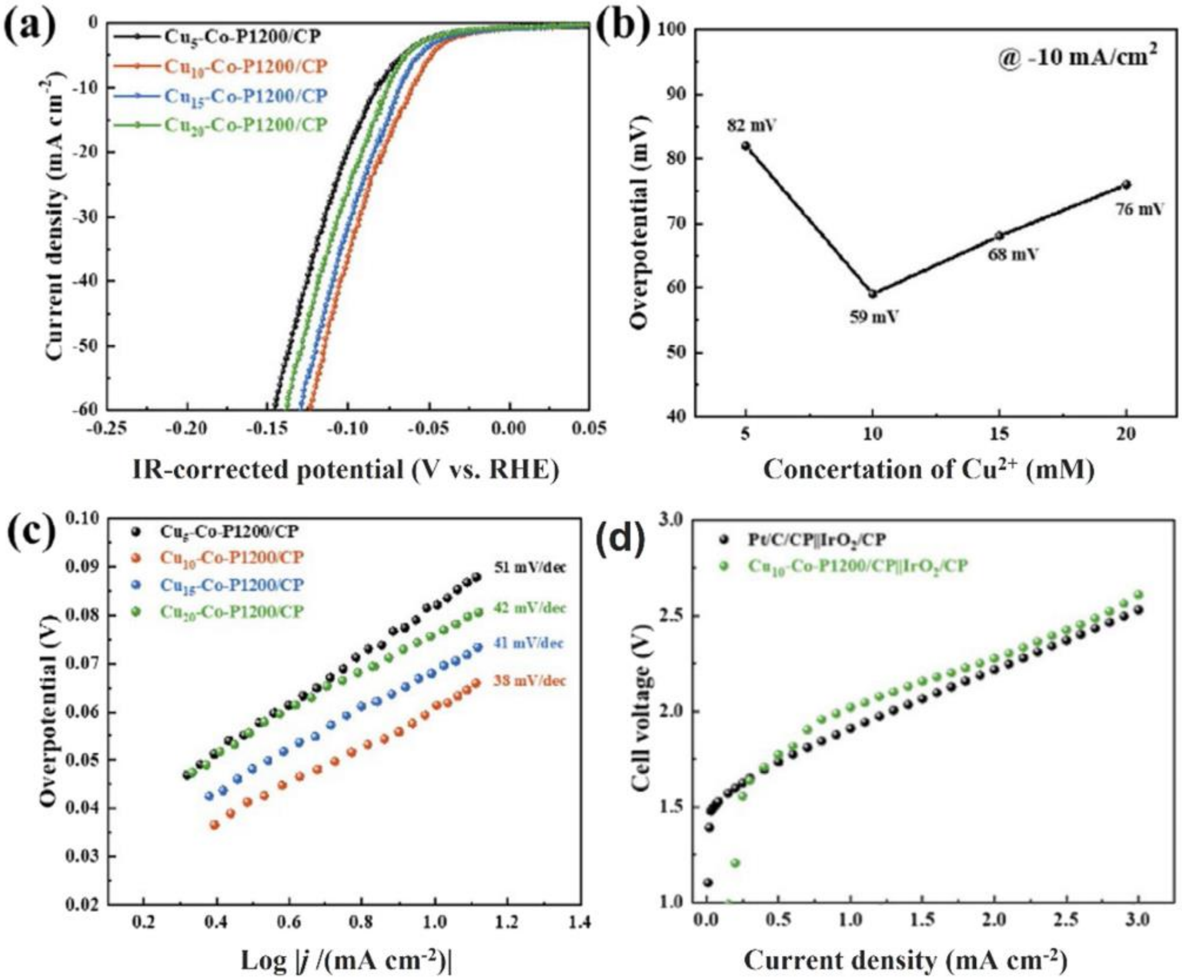


Figure 4. a) The HER diagrams depicting polarization of Cu-Co-P1200/CP electrodes were rigorously tested with varying concentrations of Cu^{2+} in a 1M KOH sol. at a scanned rate of 0.005V/s. b) Investigating the impact of changing Cu^{2+} concentrations on overpotential while upholding a constant current density of 10 mA/cm^2. c) Tafel slopes. d) Current-Voltage polarization curves of a single cell AEM water electrolyzer with IrO_2/CP as the anode, paired with the as-synthesized Cu_{10}-Co-P1200/CP electrode as the cathode, and a comparison with the commercial Pt/C/CP [32].

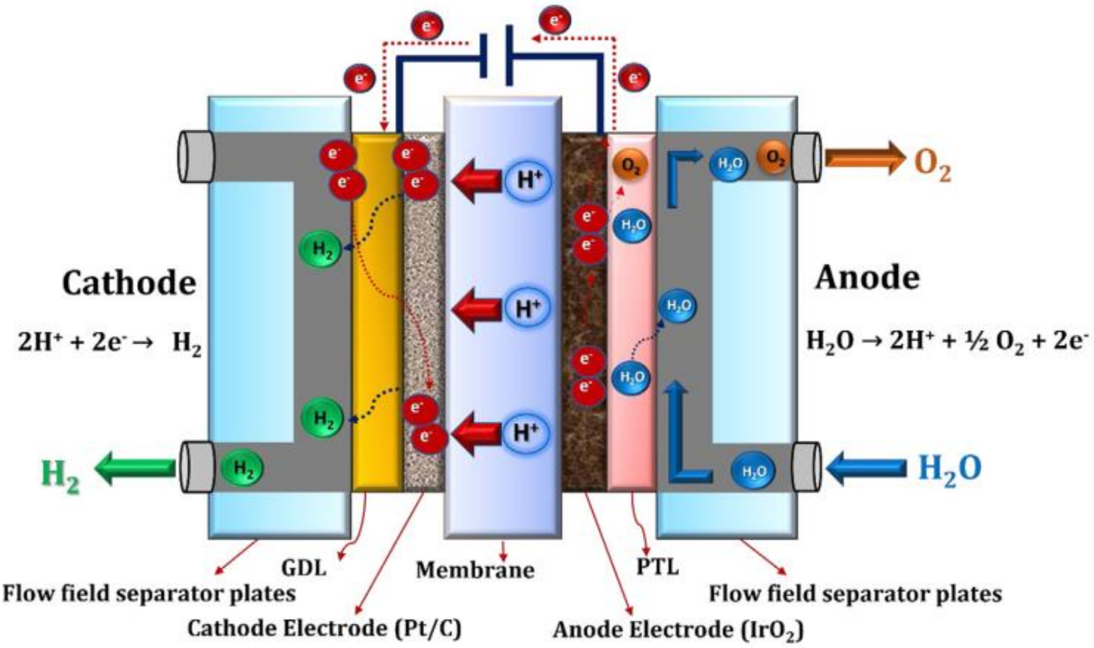


Figure 5. Schematic illustration of the PEM water electrolysis operating principle [31]

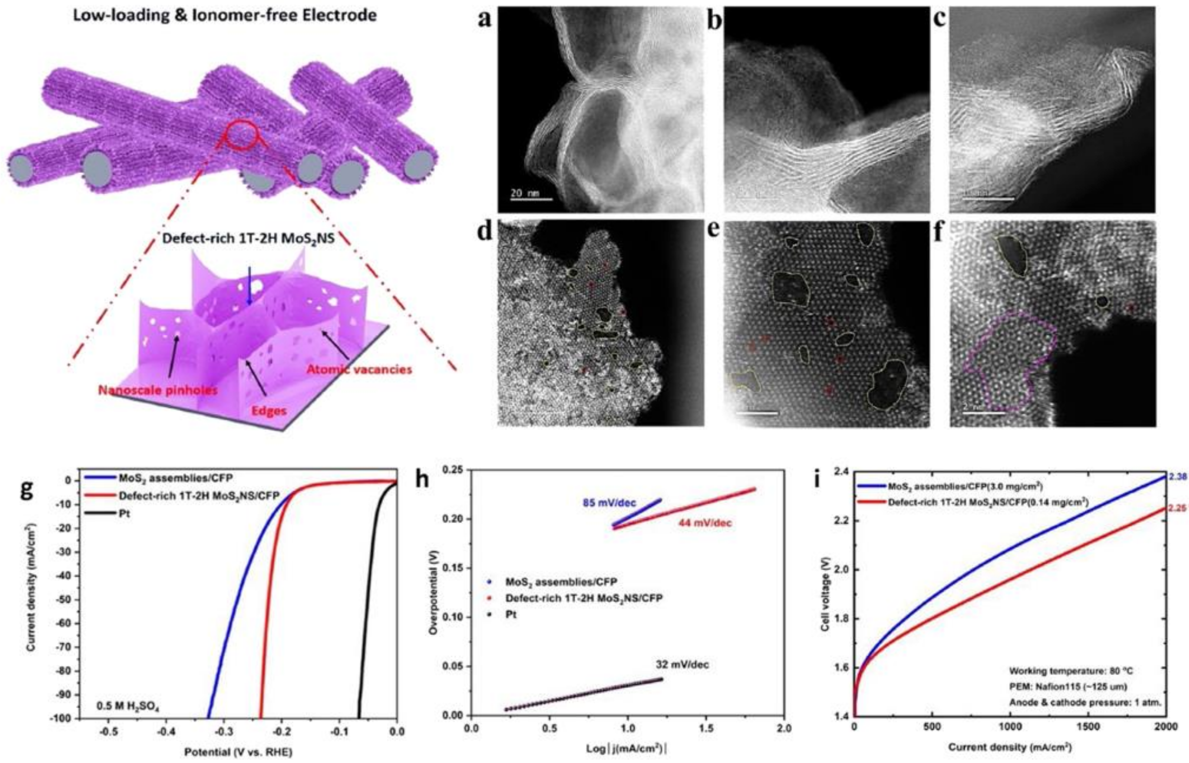


Figure 6. This is a graphical illustration of an electrolyte without ionomers featuring ultra-low-loading, defect-rich 1T-2H MoS_2 nanosheets synthesized in situ. The HAADF-STEM visuals in (a–f) confirm the presence of boundaries, fissures, and atomic holes simultaneously in defect-rich 1T-2H MoS_2NS/CFP. The polarization curves of MoS2 assemblies/CFP and 1T-2H MoS2NS/CFP with defects are displayed in (g), along with the corresponding Tafel plots in (h). Moreover, (i) demonstrates the polarization curves of defected 1T-2H MoS2NS/CFP and MoS2 assemblies/CFP in a PEMEC at 353K [36].

