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Review

Towards sustainable energy: a comprehensive review on hydrogen integration in renewable energy systems

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ABSTRACT

As the world shifts towards sustainable energy sources, incorporating hydrogen into renewable energy systems emerges as a critical pathway. This thorough analysis delves deeply into the various facets of hydrogen integration, exploring its potential to revolutionize the energy landscape. Drawing upon recent advancements and research findings, the review examines the production, storage, and utilization of hydrogen within renewable energy frameworks. Key topics include electrolysis methods, storage technologies, and diverse applications spanning transportation, residential sectors, and industry. Furthermore, the review examines the obstacles and prospects linked with hydrogen integration, shedding light on policy frameworks, economic implications, and technological innovations driving its adoption. By offering insights into the multifaceted role of hydrogen, this review aims to inform researchers, stakeholders, and policymakers about the transformative potential of integrating green hydrogen into renewable energy systems for a sustainable future.

1. Introduction

The annual growth of primary energy demand is forecasted to be 1.3%, driven by factors such as economic expansion, technological advancements, and population growth, consequently leading to increased demand for energy services, which is projected until 2040 [1-3]. Fossil fuels, encompassing coal, oil, and natural gas, have historically served as primary sources of energy generation and are projected to maintain their significant role in energy production until 2050 at least [4-6]. The utilization of fossil fuels results in the release of greenhouse gases, including volatile compounds, nitrogen oxides, and carbon dioxide, alongside solid particles, thereby playing a role in the alteration of the Earth's climate [7, 8]. Furthermore, carbon-based fuels currently fulfill 85% of the requirements of the world's energy [5,9]. In 2019, the yearly global energy-related CO_2 emissions amounted to 33.3 metric gigatons (Gt), increasing at a rate that poses a significant threat to elevate the Earth's temperature by multiple degrees unless mitigative measures are taken [10]. “Green” hydrogen serves as an alternative to fossil fuels, which is generated via the process of water electrolysis, wherein an electric current splits water into oxygen and hydrogen. This procedure results in zero greenhouse gas emissions, contingent upon the electricity powering it is sourced entirely from renewables. The lightweight properties, high mass-energy density, and efficient electrochemical conversion of hydrogen facilitate its ability to transport energy across geographical regions through pipelines or in the guise of liquid fuels like ammonia transported via freight ships [11]. Additionally, hydrogen can be produced locally, diminishing countries' reliance on external energy providers. Moreover, hydrogen can be derived from a diverse array of substances, including oil, sewage sludge, water, gas, biofuels, and more [12]. In the current era, the application of renewable-energy-driven green hydrogen production stands out as a progressively favored method for mitigating greenhouse gas emissions (GHGs) and environmental contamination in the global shift aimed at carbon reduction [9, 13]. Hydrogen (H_2) presents an economical and sustainable alternative for both storage and energy consumption [14, 15]. Moreover, it has the potential to actualize a carbon-neutral society and significantly increase the utilization of hydrogen [16]. Hydrogen technologies have emerged as a strategy to fortify diverse economic sectors following the COVID-19 outbreak. There is currently a notable consensus surrounding the potential of hydrogen, driven in part by an increasingly ambitious climate policy agenda [17, 18]. Moreover, hydrogen finds applications in fuel cell technology across various sectors, including industry, power generation, residential settings, and transportation, underscoring its potential for facilitating decarbonization [19-21]. Many nations view hydrogen as the upcoming generation solution for energy supervision and are progressively endorsing the adoption of hydrogen technology to foster a low-carbon economy. Consequently, numerous plans and strategies have been formulated for the development and implementation of hydrogen [22]. Green hydrogen holds significant potential to contribute significantly to the energy transition by serving as a means to store renewable energies as chemical energy carriers over an extended period. Moreover, current infrastructure like underground gas storage facilities and natural gas grids in Germany can be repurposed, mitigating the need for additional investment costs [23]. Green hydrogen demonstrates remarkable capability for transportation and storage within the natural gas grid with minimal loss. Consequently, this green gas can be effectively provided to industrial sectors and households, offering flexibility for applications such as heating through heating systems powered by fuel cells or industrial operations like steel production. Additionally, industries can utilize hydrogen for producing ammonia-based fertilizers, food processing, metal treatment, and various other purposes [24, 25]. In the past, review papers covering diverse focal points within the hydrogen energy systems domain have been published. Thema et al. [26] conducted a review of energy-to-gas projects, which generate either renewable or hydrogen substitutes for natural gas. Their study includes a forecast and analysis of the cost evolution concerning carbon dioxide methanation and electrolysis. Abe et al. [27] conducted a comprehensive review exploring the potential of hydrogen serving as a primary energy transporter, with a specific emphasis on the storage capabilities utilizing metal hydrides. Mazloomi et al. [28] outlined hydrogen as a highly encouraging option, serving not only as fuel for forthcoming vehicles but also as a pivotal energy preservation solution within expansive power systems. Their study comprehensively examines production and storage methods while also addressing the risk and safety considerations inherent in hydrogen technologies. Parra et al. [29] present a thorough technical-economic analysis of hydrogen-based energy systems. They outline strategies aimed at hastening the integration of hydrogen technologies, emphasizing key measures such as mass production, standardization, and the implementation of supportive policies. Moradi et al. [30] conducted a review of alternatives concerning the storage and delivery of hydrogen alongside an analysis of associated risk and safety considerations. Dutta [31] explored storage and production methodologies for hydrogen, with particular attention to risk and safety considerations. Yue et al. [9] conducted an extensive survey on hydrogen technologies within power systems, leveraging real-world projects as exemplars to elucidate diverse technologies and applications. Their techno-economic analysis integrated cost and technical considerations, emphasizing the imperative for ongoing focus on project scalability, technical advancements, political endorsement, and production expansion to attain cost competitiveness in hydrogen technologies. Bailera et al. [32] conducted a review encompassing the diverse methodologies employed to transform renewable energy into methane within power-to-gas initiatives, complemented by a summary of practical projects. Gahleitner [33] scrutinized pilot facilities for power-to-gas, focusing on instances where sustainable electricity was employed for hydrogen production via water electrolysis. Hanley et al. [34] conducted a survey on the integration of hydrogen within energy frameworks, examining potential drivers and policies that could promote hydrogen as a preferred option above alternative low-emission energy technology. To the best of the author's understanding, scientific research has largely overlooked the environmental expenses associated with green hydrogen generation. Thus, this paper, which delves into the environmental implications of green hydrogen production as a means of renewable energy storage, presents a novel contribution and addresses a growing sphere of focus [35]. The study encompasses alternative energy sources such as solar, wind, and hydro energy, which are predominant in Europe, in addition to biomass [36].

2. The generation of hydrogen from renewable energy resources

The utilization of renewable energy sources for hydrogen production stands as a highly promising avenue within the domain of sustainable energy. Ongoing endeavors in this field encompass a spectrum of technologies, notably encompassing the utilization of solar and wind power for water electrolysis [37], biomass-to-hydrogen processes including gasification and pyrolysis [38], and the deployment of solar energy-driven thermochemical reactions for water splitting [39]. The collaboration between renewable energy sources and hydrogen presents advantages like energy storage capabilities and the provision of on-demand energy supply [40]. Electrolysis, employing various types of electrolyzers, emerges as a pivotal step in green hydrogen production from renewables, with the prospect of achieving notable efficiency levels through optimization with renewable energy systems [41]. On the whole, the integration of renewable energy sources into hydrogen production holds considerable promise for realizing a sustainable and clean energy future. In broad terms, compounds originating from biomass or water have the capacity to be employed for hydrogen production via the process of extraction from natural resources [42].

2.1 Utilization of biomass for hydrogen generation

Biomass emerges as a promising avenue for hydrogen production, outstripping fossil fuels owing to its abundant supply, facile oxidation, and substantial annual output [43]. Diverse biomass sources, ranging from agricultural waste to microalgae, exemplify the vast array of plant and animal components convertible into biomass, constituting a renewable primary energy source [44]. Thermochemical and biological mechanisms serve as the two primary methodologies for hydrogen production from biomass, detailed in subsequent sections. The technical and economic feasibility of hydrogen production from biomass and residual wastes is evident in numerous developed nations, underscoring a projected contribution of over 25% to global energy demands by 2050 [45]. In stark contrast to fossil fuels, biomass-to-power processes mitigate the emissions of CO_2 and facilitate CO_2 absorption from the atmosphere, fostering a net-zero emissions scenario for greenhouse gases. Figure 1 illustrates various pathways for hydrogen production from biomass, delineating gasification to yield syngas, pyrolysis for bio-oil generation, and cellulose hydrolysis for sugar monomer extraction [46]. Syngas, resulting from gasification, can undergo a water gas shift (WGS) reaction for hydrogen conversion, albeit necessitating CO removal from the gas stream. While pyrolysis-derived bio-oil can be transformed into liquid fuel, the conversion processes are intricate with limited efficiency. Conversely, hydrogen production from bio-oil via autothermal reforming, particularly employing catalytic membrane reactors, boasts high conversion efficiency. Additionally, hydrogen generation from sugars and sugar alcohols, such as sorbitol, through aqueous phase reforming (APR) stands as a viable method. Although alternative biological pathways exist, encompassing enzymatic and bacterial routes, this article confines its discourse to heterogeneous catalytic approaches. Table 1 outlines the fundamental technologies employed in both processes, detailing the biomass type utilized, operational parameters, and technological maturity levels.

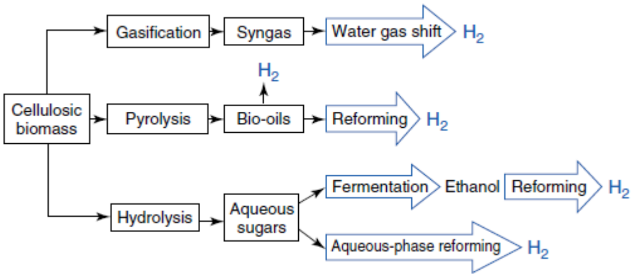


Figure 1. Diverse strategies for extracting hydrogen from biomass

Table 1. Summary of techniques for hydrogen production from biomass

Methods	Principle	Source of energy	Operating conditions	Maturity
Pyrolysis	Thermochemical	Dried biomass	300-1000°C in the absence of oxygen	Commercial
Hydrothermal liquefaction	Thermochemical	Wet biomass	250-370°C	Research and development
Gasification	Thermochemical	Dried biomass	800-900°C	Commercial