Efforts towards cost reduction include innovative approaches such as integrated electrode architectures. For instance, integrated Pt nanowires on ultrathin titanium gas diffusion layers (PtNW/Ti) have demonstrated promising performance in PEM water electrolyzers, achieving a lower overpotential of 63 mV at 100 mA cm^{-2} and a cell voltage of 1.643 V at 1 A cm^{-2} with significantly reduced catalyst loadings compared to conventional MEAs. Additionally, synthesized ionomer-free electrodes (1T-2H MoS_2NS/CFP) for hydrogen evolution, showing a minimal overpotential of 192 mV and a cell voltage of 2.25 V at 2 A/cm^2 in PEM water electrolyzers. Despite commercial Pt/C catalysts exhibiting slightly lower cell voltages (2.18 V), the performance of these integrated electrodes represents a notable advancement over non-noble catalysts. These innovations underscore ongoing efforts to enhance the efficiency and cost-effectiveness of PEM water electrolysis technologies for broader market adoption [37].

2.4 Solid oxide water electrolysis

Solid oxide water electrolysis typically operates at elevated temperatures, utilizing water in the form of steam to produce green hydrogen and oxygen. During the process, at the cathode, water molecules are initially reduced to hydrogen (H_2) and oxide ions (O_2^-) through the addition of two electrons. Hydrogen is released from the cathode, while oxide ions migrate through an ion exchange membrane to the anode. At the anode, oxide ions undergo further reduction to produce oxygen and electrons.

Oxygen is then released from the anode, and electrons travel back to the cathode through an external circuit due to the positive charge attraction. This outlines the fundamental operational principle of solid oxide water electrolysis, depicted in Figure 7. Solid oxide water electrolysis technology is currently advancing towards commercialization, with various global research institutions and organizations actively involved in its development. Several commercial manufacturers of solid oxide electrolyzers are listed in Table 1. This technology offers high energy efficiency by operating at elevated temperatures and utilizing non-noble metal electrocatalysts. However, challenges such as long-term stability and high hydrogen production costs remain significant. Presently, stability is around 20,000 hours, with a targeted improvement to 100,000 hours, while the current hydrogen production cost stands at USD 2000 per kW/H_2 (2020), with a goal to reduce it to USD ≤ 200 per kW/H_2 by 2050.To address these challenges, efforts are focused on enhancing long-term stability through electrochemical fluctuations of electrode materials and exploring new perovskite materials for improved durability. Additionally, scaling up electrolyzer production with renewable energy sources is being pursued to reduce costs. Recent advancements include the development of $Ni_{1-x}Cd_xO$-SDC composite oxide materials for hydrogen electrodes in reversible solid oxide cells. Their R-$Ni_{0.9}Cd_{0.1}O$-SDC electrode exhibited high electrocatalytic activity and stability under various conditions (Figure 8 and Figure 9).

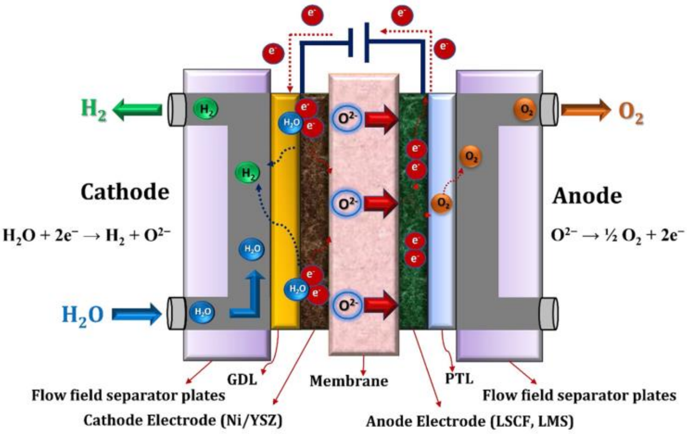


Figure 7. Schematic view of solid oxide water electrolysis working principle [31]

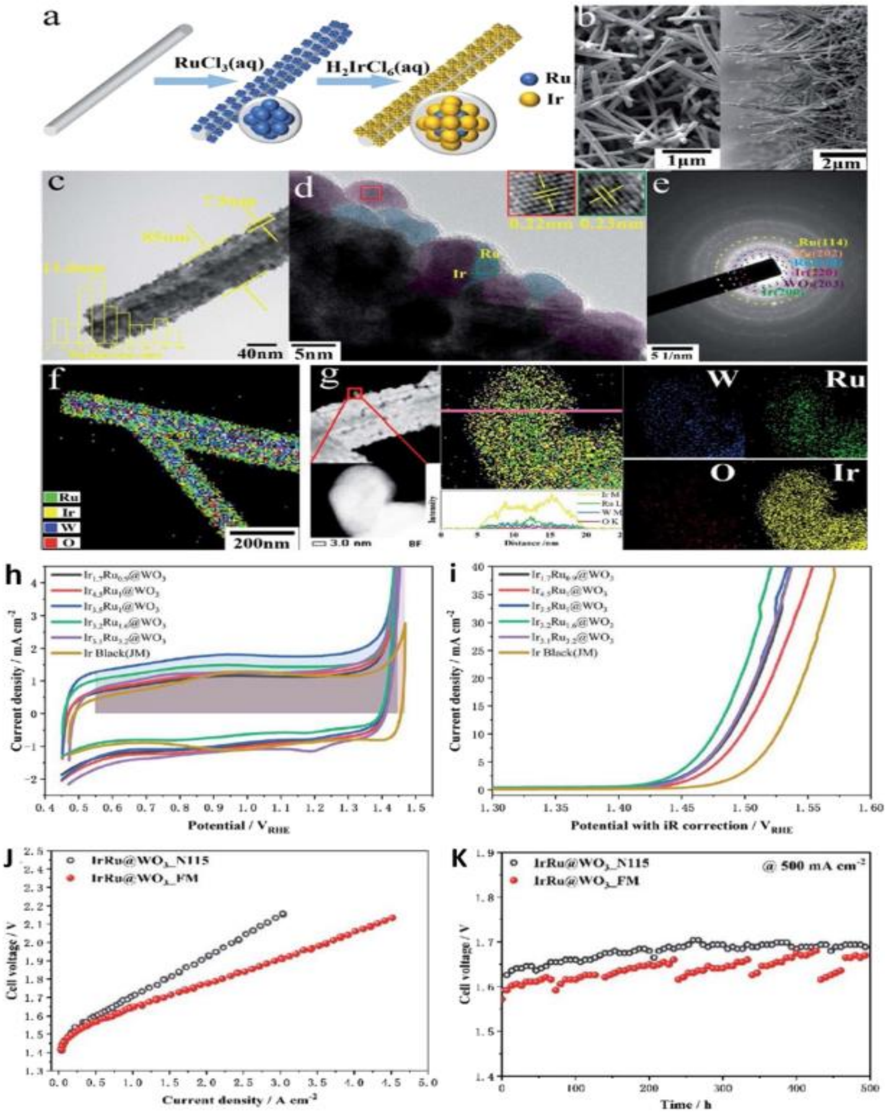


Figure 8. Physicochemical and electrochemical performance of the developed IrRu@WO3 nanorods.(a) The diagram shows the synthesis procedure of IrRu@WO3. (b) The left image is a scanning electron microscope (SEM) image, and the right image shows a sectional view of the array. (c) A transmission electron microscope (TEM) image displays a single nanorod.(d) A high-resolution TEM (HR-TEM) image demonstrates the IrRu coating, with blue indicating Ru and purple indicating Ir. Inset images provide magnified views of specific areas. (e) A selected area electron diffraction image is displayed. (f) A scanning TEM (STEM) image illustrates a single nanorod with overlapping element mapping. (g) A high-angle annular dark-field (HAADF)-STEM image displays an IrRu grain. Elemental mapping of Ir, Ru, W, and O is presented, along with a merged picture and scanning lines parallel to the pink line. (h) CV curves are included, with a darked/marked area representing the OER stabilities.(i) OER LSV curves are shown. (j) I-V polarization curves for a single electrolyzer at 353K are displayed. (k) Durability testing at 353K at same current density is also included [37]. (To understand the color references in the figure legend, please consult the online version of the article.)

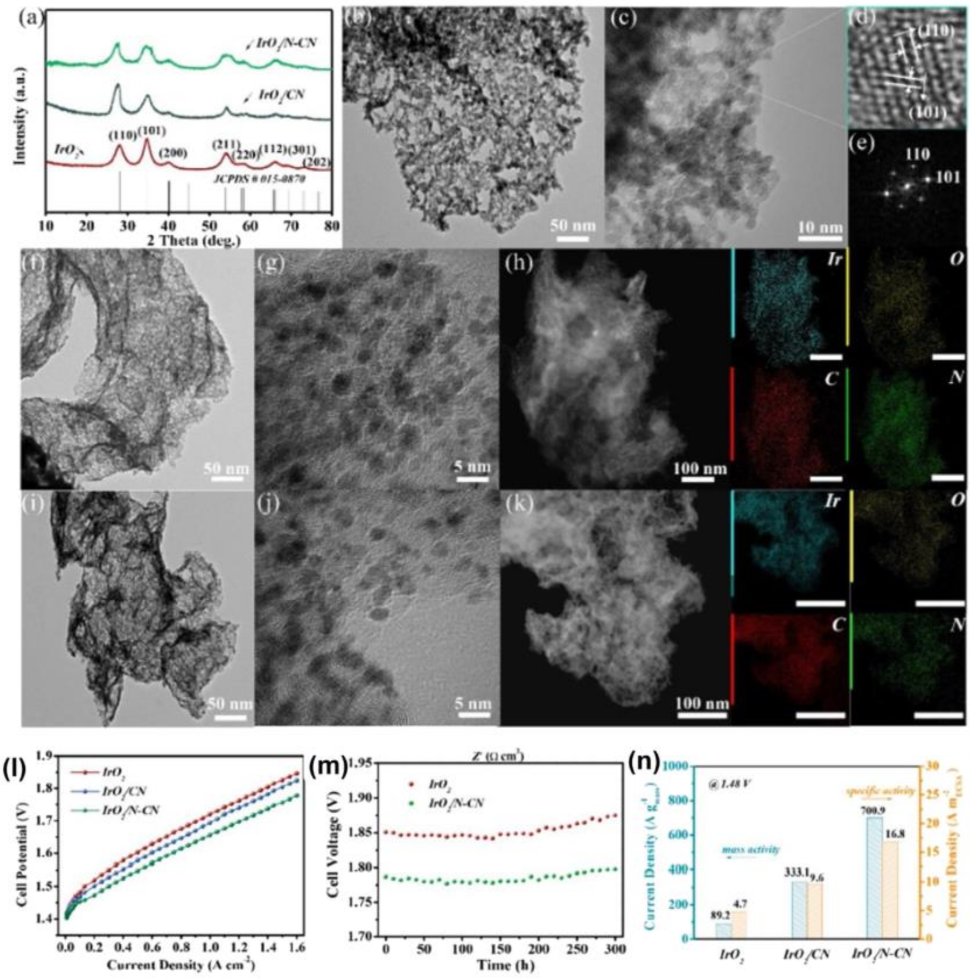


Figure 9. (a) Patterns from XRD analysis; (b) Images from TEM and HRTEM; (c, d) Patterns from corresponding Fourier transforms of IrO_2; (f) Images from TEM and HRTEM; (h) Images from HAADF; and the corresponding mapping of Ir, O, C, and N elements in IrO_2/CN; (i) Images from TEM and HRTEM; (k) Images from HAADF; and the corresponding EDX mapping of Ir, O, C, and N elements in IrO_2/N-CN. (l) I-V polarization curves, (m) IrO_2/N-CN stability over 300 hours at 1.6 A cm^2, and (n) IrO2, IrO_2/CN, and IrO_2/N-CN mass and specific activities at 12.48 V [38]