2.1.1 Gasification

Biomass gasification stands as a versatile and sustainable method for clean energy generation, with various approaches, such as steam gasification, demonstrating efficacy in hydrogen production [47, 48]. Particularly noteworthy is catalytic steam gasification utilizing calcium oxide (CaO), which exhibits the capacity to yield high-purity hydrogen through simultaneous CO_2 absorption and catalytic action [49]. Moreover, the utilization of waste biomass or agricultural residues presents dual benefits in renewable energy production and waste management [50]. Gasification, occurring at temperatures surpassing 1000K, entails a complex interplay of pyrolysis, partial oxidation, and steam-reforming reactions [51]. Oxygen or air facilitates partial oxidation, yielding gaseous products, including H_2 and CO_x, alongside bio-oils, tar, and charcoal [51]. Optimization of parameters such as temperature and residence time minimizes tar formation, with thermal cracking and the introduction of catalytic additives further augmenting efficiency [51, 52]. Advanced technologies like HyPr-RING integrate gasification with the water-gas shift reaction, aimed at enhancing hydrogen yield while curbing pollutants [53]. A diverse range of organic materials can undergo gasification using various agents, like oxygen, air, carbon dioxide, or steam, each imparting distinct effects on gas composition. Despite its heightened energy cost, steam gasification produces a gas with superior heating value and higher hydrogen content in comparison to air gasification. Furthermore, the presence of CO_2 in the synthesis, gas holds promise for specific process applications [54]. In summary, biomass gasification represents a pivotal pathway for sustainable clean energy production, with ongoing advancements in technology and process refinement aimed at optimizing efficiency and minimizing environmental impact.

2.1.2 Pyrolysis

Biomass pyrolysis emerges as a promising avenue for hydrogen production, particularly when accompanied by innovative methodologies. Notably, investigations reveal that the fast pyrolysis of algae pellets in molten $NaOH$-Na_2CO_3 at elevated temperatures can yield stable hydrogen, boasting a notable theoretical efficiency of 84.86% [55]. Furthermore, the integration of advanced artificial intelligence models, combining support vector machines and artificial bee colony optimizers, enhances our understanding of the generation of hydrogen gas from biomass composition and pyrolysis processes [56]. These advancements underscore the pivotal role of thermochemical processes such as pyrolysis and biomass gasification in deriving hydrogen from renewable biomass, emphasizing the necessity for enhanced selectivity and efficiency to realize economically viable industrial applications [47]. The efficacy of pyrolysis is contingent upon a multitude of parameters, incorporating heating rate, pressure, residence time, biomass type, and moisture content. Notably, the absence of air or oxygen during pyrolysis eliminates the risk of dioxin production and mitigates emissions. Additionally, the exclusion of air or water obviates the requirement for secondary reactors to produce carbon dioxide (CO_2) or carbon monoxide (CO), further contributing to emission reduction. Pyrolysis presents numerous benefits, incorporating fuel flexibility, reduced CO_x emissions, and operational simplicity, compactness, and a clean carbon byproduct. Nevertheless, the existence of air or water can result in significant CO_x emissions. Pyrolysis operations can be conducted at high (>800°C), moderate (500-800°C), or low (500°C) temperatures, with fast pyrolysis (FP) serving as a method to convert organic matter into products with increased energy content, albeit with challenges such as potential fouling from carbon buildup [57].

2.1.3 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is emerging as a promising method for harnessing hydrogen from biomass. HTL processes involve the conversion of wet biomass into biocrude oils and valuable biochemicals under high temperature and pressure conditions, utilizing water or water-alcohol blends, often with the incorporation of catalysts [58]. Studies have demonstrated that the use of catalysts such as Ni/AL_2O_3 and Fe can significantly enhance bio-crude yields, with optimal performance achieved at 330°C and a reaction duration of 10 minutes, leading to improved higher heating values for the biomass [59]. Additionally, research has explored hydrogen production from household mixed waste through HTL and hydrothermal gasification (HTG). HTG exhibits a maximum hydrogen yield of 39 wt%, while HTL yields a bio-oil output of 33 wt% with notable heating values [60].

2.2 Water electrolysis

In contemporary industrial contexts, primary methodologies for hydrogen production include coal gasification, steam reforming, and water electrolysis. Although alternative approaches such as ethanol and sugar reforming, photocatalytic water splitting, water biophotolysis, and high-temperature water splitting are currently undergoing development, they have yet to achieve widespread industrial deployment. Presently, there is a growing fascination with hydrogen production via water electrolysis, attributable to the declining costs associated with renewable electricity. This method entails utilizing electricity to separate hydrogen from water, thereby circumventing the generation of carbon byproducts such as CO_2 [9]. Within the configuration of a water electrolysis cell, two electrodes are immersed in an electrolyte solution and linked to a power source to enable the flow of electrical current, as demonstrated in Figure 2. Upon application of a sufficiently elevated voltage between the electrodes, water undergoes decomposition, yielding hydrogen at the cathode and oxygen at the anode. The introduction of the electrolyte serves to augment the conductivity of the water medium, thus enabling uninterrupted electrical flow. Commonly employed electrolytes in water electrolysis encompass acids and solid polymer materials, which utilize a variety of ions, including $H^+, OH^-,\ O_2^-$, and others, as charge carriers [9]. During water electrolysis, water acts as the input reactant and undergoes dissociation into hydrogen and oxygen due to the application of direct current.

$$\text{Anode: } H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \quad (1)$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2 \quad (2)$$

$$\text{Overall: } H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (3)$$

An array of electrolyte systems has been devised for water electrolysis, encompassing alkaline water electrolysis (AWE), solid oxide water electrolysis (SOE), alkaline anion exchange membranes (AEMs), and proton exchange membranes (PEMs). These systems are distinguished by their employment of diverse materials and operational parameters while adhering to shared foundational operating principles. Furthermore, depending on the temperature regimes applied, both high and low-temperature water electrolysis configurations are viable [61].