Table 1. Global main electrolyzer manufacturers and their specifications

Alkaline Water Electrolysis						
Manufactured by	Origin of Country	Generic Name	H_2 Capacity (m^3/h)	Pressure (psi)	Energy used (kWh/Nm^3)	Ref.
Nel.	Norway	A3880	2784–4500.8	2900.75	3.8–4.4	[39]
Cummins	Canada	HySTATÂ® -100–10	116	145.038	5.0–5.4	[31]
John Cockerill	Belgium	DQ-500	580	435.113	4.0–4.3	[31]
McPhy	France	MeLyzer 800–30	928	435.113	4.5	[40]
Sunfire	Germany	HyLink Alkaline	2586.8	435.113	4.7	[41]
Nuberg PERIC	China–India	ZDQ-600	696	290.075	4.6	[42]
TIANJIN Mainland	China	FDQ800	1160	72.5189	4.4	[35]
GreenHydrogen	Denmark	HyProvide A-90	104.4	507.632	4.3	[43]
AEM Water Electrolysis						
Enapter	Germany	AEM Multicore	210	35	4.8	[44]
PEM water electrolysis						
Nel.	Norway	M5000	5800	435.113	4.5	[45]
Cummins	Canada	HyLYZERÂ® -4.000-30	4640	435.113	4.3	[31]
Siemens	Germany	Silyzer 300	116–2320	507.632	N/A	[46]
Proton onsite	USA	M400	483.72	435.113	N/A	[47]
ITM Power	UK	HGASXMW	127.6–2204	290.075	N/A	[48]
Plug Power	USA	GenFuel 5 MW	1160	580.151	5.2	[31]
Elogen	France	ELYTE 260	301.6	435.113	4.9	[49]
Solid oxide water electrolysis						
Sunfire	Germany	HyLink SOEC	870	580.151	3.6	[41]

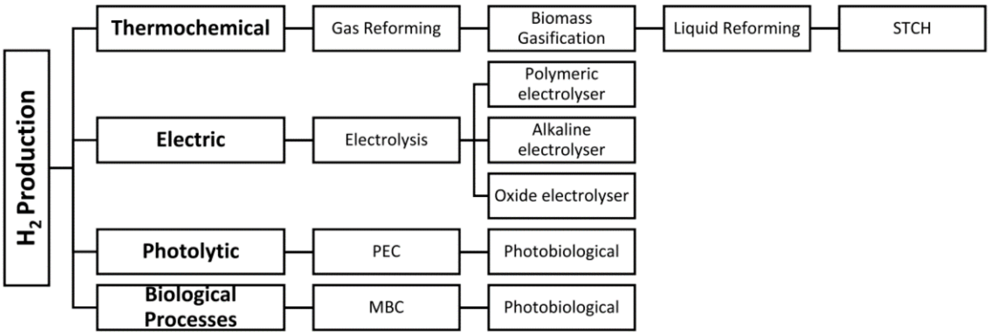
Introduction of cobalt-free $Ba_{1-x}Nd_xFeO_{3-\delta}$ perovskite materials as oxygen electrodes in solid oxide cells, demonstrating high electronic conductivity and low thermal expansion coefficients, along with significant current densities at high temperatures. These developments underscore ongoing efforts to improve the efficiency, stability, and cost-effectiveness of solid oxide water electrolysis technology for broader commercial applications [50–52].

2.5 Biomass gasification

Hydrogen can be produced through various methods, as illustrated in Figure 10. These methods include thermochemical processes, which require heat, organic reactants like water or ammonia, and fossil fuels to be effective [53]. The biological technique uses microbes (bacteria and microalgae) to convert biomass into hydrogen through a biological reaction [55]. Sunlight or organic molecules serve as the activator for this approach. Two biological processing technologies, microbial biomass conversion (MBC) and photobiological techniques, are employed to produce hydrogen. The most common method for producing hydrogen is through electrolysis using electricity, assuming the electricity comes from zero-carbon sources such as solar and photovoltaic energy [50,56–59]. Variable electricity generation from sources such as solar and photovoltaics is insufficient to guarantee a consistent hydrogen supply. Consistent production methods, which are currently reliant on fossil fuels, need to be supplemented. Utilizing established technologies, biomass energy has the potential to play a significant role in producing energy carriers like biomethane or syngas, which can be converted into hydrogen as required. There is a wealth of scientific literature [60–65], which showcases the different methods of converting biomass into hydrogen, which can be categorized into two main groups. These processes involve biochemical reactions driven by microorganisms and photo-fermentation, as well as thermochemical reactions like pyrolysis & gasification. After that, the subsequent procedures involve syngas upgrading and biomethane reforming. In order to generate a gas that contains a high proportion of hydrogen and minimal carbon content, it is essential to utilize a hydrogenizer to alter the hydrogen-rich syngas. This process involves reducing the carbon monoxide (CO) content by converting it into carbon dioxide (CO_2) and hydrogen (H_2), and then eliminating the CO_2. Specialized water-shift reactors with steam injection that are pressurized and CO_2 removal systems can be employed to effectively eliminate the carbon content [66].

2.6 Experimental gasification plant

An early version of the gasifier, designed for the process of converting a substance into gas using air, was adapted for oxy-gasification experiments, requiring technical and mechanical modifications to the feed framework, piping, and gasification agent allocation to guarantee consistent reaction conditions (Figure 11). Special attention was given to sealing the gasifier to prevent air infiltration during the oxy-steam gasification process, which operates at higher temperatures. Oxygen was kept in pressurized tanks at 200 bars for gasification, while a small electric boiler produced saturated steam at 4 bars, with a capacity of up to 10 kg/h. The process line had different meters and sensors to control and oversee the conditions during experiments. The gasifier functions in a semi-batch manner, where biomass is held in a tightly sealed container, allowing for around 8 hours of self-sufficiency. The biomass is transported into the reactor by a screw conveyor in an automated manner. Upon ignition with a removable external heater, the process becomes auto-thermal. The gasifier is maintained at near-atmospheric pressure by a blower and oxygen supply, with downstream sections at slightly lower pressure to prevent air leakage. A mobile scraper is used to frequently clean the grate supporting the reaction bed in order to avoid the accumulation of char along with ash. The system for removing impurities from syngas consists of three cyclones in a row and a filter made of biomass and fabric. After the experiment, the ash is kept in a sealed tank for later removal. An Agilent 3000 micro-gas chromatograph is used to constantly check the composition within the syngas. It measures significant elements like CO, CO_2, H_2, CH_4, N_2, O_2, and other hydrocarbons. This allows for ongoing evaluation of the gasification process. Analysis of tar and solid particles is conducted once the operating conditions become stable, following the guidelines outlined in CEN/TS 15439:2006. The facility is outfitted with an electronic system that gathers data to oversee and document the primary operational variables, such as temperatures, pressures along with syngas flow. This ensures accurate control and assessment of the gasification process [67,68].



STCH, PEC, MBC represent solar thermochemical hydrogen, photoelectrochemical, and microbial biomass conversion, respectively.

Figure 10. Production methods of hydrogen [54]

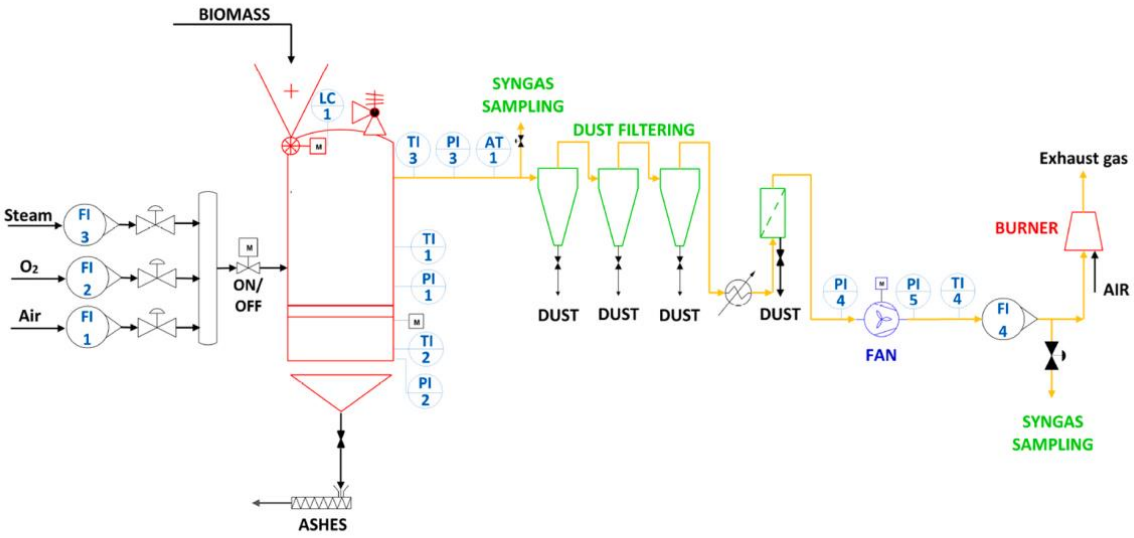


Figure 11. Diagram illustrating the flow of the experimental gasification plant [54]

3. Hydrogen generation from syngas evaluation of effectiveness

Enhancing the level of hydrogen concentration in syngas generated by oxy-steam gasification can reduce its carbon content. A hydrogenation plant capable of producing large amounts of H_2 and CO_2 gases and the system was constructed and tested using the Aspen Plus® tool. The hydrogenizer, depicted in Figure 12a, relies on syngas generated from the oxy-steam gasification process. To lower CO content, we employed a straightforward configuration with a single water-shift. To reduce the amount of steam used and minimize its effect on the energy requirements of the hydrogenizer, the method employs absorption using a heated potassium carbonate solution to remove CO_2. This method is chosen for its well-established efficiency in CO_2 removal; the off-gas experiences low hydrogen loss, and the rich solution requires modest heat for regeneration. The hydrogenizer efficiently recovers sensible heat from several streams to improve energy sustainability [69].

3.1 Configuration of the plant

The plant operates by first cooling high-temperature syngas to 300°C to prevent TAR condensation, producing some steam in the process. The resulting syngas is subsequently cooled to the surrounding temperature by employing a water-based scrubber, which eliminates small particles and condensable TAR. The treated water is utilized on steam generators downstream. A portion of the purified syngas is directed towards a boiler in order to provide the steam required for the complete gasification and hydrogen production facility. A three-way modulating valve ensures the correct amount of syngas is sent to the boiler, making the system self-sufficient and not reliant on external energy sources. The carbon dioxide emissions resulting from this technique are deemed to be carbon neutral due to the bio-origin of the syngas. The remaining syngas is used for hydrogen production. Operating at 3.9 bar, prior to entering the CO-Shift catalytic reactor, the syngas undergoes compression and is combined with steam, where CO reacts with steam to produce CO_2 and H_2.

The mixture needs to enter the reactor at 320°C, so it is preheated using a heat regenerator that recovers heat from the reactor's exothermic reaction. The reaction that occurs is,

$$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g) \quad (2)$$

The gas produced by the CO-Shift reactor contains a significant amount of CO_2, which is captured using a hot potassium carbonate solution. This process involves an absorber to separate CO_2, a heat exchanger for heat recovery between lean and rich solvents, and a heat exchanger is used to recycle heat within lean and rich solvents, while a stripper is employed to extract carbon dioxide (CO_2) from the rich solution by utilizing heat from medium-pressure steam condensation. The reaction taking place for CO_2 capture,

$$CO_2(g) + K_2CO_3(aq) + H_2O(l) \rightarrow 2\ KHCO_3(aq) \quad (3)$$

The plant requires a significant amount of steam for various processes: in order to make gas with oxygen in the gasification process, to keep the exact molar ratio of steam to carbon in the CO-Shift reactor, and to strip CO_2 in the reboiler. To ensure the system's independence from external energy sources and to maintain the renewable origin of the hydrogen, part of the syngas is used to meet the thermal power demand. A syngas cooler located downstream of the gasifier is responsible for the production of steam and additional steam is generated in a syngas-fired boiler, ensuring the hydrogen production system is energetically autonomous.

3.2 Photocatalytic water splitting

Photocatalysis, sometimes termed artificial photosynthesis because it mimics the process of photosynthesis in plants, involves enhancing or altering the rate of redox reactions with the help of solar energy and a stable semiconductor that remains unaffected and unconsumed during the reaction [70]. The core of photocatalytic hydrogen production is a semiconductor photocatalyst capable of converting solar energy into chemical energy. Ideal photocatalysts should be efficient, affordable, recyclable, and non-toxic, with proper band alignment and bandgap. When these criteria are met, the photocatalyst can generate excitons that participate in redox reactions to split water into hydrogen and oxygen.

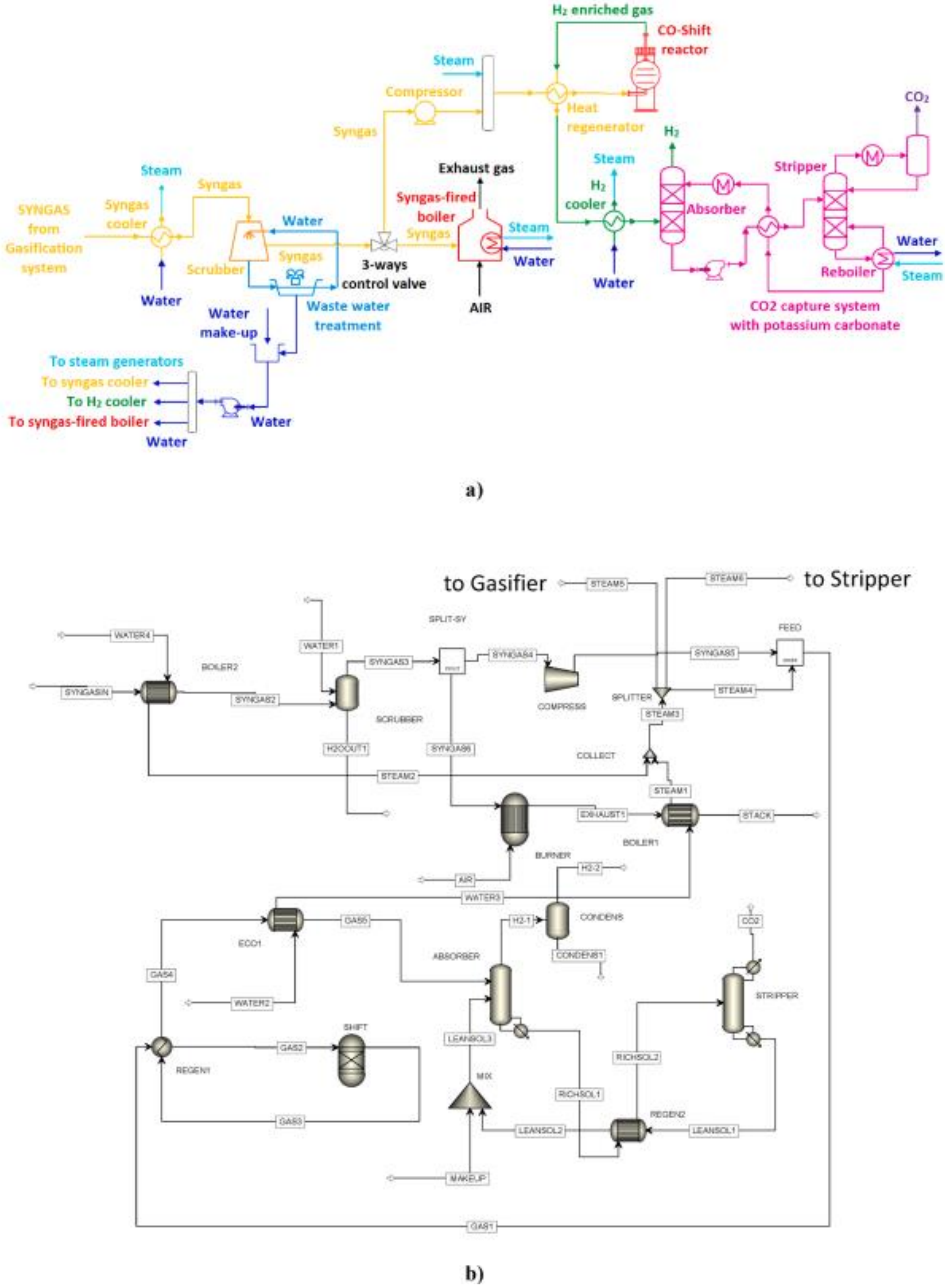


Figure 12. a) Aspen Plus process flow diagram; b) process flow diagram for the hydrogenation of syngas plant [54] (The reader is suggested to use the referred paper for a better view of the image).

The fundamental steps in photocatalytic water splitting to produce hydrogen fuel are illustrated in Figure 13. When a photocatalyst is exposed to solar energy equal to its bandgap, it generates charge carriers (electrons and holes). Electrons move to the conduction band, while holes stay in the valence band.

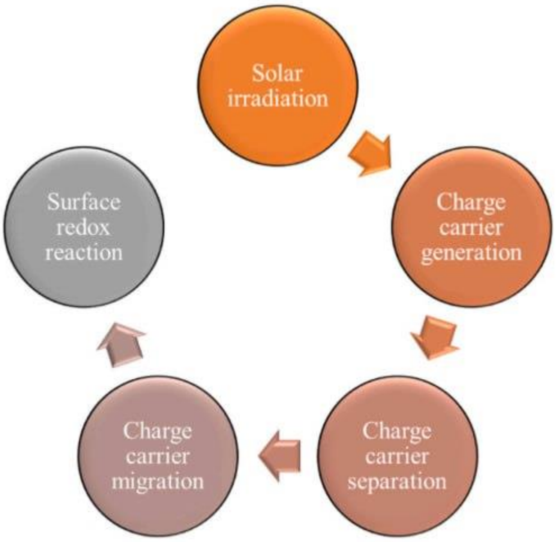


Figure 13. Illustration of the fundamental steps in the process of photocatalytic hydrogen production [71]

These carriers then reach the surface and engage in redox reactions, producing hydrogen and oxygen. This rapid water-splitting process occurs in nanoseconds to microseconds and competes with charge recombination. It involves two half-reactions: hydrogen evolution (HER) and oxygen evolution (OER), which together make up the overall water splitting reaction (OWR). These reactions are given below one by one [70],

HER: $4H^+ + 4e^- = 2H_2$

OER: $2H_2O = 4H^+ + 4e^- + O_2$

OWR: $2H_2O = 2H_2 + O_2$

When energetic photons are absorbed, they generate and separate charge carriers. The holes in the valence band split water molecules into protons and oxygen gas, as described by the second reaction. These protons then react with the free electrons in the conduction band to produce hydrogen gas, as shown in the first reaction.

4. Methane pyrolysis

Methane pyrolysis offers a way to produce CO_x-free hydrogen through an endothermic reaction:

$$CH_4(g) = C(s)+2H_2(g),\ \Delta H(1000K)=89.8\text{kJ mol} \tag{4}$$

Noncatalytic methane pyrolysis requires very high temperatures, around 1300°C, to decompose methane effectively and achieve high hydrogen selectivity, which is impractical for industrial use. Therefore, research has focused on two main areas to commercialize this process:

1. Developing commercially viable catalysts to lower the reaction temperature and enhance methane conversion and hydrogen selectivity.
2. Controlling and producing valuable, separable carbon allotropes.

Since solid catalysts have been extensively reviewed, this paper will provide a detailed and updated analysis of liquid catalysts and discuss the main challenges to commercializing methane pyrolysis. It will also review the latest advancements in each type of catalyst, outlining their advantages and disadvantages see Figure 14.

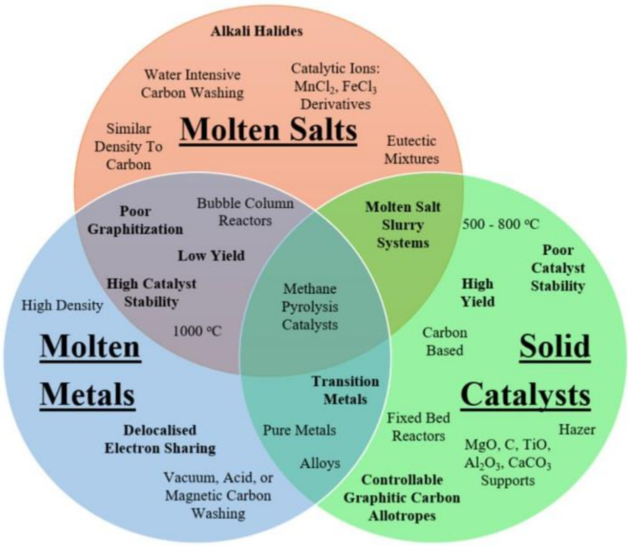


Figure 14. An overview of the different catalysts used in methane pyrolysis [72]

The autocatalytic pathway for methane pyrolysis is a multifaceted, high-temperature process with various routes and intermediates [73]. Abanades and colleagues detected hydrocarbons, besides methane, along with radicals in the outlet stream while investigating methane's thermal decomposition [74]. The authors did not specifically pinpoint the types of species present. Matheu and collaborators constructed a simulated mechanism for methane pyrolysis that closely matched existing literature [75]. So, methane pyrolysis is seen as a practical and economical way to produce hydrogen with minimal emissions at a low cost.