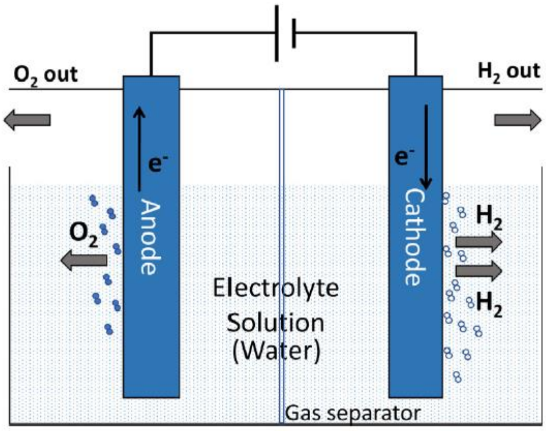


Figure 2. Water electrolysis principle

2.2.1 PV-electrolysis system

This system comprises photovoltaic cells, which generate electricity to operate an electrolysis unit, as depicted in Figure 3. Water electrolysis, an electrochemical reaction delineated in Figure 4, facilitates the disintegration of water molecules (H_2 O) into oxygen (O_2) and hydrogen (H_2) gases [62]. The O_2 and H_2 ions migrate to the anode and cathode, respectively, within the water medium. The resultant hydrogen boasts numerous merits, including its utility in welding applications and fuel cells, particularly when blended with O_2 to produce oxyhydrogen gas. This approach yields a substantial volume of high-purity hydrogen with minimal ecological ramifications, leveraging solar energy as its power source.

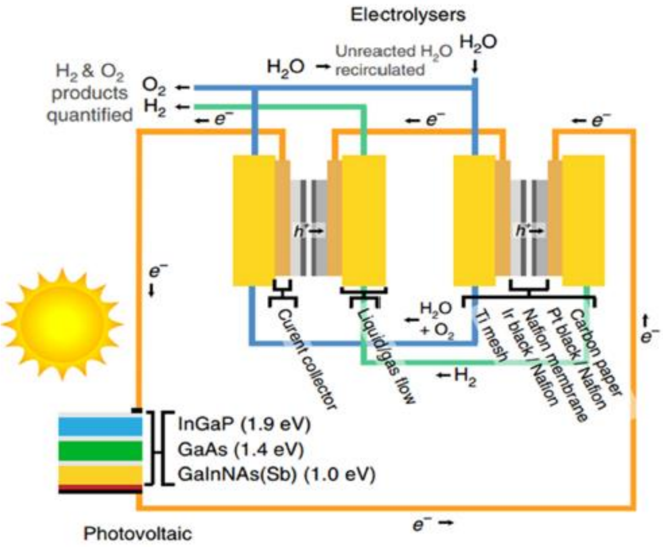


Figure 3. Diagram illustrating the PV-electrolysis apparatus [63]

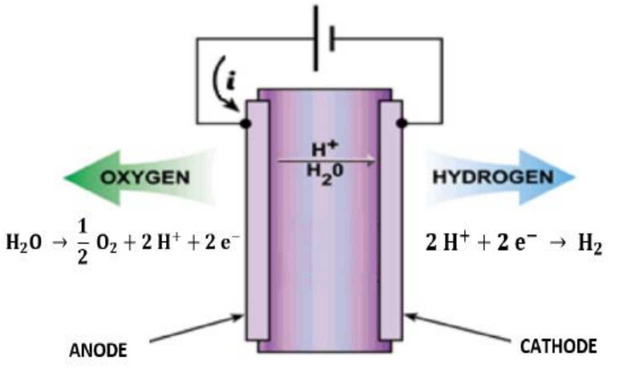


Figure 4. Electrolysis of water [63]

2.2.2 Hybrid photovoltaic/thermal (PV/T)-electrolysis system

A Hybrid PV/T-Electrolysis System represents a sophisticated integration of photovoltaic (PV) and thermal technologies to concurrently produce electricity and heat, thereby offering a sustainable solution for hydrogen production [64]. This sophisticated system harnesses solar energy through both electricity generation and thermal absorption, driving an electrolyzer via water electrolysis and presenting a renewable substitute for conventional hydrogen production methods. Consisting of photovoltaic panels and a Proton Exchange Membrane (PEM) electrolysis unit, its components include a PV-thermal array, a DC/DC converter, and the electrolysis unit, as delineated in Figure 5.

2.2.3 Wind-electrolysis system

A Wind-Electrolysis System is engineered to utilize wind energy for hydrogen production via electrolysis. This innovative setup incorporates wind turbines to capture kinetic energy from the wind and transform it into electricity. This electricity then powers an electrolyzer, facilitating the separation of hydrogen and oxygen from water. By harnessing wind power, this system presents a sustainable and renewable approach to hydrogen production, thereby contributing significantly to the transition towards cleaner energy sources and reducing dependency on fossil fuels. The components of a wind-electrolysis device typically include a wind turbine generator, a water electrolyzer, and a converter (AC/DC) [65]. This system can be deployed in various configurations tailored to different operational scenarios: firstly, the direct wind-electrolysis configuration is suitable for remote regions equipped with wind farms [66]. Secondly, the hybrid wind/grid-electrolysis setup enables the grid to provide supplementary energy during periods of low wind activity. Thirdly, surplus wind energy can be supplied back to the grid while hydrogen is concurrently produced. Lastly, in the fourth scenario, excess hydrogen can be stored for future utilization, facilitating electricity generation through a fuel cell [67]. Figure 6 illustrates the distinct elements comprising the wind-electrolysis system.