5. Techno-economic analysis for green hydrogen production

The ever-present threat of climate change propels green hydrogen into the spotlight as a potential game-changer in the global energy discussion. Experts and analysts around the world are highlighting its potential as a game-changer in reducing carbon emissions and paving the way for a low-carbon future. If we're going to unlock the true potential of green hydrogen and fight the urgent climate crisis, we need a deep understanding of the technologies and economic factors surrounding its production right now [76–79]. The future of clean energy is getting a significant boost from green hydrogen, a fuel produced using renewable sources like sunshine and wind [80]. This eco-friendly option is showing immense promise across various industries, with significant advancements in the technologies that create it. These advancements include electrolysis, biomass gasification, and even splitting water directly using solar power. One fascinating area of exploration is using renewable biomass resources like plant matter to generate green hydrogen through gasification [80,81]. Additionally, the integration of solar water splitting, which directly converts sun energy converted to hydrogen [82], displays creative methods that are influencing the growth of the green-hydrogen industry. Electrolysis advancements, gasification of biomass, and water splitting by the sun have accelerated the development of green hydrogen production methods Figure 14. Green hydrogen (Table 2) is a game-changer due to its versatility across various sectors. From powering our industries and transportation to generating cleaner electricity, this clean-burning fuel offers a promising solution for a sustainable future (Figure 15). Several techno-economic frameworks have been developed to evaluate the viability of green hydrogen-generating systems. One of the most popular methods is electrolysis, specifically proton exchange membrane (PEM) technology, which has evolved dramatically. Studies showed PEM electrolysis as an eco-friendly method of hydrogen production. This approach enables the generation of green hydrogen from clean energy sources, wind, and solar, whose prices vary from 2.94-3.32 USD/kgH_2 [85,86]. In the research [80] also investigated the feasibility of integrating a Ten-megawatt PEM electrolysis apparatus with an organic Rankine cycle with waste heat recovery to establish economically viable large-scale storage of green hydrogen that is sustainable. The study investigates the manufacture of hydrogen utilizing solar energy, namely photovoltaic systems. It demonstrates the potential for this technology to serve as a green hydrogen production method in Iraq, playing a part in a global zero-emissions economy. This research highlights the potential of biomass gasification technology as a game-changer in producing clean, sustainable hydrogen. This technology holds particular promise for tackling decarbonization challenges in sectors like industrial heating and even home heating systems [86].

The study especially looked at whether gasification of biomass might be used in the US to produce hydrogen. It yielded valuable insights regarding the economic costs, environmental impact of biomass sources, and the technical hurdles and successes of generating hydrogen through this method [87]. The research investigates the generation of hydrogen from combustion of biomass and gives a thorough analysis of the current challenges and possible prospects, particularly in establishing a comprehensive pathway for this process. Edou et al. [39] researched the production of a significant amount of hydrogen using gasification using a fluidized bed , Steam reformation of biogas from breaking down anaerobically (AD) , and various other thermo-chemical technologies. Among these, fluidized bed gasification (FB) emerged as the most cost-effective method, producing hydrogen at \$3.40/kg for potential use in public transportation buses. AD-biogas reforming followed at \$4.20/kg. Additionally, Arcos et al. [40] discussed photocatalysis, a method that utilizes light to produce hydrogen gas [88,89]. The research explores thermo-chemical water splitting (TWS) as a viable method for large-scale production of clean hydrogen, emphasizing that optimization can reduce costs and environmental impact. It introduces ceria thermochemical water-splitting (TCWS) as an innovative technique for solar hydrogen synthesis, improving hydrogen production with solar-heated nitrogen. Another advanced technology, developed by Mehrpooya et al., incorporates solar thermal energy, An overheated heat pump, a natural cycle of Rankine, and a four-phase thermochemical cycle for Cu-Cl, achieving a hydrogen production rate of 21.75 kg/h. Additionally, the Power-to-Hydrogen-to-Combined Heat and Power (PtH2tCHP) system offers a cost-effective, low-emission approach that supports a low-carbon, clean energy infrastructure. The study also indicates that the generation of hydrogen using renewable resources could become as cost-effective as conventional techniques in countries with strict carbon pricing [91–95].

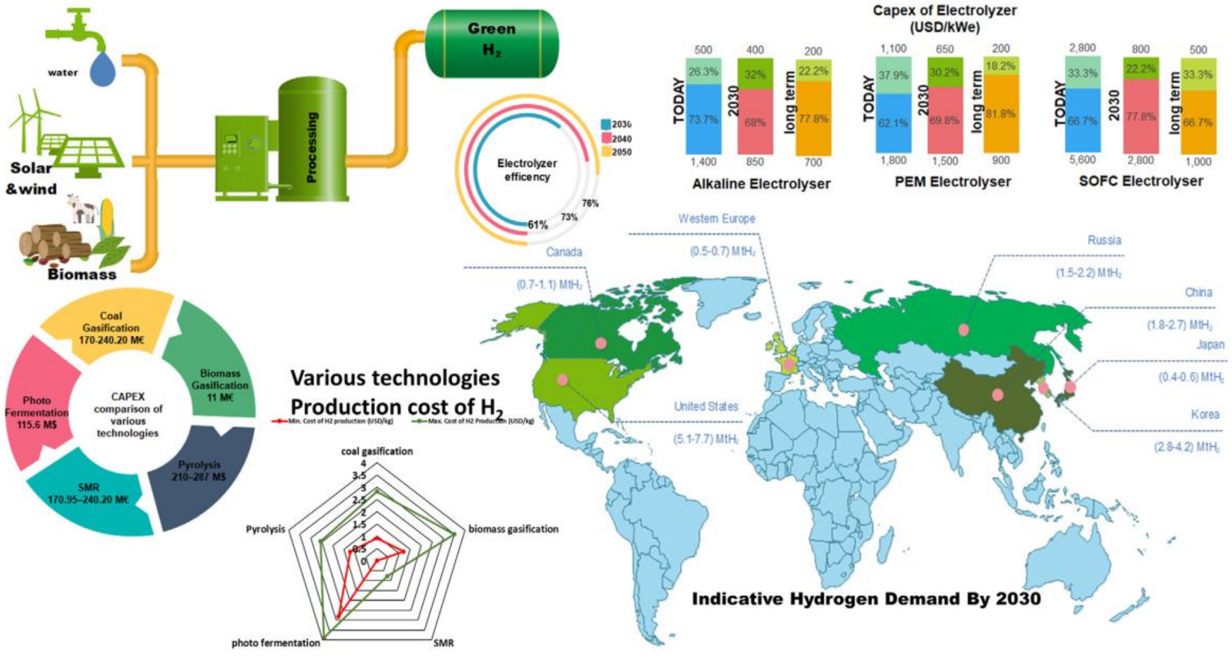


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Figure 15. Indicators of both technological advancements and economic viability across different global technologies for green hydrogen production [60,83,84].

Table 2. Various studies conducted for the advancement of the green hydrogen production

Literature perspective on the various studies conducted for the advancement of green hydrogen production						
Year	technology	Yield of H_2	Cost of H_2 Production	Capital Cost	Operational cost	Ref.
2023	proton exchange membrane (PEM) electrolysis	–	2.94–3.32 USD/kgH_2	600 USD/kW	1.5% of Capex	[86]
2023	photovoltaic energy system	–	3.79–4.11 USD/kgH_2	1.29 × 10^6 USD	7,166.76 USD/yr	[90]
2023	PEM coupled with waste heat recovery and an ORC	–	–	79.29 × 10^6 £	133.92–283.80 £/MW	[80]
2023	biomass gasification	94.9–99.1 kg H_2/ ton of biomass	3.47–4.11 USD/kgH_2	1.7–2.51 × 10^8 USD	24.55–29.95 USD/kgH_2	[87]
2023	thermochemical water-splitting	168.3 kg/h	3.92 USD/kg H_2	48.3 × 10^6 USD	15.6 × 10^6 USD/yr	[91]
2022	integrated systems of Power-to-Hydrogen-to-Combined Heat and Power	–	5.76 V/kg	700-1500 V/kW	3 V/MW	[92]

6. Recent advances and innovations

In recent years, significant progress has been made in green hydrogen production technologies, improving their efficiency, cost-effectiveness, and scalability. The current cost of green hydrogen typically falls between $2.50 and $6.80 per kilogram [96]. However, the declining costs of renewable energy and electrolyzers are driving down the price of green hydrogen, making it increasingly competitive with blue hydrogen. The decreasing costs of renewable energy and electrolysers are effectively lowering the price of green hydrogen, making it more competitive with blue hydrogen. The United States Department of Energy aims to reduce hydrogen production costs to $1 per kilogram by 2030. Table 3 outlines recent hydrogen production technologies, detailing their sources, processes, benefits, drawbacks, and maturity. Due to data limitations, life cycle assessments and techno-economic analyses are not included. Figure 16 summarizes these technologies, focusing on ESMR, SOEC, AEM, BPV and DAE as key methods. Electrolysis powered by wind or hydro-generated electricity is considered one of the most effective methods for producing green hydrogen [97]. Of the three electrolysis methods, solid oxide electrolysis cells (SOECs) are regarded as the most efficient for hydrogen production. Table 3 (Appendix) indicates that SOECs outperform other methods, achieving efficiencies of up to 90%, the highest among hydrogen production technologies [98]. SOECs use ceramic electrolytes instead of hydroxide exchange membranes, resulting in lower material costs despite a longer initial setup time. They are currently at a technology readiness level (TRL) of 6–7, indicating readiness for demonstration and commercialization. However, their lifespan of less than two to three years contrasts with PEM and alkaline electrolysis technologies, which typically last 10-20 years. The current emphasis of our research and development endeavors is on extending the operational lifespan of Solid Oxide Electrolysis Cells (SOECs) [99]. AEMs represent a new era in high-efficiency energy devices, characterized by their strong mechanical, thermal, and chemical properties that address fuel crossover and carbonation challenges seen in traditional alkaline fuel cells utilizing aqueous KOH [100]. AEMs are approaching readiness for demonstration and commercialization, while ESMR holds promise in reducing GHG emissions but faces methane leakage and high energy consumption issues. Hydroxide exchange membrane water electrolyzers show potential for efficient hydrogen production, yet improvements are needed in durability and commercial viability [101]. A range of emerging green hydrogen technologies, such as AEM and PEM electrolysis, SOECs, ESMR, DAE, and MECs, are progressing towards applications in transportation and industry. These innovations aim to mitigate emissions, improve energy efficiency, and support the shift towards cleaner energy sources. As these technologies advance and achieve greater cost efficiency, they will undoubtedly play a pivotal role in catapulting us into a sustainable energy future.

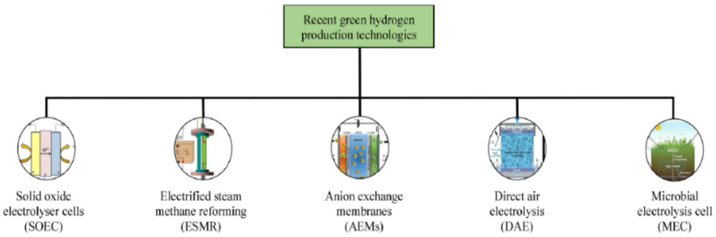

Figure 16. Latest innovations in green hydrogen production [118]

7. Challenges and solutions

Clean hydrogen's potential for a global energy shift is hampered by two main challenges. First, the infrastructure needed to use hydrogen widely is still under development. This lack of infrastructure is a major roadblock to widespread adoption. Second, producing clean hydrogen using renewable energy sources is currently too expensive (Figure 17).

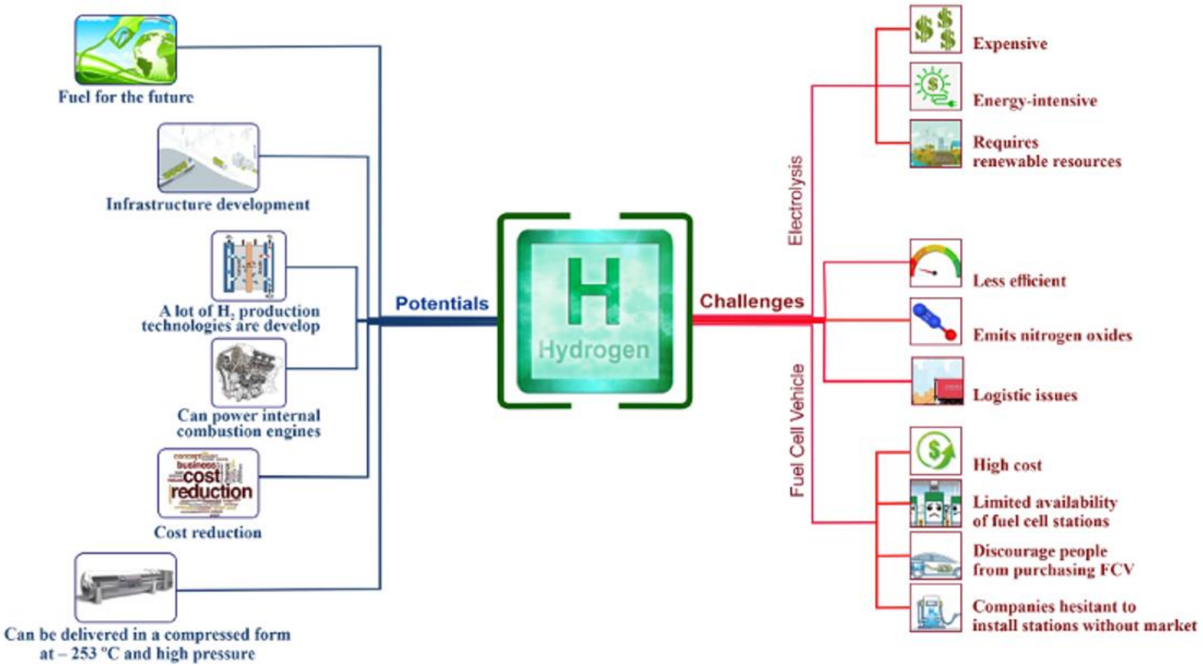

Figure 17. Current challenges and potentials of hydrogen production [118]

As a result, most hydrogen production relies on fossil fuels like natural gas and coal, which undermines its environmental benefits [119]. Despite current regulatory hurdles, the clean hydrogen industry is making significant progress, with many industries and companies incorporating green hydrogen into their products. The growing demand for green hydrogen indicates its potential to become a highly sought-after renewable energy source shortly. The increasing recognition of its significance spurs the advancement of more environmentally friendly technologies and global approval. The significant recent decrease in the costs of renewable energy clearly indicates that producing hydrogen from renewable power through the power-to-gas process will become more cost-effective [120]. Some methods of making hydrogen, like electrolysis, use a lot of water. In fact, it takes roughly 9 kilograms of water to produce just 1 kilogram of hydrogen [121]. For over 200 years, scientists and engineers have been refining water electrolysis techniques for industrial use. This development can be broadly categorized into five distinct phases. Each phase is characterized by its own set of challenges, technological advancements, and contributions to the overall progress of water electrolysis technology (as illustrated in Figure 18).

Hydrogen can indeed be used in traditional engines, but it unfortunately produces nitrogen oxide emissions and is not as efficient as fuel cells. Nevertheless, the environmental advantages of hydrogen fuel cannot be disregarded. The scarcity of hydrogen stations and fuel cells' exorbitant prices are the principal factors contributing to the limited presence of H_2-powered cars on the roads today. The limited availability of hydrogen fueling stations presents an opportunity for expanding the market for hydrogen vehicles. As more stations are built, it will encourage more people to consider purchasing hydrogen vehicles, leading to a positive cycle of growth for the industry. It is a chicken-and-egg situation [123]. Storing hydrogen in its liquid form is tricky because it needs super cold temperatures and special equipment.

That's why scientists are putting a lot of effort into developing technology that can convert hydrogen from electrolysis (made with renewable energy sources) into liquid fuels like diesel, methanol, or ammonia. This would be a game-changer! These fuels are easier to transport, allowing us to move clean energy from places with lots of renewable resources to areas with limited options [124]. Adding to the challenges, safety is a major concern with hydrogen. Because it's highly flammable and can ignite easily under many conditions, there are significant worries about its safe handling and use.

8. Solution to the challenges

The fight against climate change hinges on researchers developing clean ways to produce hydrogen. But for it to be truly impactful, industries need solutions for transporting, storing, and distributing hydrogen – including making it readily available in rural areas. Governments also have a critical role. They need to craft policies that make green hydrogen a key player in the global shift towards a clean, reliable, and affordable energy system. This includes securing domestic supplies of zero-carbon hydrogen, as current production methods are expensive and limited in scale. The current infrastructure simply can't handle large-scale storage, long-distance transportation, and distribution of liquefied hydrogen [125]. No country is currently self-sufficient in carbon-neutral or zero-carbon hydrogen, meaning imports will be necessary. Hydrogen energy's potential for the future relies on global competition and consumer demand. For instance, for hydrogen-powered vehicles to succeed, they need to be priced competitively compared to other options. Right now, the lack of hydrogen stations and high refueling costs are major roadblocks for fuel cell vehicles. However, with increased demand, economies of scale could bring down refueling costs. Hydrogen might find its biggest advantage in powering heavy-duty vehicles like buses, trains, and industrial trucks used in mining. This is because fuel cells excel where high energy storage per weight is crucial [126].

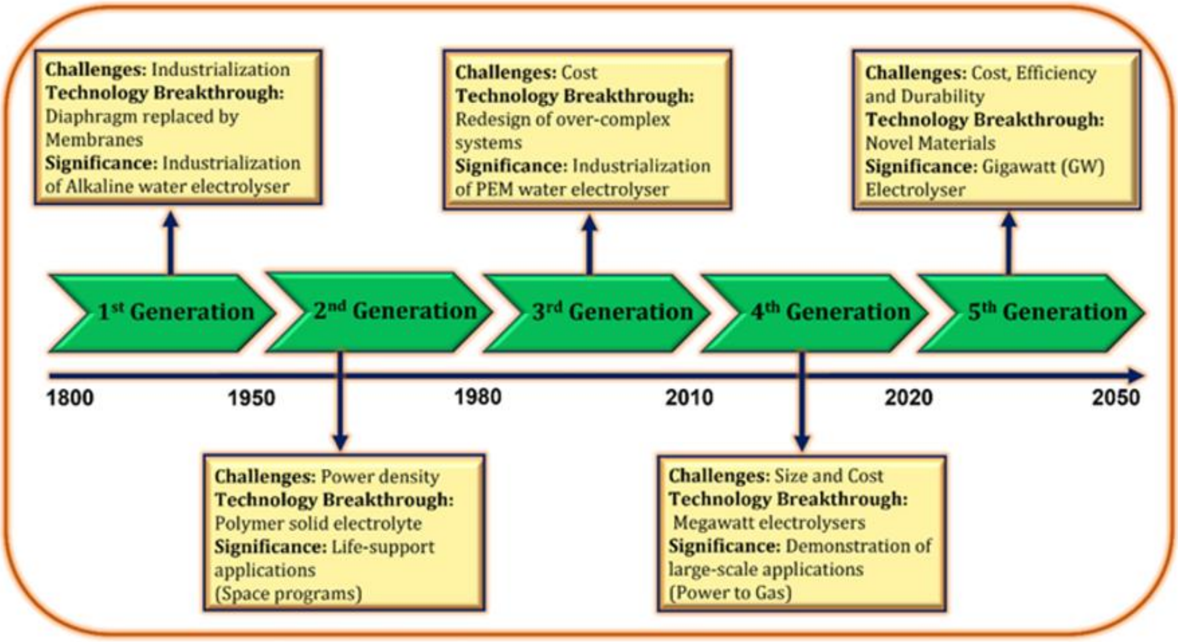

Figure 18. Water electrolysis generation wise development [122]

The utilization of hydrogen in sectors such as methanol production and refining is expected to experience gradual expansion by the year 2050, a major shift is expected for hydrogen as a fuel. The use of hydrogen as an energy source is anticipated to increase significantly by the year 2030, making up a significant portion (35%) of total hydrogen demand by 2050 [127]. Our present energy infrastructure, which has evolved over decades, is a complicated network of extraction, processing, and transportation. The transition to a hydrogen-based system will be sluggish, maybe spanning many decades. Rebuilding or changing a huge percentage of existing infrastructure is a significant challenge for hydrogen. Furthermore, hydrogen will face fierce competition from alternative energy sources. The economic effect of the COVID-19 epidemic may postpone this transformation even further. Policymakers must identify cost-effective ways to incorporate hydrogen and investigate how the hydrogen and natural gas businesses might collaborate, possibly complementing one another.

9. Applications and impact

Hydrogen is employed in various industries, such as electricity generation, transportation, processing, medicine, chemical production, heating, and steelmaking [128]. Environmentally friendly hydrogen's benefits include its compatibility with existing natural gas pipelines for storage and transport, which can be readily adapted for hydrogen use. Green hydrogen offers the advantage of being stored and transported through existing natural gas pipelines, making it distinct from other energy storage types. The natural gas infrastructure can be easily adapted for hydrogen transport Transportation across air, sea, and land can become carbon-free with hydrogen. Some examples of such cars include HFCVs, EVs, and NGVs, which stand for natural gas vehicles [129]. Given its advantages compared to alternative energy storage technologies, P2H could be an extremely efficient option for addressing challenges in transitioning to renewable energy, offering reliable, cost-effective, efficient, long-term, and high-capacity storage [129].