2.2.4 Thermolysis system

The Thermolysis System utilizes solar energy to drive the disintegration of water into hydrogen and oxygen gases by concentrating solar radiation onto a reactor containing water, achieving elevated temperatures conducive to the endothermic water-splitting reaction. This approach presents potential advantages over conventional electrolysis, including enhanced efficiency and reduced costs, particularly when integrated with high-temperature electrolysis. Nevertheless, significant challenges persist in scaling up and optimizing this technology for large-scale hydrogen production. Ongoing research endeavors are dedicated to surmounting these hurdles and fully realizing the potential of thermolysis for sustainable hydrogen production.

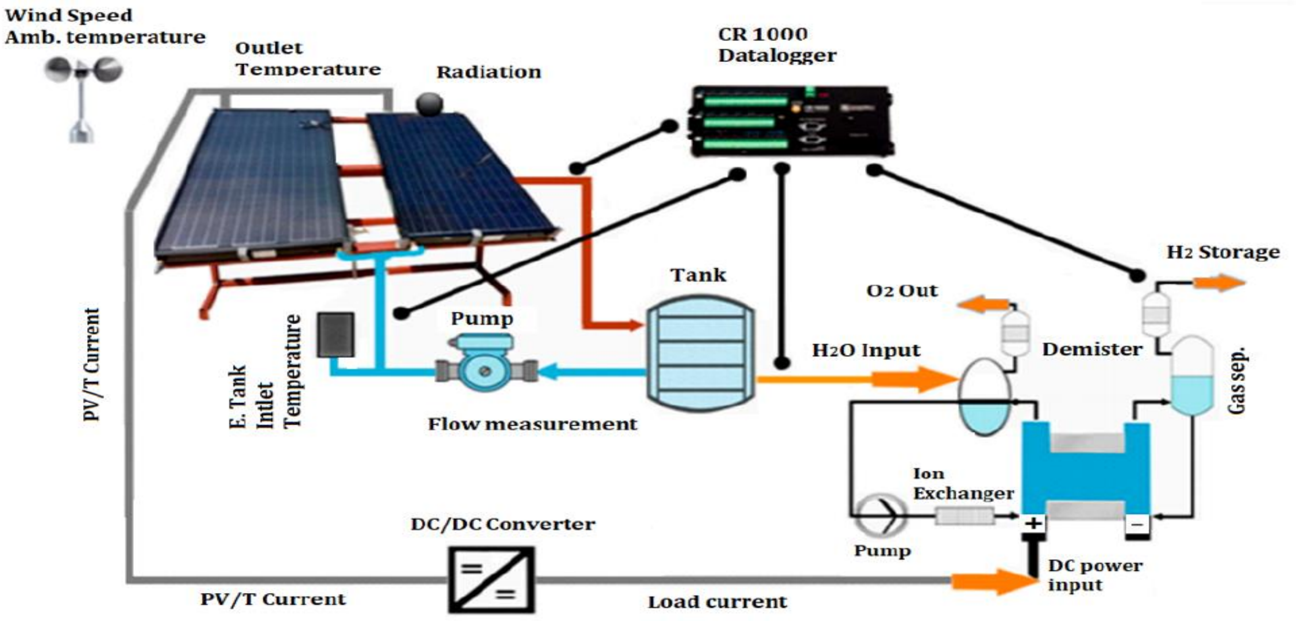


Figure 5. A schematic representation of the envisaged system [63]

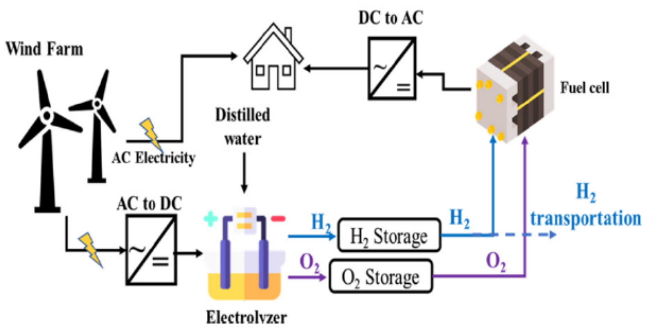


Figure 6. The fundamental concept of the wind-electrolysis system entails harnessing wind energy to drive the process of electrolysis for hydrogen generation [63]

Furthermore, the amalgamation of solar thermal dissociation with high-temperature electrolysis has demonstrated a lower production cost compared to PV-electrolysis, as evidenced in Reference [68]. Through the strategic utilization of concentrators, thermal energy is generated to heat water or fossil fuels within the thermolysis system, thus presenting a promising avenue for hydrogen production. Additionally, the high-temperature decomposition of natural gas emerges as a particularly promising method for producing hydrogen.

2.2.5 Thermochemical system

The Thermochemical System employs both heat and chemical reactions to initiate the disintegration of water into hydrogen and oxygen. This intricate process involves the recycling of chemicals through successive thermochemical cycles. Three critical prerequisites for its success include the availability of a high-heat source, the use of materials resilient to such extreme temperatures, and the application of sophisticated chemical methodologies for the effective separation of hydrogen and oxygen [69]. This thermochemical process entails the breakdown of water into its constituent elements through the synergistic application of heat sources and chemical reactions.

These reactions rely on chemicals that undergo recycling within a series of thermochemical cycles. The successful execution of this method hinges upon meeting three fundamental conditions: the provision of a high-heat source, the utilization of materials capable of enduring these elevated temperatures, and the implementation of intricate chemical techniques to facilitate the separation of hydrogen and oxygen.