10. Production method wise applications

In water electrolysis, external energy flows through a circuit to drive a reaction that splits water molecules into hydrogen and oxygen atoms, a process known as dissociation. Combining photocatalysis with electrocatalysis, the technique behind photoelectrocatalysis (PEC), which work together to enhance this electrochemical reaction [130]. At the anode, water undergoes oxidation, producing oxygen gas, protons, and electrons. These protons pass through the proton exchange membrane electrolysis (PEMEL) and are then reduced, where they react with electrons to produce gaseous hydrogen at the cathode. Future work on Proton Exchange Membrane Electrolyzers (PEMEL) includes the following:

Higher temperature operation: Operating at temperatures between 60°C and 120°C is critical for enhancing voltage efficiency. However, higher temperatures can dehydrate the PEM, so maintaining adequate water content is essential [131].

Increased operating pressure: Another important area of research is increasing the operational pressure of PEMEL systems. Higher pressure is crucial for the widespread use of hydrogen, particularly in hydrogen plants, due to the very low volumetric energy density of hydrogen gas under ambient conditions. Currently, mechanical compressors are used to pressurize hydrogen gas, but they are inefficient and noisy (Figure 19). AEL can create significant volumes of clean hydrogen. Featuring an 8-year membrane and electrode exchange, an operational efficiency of 62-82%, and a lifespan of up to 30 years, this equipment is reliable and safe. Fundamentally, two terminals are immersed in an aqueous solution containing 25-30% KOH or NaOH. KOH is used for its higher ionic conductivity and lower CO_2 solubility. The positive electrode generates oxygen, while the negative electrode generates hydrogen [132].

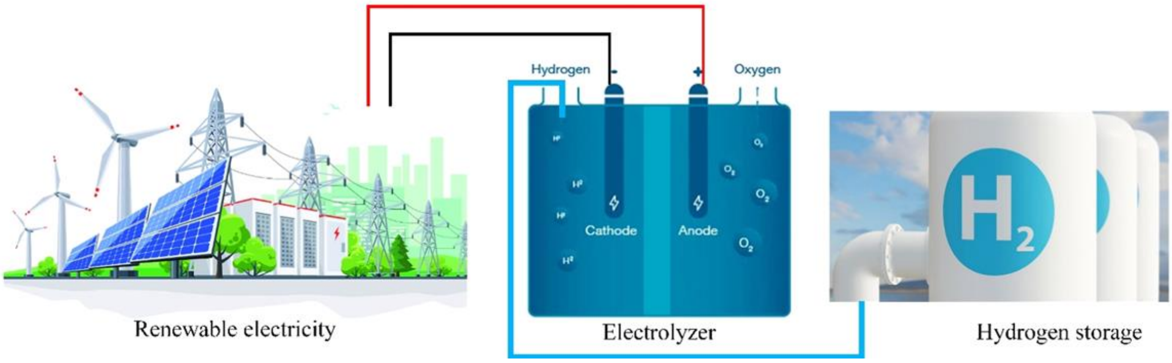

Figure 19. The basic methods of green hydrogen technology [131]

11. Photovoltaic (PV) systems with electrolyzers

a. One cutting-edge method of producing and storing energy is a PV system that incorporates an electrolyzer.
b. This system harnesses solar power to produce electricity, which is then used by the electrolyzer to split water into hydrogen and oxygen.
c. A research examines photovoltaic (PV) on-grid systems that include electrolyzer technology. The paper presents a techno-economic model for PV-linked electrolysis facilities that takes into account the dynamics of the system.
d. Water electrolysis-coupled PV off-grid systems are efficient.

11.1 Solar-powered water-splitting system

a. Three state-of-the-art PEMELs with a total area of $730\ cm^2$ and a bifacial (SHJ) solar module make up a dependable solar-powered water purification system.
b. The system parameters, including the cell count, inclination, and elevation of the solar panel, were fine-tuned for optimal performance.
c. At an irradiation level of $1000\ W/m^2$, the system achieves an 11.55% efficiency in converting solar energy to hydrogen.

12. Wind turbines with electrolyzers

a. Wind turbines are a promising renewable energy source, but their intermittent nature poses challenges.
b. Wind turbines generate extra power that electrolyzers may store and utilize as fuel.
c. This technique improves wind energy dependability and efficiency, enabling clean energy transition.
d. Electrolysis wind turbines produce green hydrogen and sell excess energy to the grid when hydrogen storage is full.
e. Factors affecting wind energy production include wind speed at the site, tower height, and blade diameter.
f. Frequent wind power fluctuations can cause electrolyzers (AEL) to start up and shut down frequently, reducing hydrogen production.
g. Supercapacitors can be integrated into a wind/hydrogen (W/H_2) grid-tied system for attenuating wind power variations.

13. Hybrid Microgrid (HμG)

a. The proposed hybrid microgrid comprises three distributed generation (DG) units: two that are wind-and solar-powered, and remaining using Proton Exchange Membrane Fuel Cell (PEMFC) technology (Figure 20).
b. The AEL in the system balances the variable renewable energy sources (VRES) by producing hydrogen.
c. When there is excess generation, hydrogen is stored in a hydrogen tank and used to feed the fuel cell during low generation periods.
d. The hydrogen microgrid demonstrates the benefits of using hydrogen to store energy produced by sun and wind systems, enhancing system self-sufficiency [133–136].

14. Policy and Regulatory Framework

The World Bank Group is actively advancing green hydrogen initiatives in Latin America, with countries such as Brazil, Costa Rica, Colombia, Panama, and Chile actively exploring its potential for fuel and energy storage. This renewable energy option is gaining attention on a global scale, with Australia, China, India, Japan, Bangladesh, and Germany all emphasizing its significance in their energy shifts [137]. It's worth noting that Sub-Saharan Africa holds the greatest potential for producing green hydrogen (2715 EJ), followed by the Middle East and North Africa (2023 EJ), North America (1314 EJ), and Oceania (1272 EJ). India's National Hydrogen Mission exemplifies this global focus. The recently unveiled initial phase of its Green Hydrogen Policy aims to position the country as a leader in this domain. Targeting a production capacity of 5 million metric tons per annum (MMTPA) by 2030, the policy also emphasizes boosting renewable energy sources and offering incentives to attract investment in green hydrogen and ammonia production. This initiative comes amid projections of India's hydrogen consumption doubling to 6.7 million tonnes per year by 2030 [138]. Currently, most hydrogen is utilized by industries like steel mills, fertilizer plants, and oil refineries as a process fuel. The challenge? While green hydrogen boasts a lower environmental impact, it is not yet cost-competitive with its "grey" counterpart derived from valuable fossil fuel sources like natural gas or naphtha, despite its decreasing costs of renewable electricity [139]. Looking towards the future, Japan's Ministry of Economy, Trade and Industry (METI) is outlining a roadmap for establishing a global hydrogen supply chain by 2030. Their Strategic Roadmap and Basic Hydrogen Plan for Hydrogen and Fuel Cell highlight the potential of NH3 as a low-carbon fuel option. Bangladesh is expanding its energy diversification efforts with a hydrogen research facility, emphasizing a cost-efficient solar-wind hybrid power plant model along its coastline [140]. Germany's forward-looking hydrogen policy involves significant state funding for green hydrogen initiatives, alongside research into low-carbon hydrogen options, positioning the country as a leader in technology development and international partnerships to ensure energy security [141].

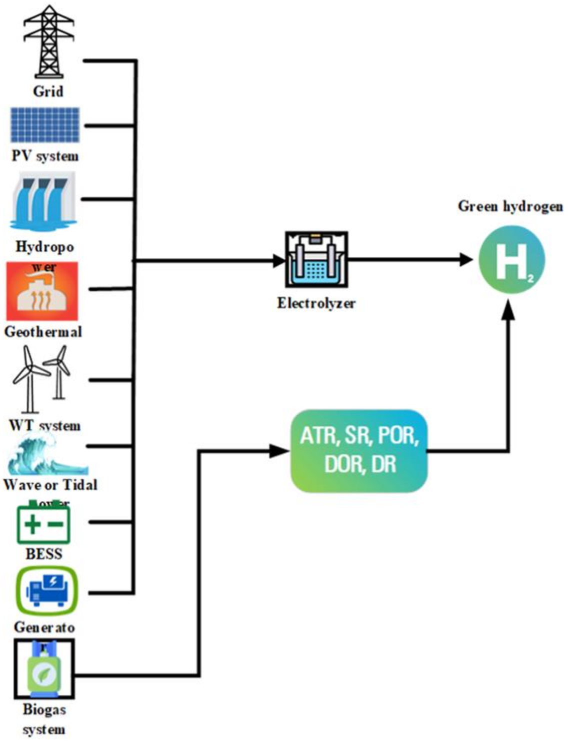

Figure 20. Hybrid system for green hydrogen production

China's 2021–2035 hydrogen energy plan aims to establish a robust industry by 2025 and scale up renewable hydrogen production, targeting significant carbon emissions reductions. By 2035, China plans to rely heavily on renewable hydrogen to advance its transition to sustainable energy sources [142]. The UK is working to build a hydrogen economy with flexible guidelines focused on long-term decarbonization and economic benefits, in alignment with national goals. By 2030, it aims to lead in low-carbon hydrogen production, supporting both carbon reduction and economic growth. The strategy emphasizes adaptability to market changes and explores various technologies to meet Carbon Budget 6 and net zero targets by 2050 [143].

15. Future directions and research gaps

Future research should prioritize advancing green hydrogen technologies to TRL 5–6. Researchers need to improve production methods, industries must develop better systems for storage, transportation, and distribution, and governments should create policies that support a sustainable and secure energy future. Addressing the high costs and infrastructure limitations is crucial for making green hydrogen a viable energy source [125]. Governments in every country depend significantly on importing carbon-neutral and zero-carbon hydrogen to meet their domestic needs. The effectiveness of hydrogen energy systems in the future hinges on competitive market conditions and demand. Challenges such as insufficient refueling infrastructure and expensive hydrogen refueling costs are barriers to the widespread use of fuel cell vehicles at present, but increased demand could drive down costs as economies of scale come into play [126]. While traditional hydrogen applications, like making methanol and refining oil, are expected to grow slowly by 2050, the future looks bright for its use as a fuel. Demand in this sector is predicted to skyrocket after 2030, accounting for a significant portion (35%) of total hydrogen demand by mid-century [127]. However, transitioning our energy infrastructure to accommodate this shift is a complex undertaking, potentially spanning decades. The challenge lies in adapting existing systems and navigating competition from other energy sources. Economic hurdles, like the recent COVID-19 pandemic, could further slow down this progress. To address these obstacles, policymakers must find cost-effective transition strategies and encourage collaboration between the hydrogen and natural gas sectors (Figure 21).