2.2.6 Steam electrolysis

Steam electrolysis is a process utilized for hydrogen production by passing steam through an electrolyzer. Within the electrolyzer, electrical energy is applied to split water molecules (H_2O) into oxygen gas (O_2) and hydrogen gas (H_2). This method is regarded as environmentally benign as it emits no greenhouse gases when powered by renewable energy sources. Its utility lies in its ability to utilize water as a readily available resource, albeit it demands substantial energy input. Ongoing research endeavors aim to enhance its efficiency and cost-effectiveness. The cornerstone of High-Temperature Steam Electrolysis (HTSE) is the electrochemical cell, typically composed of ceramics due to the elevated operating temperature [70]. This cell, referred to as the solid oxide electrolysis cell (SOEC), comprises three ceramic layers: a dense electrolyte and two porous electrodes (a cathode for H_2 and an anode for O_2), as depicted in Figure 7. Table 2 presents a comparative analysis of different methods, outlining their respective benefits, drawbacks, and associated references.

3. Hydrogen's role in storing energy within renewable systems

According to forecasts by the IEA, approximately one-third of the world's electricity generation is projected to come from intermittent renewable sources such as wind and solar by 2040 [86]. To meet this demand, long-term solutions for large-scale electricity storage are necessary. Hydrogen storage and production emerge as prospective technology, as depicted in Figure 8 [87].

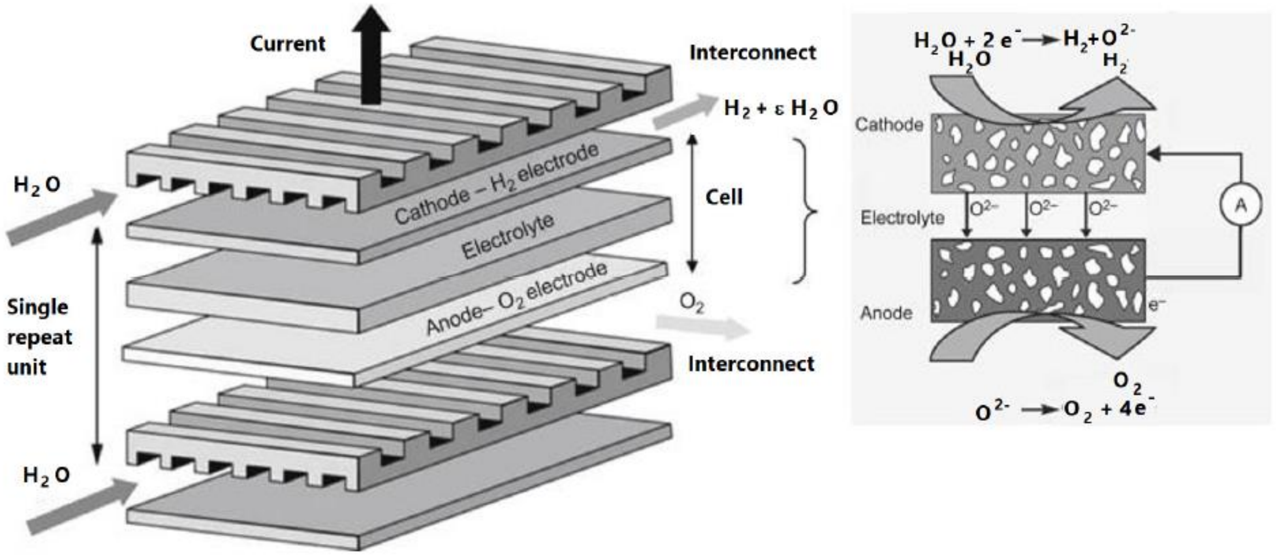


Figure 7. Depiction of an electrochemical cell [63]

Table 2. A comparison of various methods for producing hydrogen utilizing wind and solar energy

H_2 Production Methods	Advantages	Disadvantages	Ref.
Wind-Electrolysis system	• Suitable in remote areas • Wind intermittency • Low electricity production cost • Technically mature and has already been commercialized	• Power fluctuation varies according to wind speed	[66], [67], [71], [72], [73], [74], [75], [76]
Steam electrolysis	• Less energy is needed to separate steam compared to liquid water.	• The lifespan of the hydrogen electrode is constrained by degradation.	[77]
PV-Electrolysis system	• Quick response time and rapid startup. • Elevated levels of hydrogen purity. • Reduced cost of electricity production.	• Delayed loading response. • Decreased current density.	[62], [71]
Hybrid PV/T-Electrolysis system	• Readily adjustable to achieve the desired rate of hydrogen production or to correspond with the output of PV energy. • The feedwater undergoes preheating. • It generates highly pure hydrogen while simultaneously demanding significantly lower maintenance.	• Distilled or deionized water is required instead of tap water.	[78- 82]
Thermolysis system	• Optimal efficiency. • Cost-effective.	• Necessitates elevated temperatures. • Inapplicable for practical use because of the elevated temperature requirement. • Challenging to timely separate hydrogen and oxygen.	[68], [83], [84]
Thermochemical system	• Significant potential for theoretical efficiency. • Minimal or absent greenhouse gas emissions.	• Sophisticated chemical techniques are employed for the separation of H_2 and O_2. • Produces a substantial amount of waste.	[69], [77], [85]

The extensive utilization of hydrogen as a sustainable and clean energy source, applicable to various sectors, including energy storage and transportation, hinges on advancements in storage technologies. Therefore, the immediate development of improved storage methods with the potential for higher energy density is imperative. In contemporary times, hydrogen is stored for onboard applications using high-pressure tanks for compressed gas, in cryogenic liquid form (below the critical temperature of 33 K), or in solid-state compounds like complex hydrides, metal hydrides, or porous materials. Figure 9 illustrates the practical methods for hydrogen storage, which are categorized into four main types: hydrogen liquefaction, physical adsorption, chemical absorption, and pressurized gas storage. Hydrogen gas possesses remarkable energy value per unit mass due to its high molar combustion heat and low molecular weight [88]. Currently, the most common method for hydrogen storage is compressed gas. Commercial hydrogen storage tanks, such as those utilized in Toyota's Mirai fuel cell car, can accommodate hydrogen gas at pressures reaching 700 bar [90].

Typically, the compression process consumes roughly 20% of the energy held within the hydrogen [91]. Utilizing compressed hydrogen storage offers advantages in terms of technical simplicity and relatively low cost. Downsides involve relatively lower system energy density compared to fossil fuel-based systems, alongside safety considerations due to high pressure [92]. Hydrogen can alternatively be stored in liquid form, significantly boosting its volumetric energy density compared to storage as a compressed gas. Liquid hydrogen exhibits an energy density of 2.2 kWh/L, while compressed hydrogen gas provides 1.3 kWh/L at 700 bar and 0.8 kWh/L at 350 bar [93]. The drawbacks of liquid hydrogen encompass the significant energy consumption during the liquefaction process, hydrogen boil-off, and the considerable expense of storage systems. Due to the boil-off issue, liquid hydrogen is primarily suited for applications where rapid consumption is anticipated, such as transport scenarios with frequent refilling options. Consequently, it is not regarded as a feasible option for long-term energy storage in stationary power systems [92].

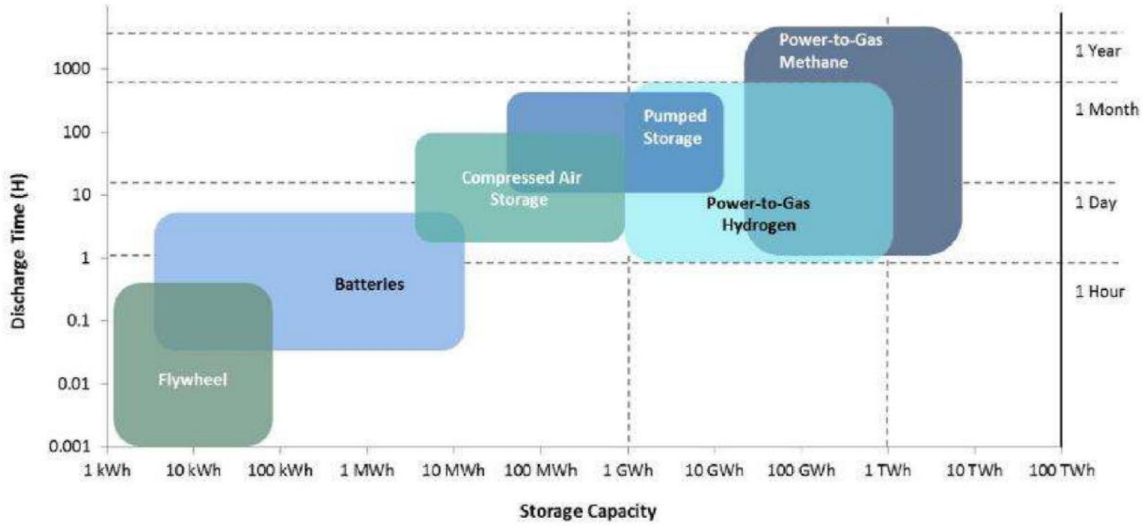


Figure 8. Analyzing Storage Capacity and Discharge Time Across Diverse Energy Storage Solutions [87]

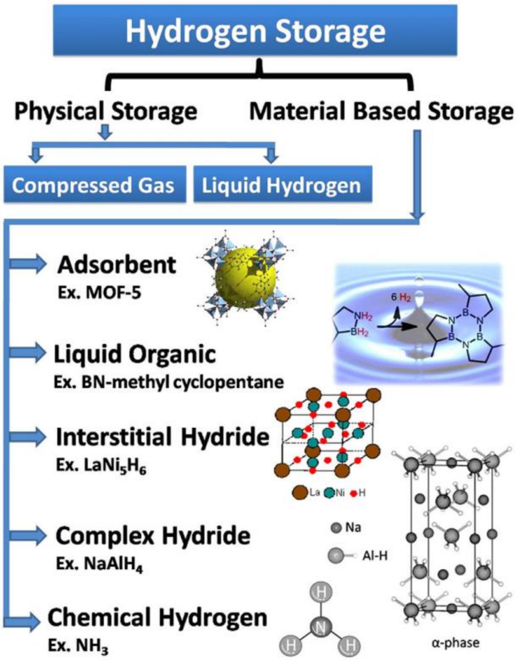


Figure 9. Processes and phenomena of different hydrogen storage systems [89]

Solid-state storage emerges as a secure, promising, and efficient method for hydrogen storage. This approach involves storing hydrogen within a material, either in atomic form or as H_2 molecules, through two established processes: physisorption and chemisorption [94]. Physisorption presents an additional approach to hydrogen storage. In this method, hydrogen gas molecules adhere to the surface of a solid material through adsorption and are subsequently released as gas when required, such as in fuel cell applications. The prevalent materials utilized for hydrogen gas adsorption include metal-organic frameworks and carbon-based materials [91].