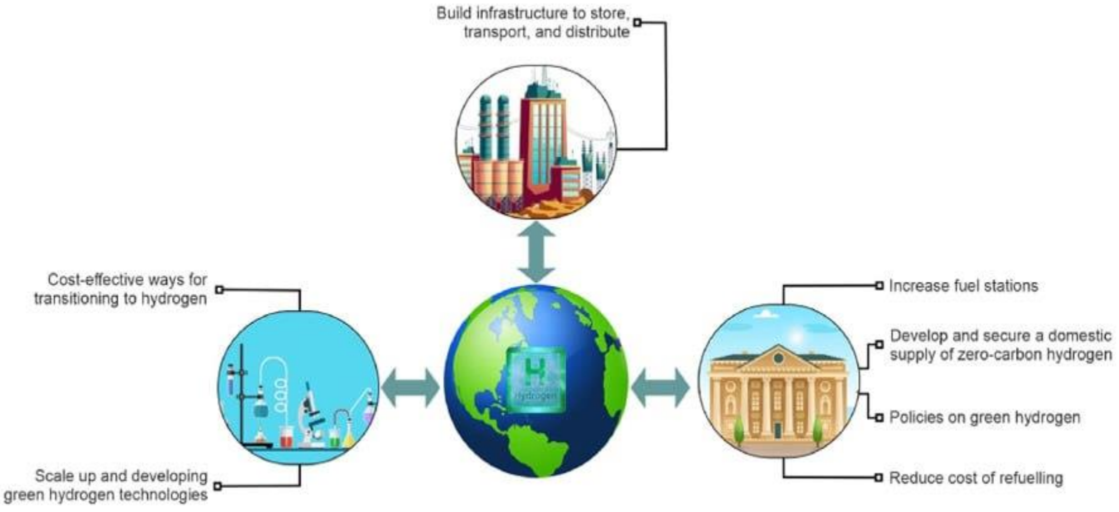

Figure 21. To ensure the successful development of green hydrogen, it is crucial for the government, hydrogen producers, and researchers to work together actively [118]

16. Conclusion

Green hydrogen is at the forefront of the global energy transition, presenting a versatile and sustainable alternative to conventional fossil fuels. This comprehensive review has elucidated the multifaceted approaches to green hydrogen production, including water electrolysis, biomass gasification, and thermochemical processes. Among these, water electrolysis stands out due to its maturity and scalability, particularly through the use of alkaline and PEM electrolyzers. However, the efficiency and cost-effectiveness of these technologies remain challenges that require continued research and development. Significant advancements in electrocatalysts and electrode materials have shown promise in enhancing the efficiency of hydrogen production. For instance, the development of bifunctional electrocatalysts and heterostructured interfaces has led to lower overpotentials and increased stability, crucial for both hydrogen evolution reactions (HER) and oxygen evolution reactions (OER). Additionally, the integration of renewable energy sources, such as solar and wind, with hydrogen production systems offers a pathway to further reduce environmental impacts and improve energy security. The importance of green hydrogen extends beyond energy production; it is integral to decarbonizing sectors like transportation, industry, and power generation. This transition is critical as nations worldwide strive to meet their climate goals, particularly the ambitious goal of reaching zero emissions by the year 2050. The successful implementation of green hydrogen technologies can significantly mitigate CO2 emissions, combat climate change, and foster sustainable economic growth. Despite the progress, several research gaps and commercial limitations need to be addressed. Key areas for future research include improving the efficiency of electrolysis processes, developing low-cost and durable materials, and enhancing hydrogen storage and distribution systems. Policy support and strategic investments are essential to accelerate the deployment of green hydrogen technologies and realize their full potential in the energy transition.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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Appendix I

Table 3. Latest innovations in green hydrogen production [118]

Process	Sources	Process and range	Advantages	Challenges	TRL	Cost of production	Ref.
Solid oxide electrolyser cells (SOECs)	Steam heat sources include: 1. Utilization of thermal energy waste from industry. 2. Harnessing heat energy from solar and geothermal systems. 3. Generation of heat through nuclear power.	1202–1832 ◦ F, <25 bar	1. Able to maintain very high rates of electrochemical reactions, with current densities greater than $1\ A/cm^2$. 2.Demonstrates excellent load-following ability, thus well-suited for use with intermittent renewable energy. 3.Produces compact systems that take up less space than those using liquid-alkaline electrolytes. 4.Perfect for on-site usage. 5.Less-cost materials, utilizing ceramics for the electrolyte. 6.Can function in alter mode.	1. Cellular constituent parts deterioration. 2.The gasket or electrolyte fails, allowing the gas to escape. 3. Unstable mechanical conditions caused by thermal stress. 4. Extended start-up and break-in durations.	6–7	Capital expenditures for solid oxide electrolysers are estimated to be around $2,000/kW based on Irena's estimations for 2020.	[102,103]
Methane pyrolysis/ splitting	Source of energy: Electricity Feedstock: Methane	>1472 ◦ F	1.Straight CO_2 emissions are absent. 2.Forms solid carbon, resulting in carbon black.	1. Significant heat wastages may impair its efficiency. 2. Needs high-temperature plasma.	3–6	Hydrogen produced by methane pyrolysis now costs between $2,600 and $3,200 per metric ton, with the exact amount dependent on the price of carbon.	[104]
Electrified steam methane reforming (ESMR)	(Methane) extracted from natural gas	1. The formative years 2.Reforming 3.Shift change 4.CO_2 removal 5.Compression and purification 6.Utilisation	1.Amenable to incorporating carbon capture, utilization, and maintain (CCUS) to lower CO_2 emissions. 2.Can decrease the cost of decarbonizing H_2 production.	1. As of right now, the procedure costs more than conventional SMR. 2. The possibility of methane seepage.	3–4	A particular investment cost of about 422 Euros/kW net equivalent is associated with traditional steam reforming that does not use CCS.	[105]
Anion exchange membranes (AEMs)	Membrane: solid polymer electrolyte	Using catalyst of transition metals (CeO_2–La_2O)	1.Doesn't rely on Pt. 2.Utilizes an AEM to serve as a solid electrolyte, thereby obstructing damage from corrosive electrolytes. 3.Operates effectively in acidic settings.	1. Not as robust. 2. Not as steady. 3. Poor performance in hot and high pressure environments.	6–7 (for lab scale system)	Hydrogen generation costs utilizing AEM-based water electrolysis are anticipated to be $2 to $3/kg. The use of metals from the non-platinum group and the effectiveness of the AEMs in facilitating hydroxide conduction and limiting fuel	[106,107]

			4.Demonstrates reduced internal resistance and high levels of conductivity.			crossover both contribute to the competitive cost and improve the electrolyzers' overall performance and durability.	
Hydroxide exchange membrane water electrolyzers	Highly-purified water as the feedstock	Make use of an electrolyte that is hydroxide exchange membrane to separate oxygen and hydrogen from water.	1.Utilizes catalysts devoid of platinum group metals. 2.Enables the use of economical stack components such as stainless steel, preserving the advantages of membrane-based technologies.	1. In order to function, electrolytes must be supported, rather than liquid water. 2. The solid-state ionomers are immature. 3. Not very long-lasting. 4. Not fully developed technology. 5. Ionomer breakdown occurs quickly.	3-5	Depending on the exact configurations and operating circumstances used, the projected production cost of hydrogen utilizing HEME ranges from around $2.50 to $4.50 per kilogram. Factors such as material cost, manufacturing size, and electrolyser efficiency determine this price range.	[108–110]
Direct air electrolysis (DAE)	External input: Such as solar panels, tidal, geothermal, or wind Water source: Water Oxygen source: Atmospheric air Electrolyte: Alkaline solution such as KOH	Directly produce hydrogen from atmospheric CO2 using an electrochemical technique	1.Harnesses renewable energy sources. 2.Scalable in size. 3.Demonstrates high efficiency. 4.Cost-effective by eliminating the need for expensive membranes or electrodes.	1. The expense of initial investment is great. 2. A number of variables, such as catalysts, pressure, and temperature, must be carefully controlled. 3. Hydrogen production is low.	4-6	the cost of hydrogen production using DAE is estimated to be around $2.5 to $3 per kilogram of hydrogen. This cost is comparable to other environmentally friendly methods for producing hydrogen that harness renewable energy	[111]
Biophotovoltaics (BPV)/ Biophotoelectrolysis cell (BPE)/Microbial electrolysis cells (MEC)	Employing photosynthetic microorganisms like algae and cyanobacteria	By using biological photosynthetic materials, solar energy may be transformed into electrical current.	1. Converts industrial CO2 waste into a feed for microorganisms, offering a sustainable and economical route for hydrogen production. 2. The technology is environmentally sound and generates almost less harmful emissions or pollutants.	1.The goal is to use microbial electron transport pathways to transfer electrons to a solid-state anode. 2. The experimental setup lacks comparability and standardisation. 3. The devices' current outputs are quite low.	1-3	Hydrogen generation with BPE devices is now estimated to cost between $2.5 and $3/kg, which is competitive with other environmentally friendly ways of hydrogen production.Depending on the design and operating conditions, MECs can create hydrogen for $2.75 to $4.00 per kilogram, according to recent study.	[102,112–114]
Membrane-less electrolysers	Source: Different types of high-conductivity aqueous electrolytes	The electrodes that evolve H2 and O2 do not have a diaphragm or membrane divider.	1. Requires fewer and simpler components (anode, cathode, and device body), leading to reduced manufacturing and assembly costs. 2. Simplifies device complexity. 3.Shows potential for robust devices that can withstand severe operating conditions without membrane damage, have high impurity tolerance, and long operational lifetimes. 4.Capable of functioning with a variety of aqueous conductive electrolytes.	1. The decreased voltage efficiency was caused by the high operational current densities (≥0.5 A cm-2) that resulted from the increased ohmic solution (IR) losses. The ohmic voltage loss is larger in most membrane-less electrolysers because the ion transport distance is longer, which increases the total ohmic resistance (Rs) of the electrolytic solution. 2. It is difficult to produce and sustain a large enough pressure gradient between the electrodes to conduct electrochemical hydrogen compression.	4.3	An estimated $2 to $2.5 per kilogram of hydrogen may be produced utilizing electrolysers that do not use membranes.	[101,115]

				No, it can't manufacture hydrogen with a purity level of 99.99% when compared to PEM. Fourthly, difficulties associated with materials. 5. Issues with scaling-up.			
Redox decoupling	Source: Water or solutions with alkaline properties	1) Use electricity to separate water into its component hydrogen and oxygen. Has a two-step process: (i) The OER is the process by which oxygen is formed; (ii) the HER is the process by which hydrogen is formed.	1.Utilizes redox-mediated reactions in dual electrochemical cycles to produce high-purity hydrogen from alkaline solutions. 2.Shows consistent and rapid hydrogen production with nearly perfect steady-state faradaic efficiency.	Because of the inherent relationship between OER and HER, any changes or improvements to one will have an effect on the other.	2-4	One method that might bring the price of hydrogen generation down to about $2/kg is an electrochemical and thermally-activated chemical (ETAC) cycle, which has shown an efficiency of 98.7 percent.	[116,117]