Hydrogen storage through physisorption offers advantages such as simplified system design, low-pressure requirements, and the use of relatively inexpensive materials. Challenges include the relatively low hydrogen density achieved on carbon and the requirement for low temperatures [95]. Another method for hydrogen storage is chemisorption in metal hydrides, where hydrogen gas is absorbed and retained within a metal powder, which can be either a metal alloy or a pure metal. Heat is generated during the absorption of hydrogen gas into the metal hydride material, and conversely, applying heat is essential to facilitate the release of hydrogen from the metal hydride. A limitation of the metal hydride storage method, observed with certain materials, is the strong bonding between hydrogen and the metal hydride, requiring relatively high temperatures for hydrogen release. For instance, temperatures exceeding 650°C are necessary for lithium. Yet, one advantage is that certain materials boast remarkably high gravimetric hydrogen capacities, reaching up to 18 wt% for $LiBH_4$ [91]. Hydrogen stands at the forefront of renewable energy storage solutions, offering a versatile and scalable option to address the intermittent of renewable sources. Its potential for long-term storage, coupled with its versatility in various applications, makes it a compelling choice for integration into renewable energy systems.

4. Hydrogen's role in future energy generation and applications

Both developed and developing nations increasingly acknowledge the significance of hydrogen energy as an energy carrier for achieving sustainable growth on a global scale [96]. Despite its remarkable power generation capacities, hydrogen is predominantly utilized in sectors beyond power generation. A considerable portion of commercially generated hydrogen finds application in diverse sectors such as oil refining, recycling, metalworking, chemical processing, and fertilizer production, as shown in Figure 10.

Figure 10. Present and prospective industrial uses of hydrogen

While hydrogen products currently serve as foundational resources within the industrial sector, their potential as a comprehensive energy carrier remains largely untapped. Of the approximately 50 million metric tons produced annually worldwide, the primary application is as a feedstock for ammonia production, with oil refining accounting for 35% of its usage [34]. Fuel cells and hydrogen are widely regarded as pivotal technologies for a sustainable future energy source. Projections suggest that increasing renewable energy shares to 36% by 2025 and 69% by 2050 could result in hydrogen shares rising to 11% by 2025 and 34% by 2050, contributing significantly to meeting total energy demand [97]. Hydrogen holds the potential to generate electricity, produce synthetic fuels, and perform mechanical work [98]. Fuel cells possess the capability to convert hydrogen into electrical energy, facilitating its transfer and storage for subsequent use [99]. One of the main reasons for considering hydrogen is its ability to complement electricity in energy transport. Currently, a prominent application of hydrogen occurs within the transportation sector. While electric vehicle users often express concerns about limited range and long recharge times, these worries are alleviated by hydrogen-powered fuel cell electric vehicles, which offer significantly faster refueling times, minimal behavioral adjustments, and extended range compared to electric vehicles [100]. Hydrogen shows promising potential for utilization in spark ignition engines [101].

Internal combustion engines (ICEs) utilize the energy from a fuel, like hydrogen, to generate mechanical power, which in turn drives a shaft. In power generation, a generator is coupled to convert this mechanical energy into electrical power. Hydrogen-fueled ICEs emit fewer pollutants, mainly nitrous oxides, compared to traditional ICEs. Moreover, they exhibit up to 25% higher fuel efficiency than standard gasoline engines, with conventional car fuels typically achieving efficiencies of only 20-25%, while hydrogen ICEs can reach rates of 30-40% [102]. Hydrogen is regarded as a promising energy source with the potential to mitigate CO_2 emissions. Figure 11 illustrates a comparison between fossil fuels and hydrogen technologies. It is estimated that employing hydrogen derived from conventional methods can reduce carbon emissions by nearly 20% when utilized in fuel cells. Thus, the production of hydrogen using RS could substantially mitigate carbon emissions [103]. The research conducted by the Hydrogen Council indicates that demand and supply for hydrogen (H_2) could potentially reach 10 exajoules annually by 2050, with further anticipated growth of approximately 5%–10% per year beyond 2050. Therefore, it can be asserted that hydrogen is poised to emerge as a formidable contender in the future global energy landscape [104].

5. Challenges and perspectives

The cost dynamics associated with hydrogen production are contingent upon numerous factors, with the primary determinant being the expense linked to the electricity required for electrolysis. Additional considerations include investments in diverse equipment for establishing sustainable energy sources, land procurement expenses, and the anticipated lifespan of the infrastructure. These financial commitments can be categorized into two main areas: production and logistical costs. Furthermore, local regulatory frameworks and financial variables such as capital outlays play a significant role in determining the final delivery cost. Throughout the production process, the pricing mechanisms governing renewable energy and fossil fuels, like coal and natural gas, significantly influence variable costs, thereby shaping the comparative competitiveness of each technology.

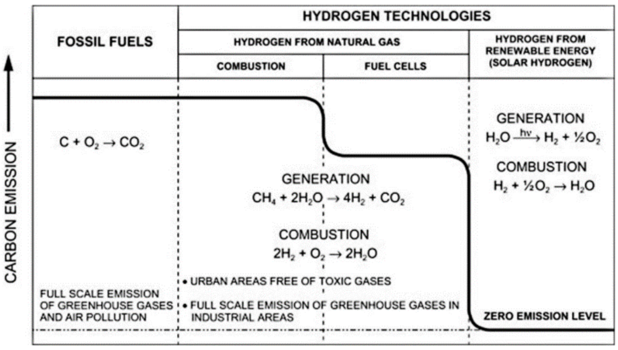
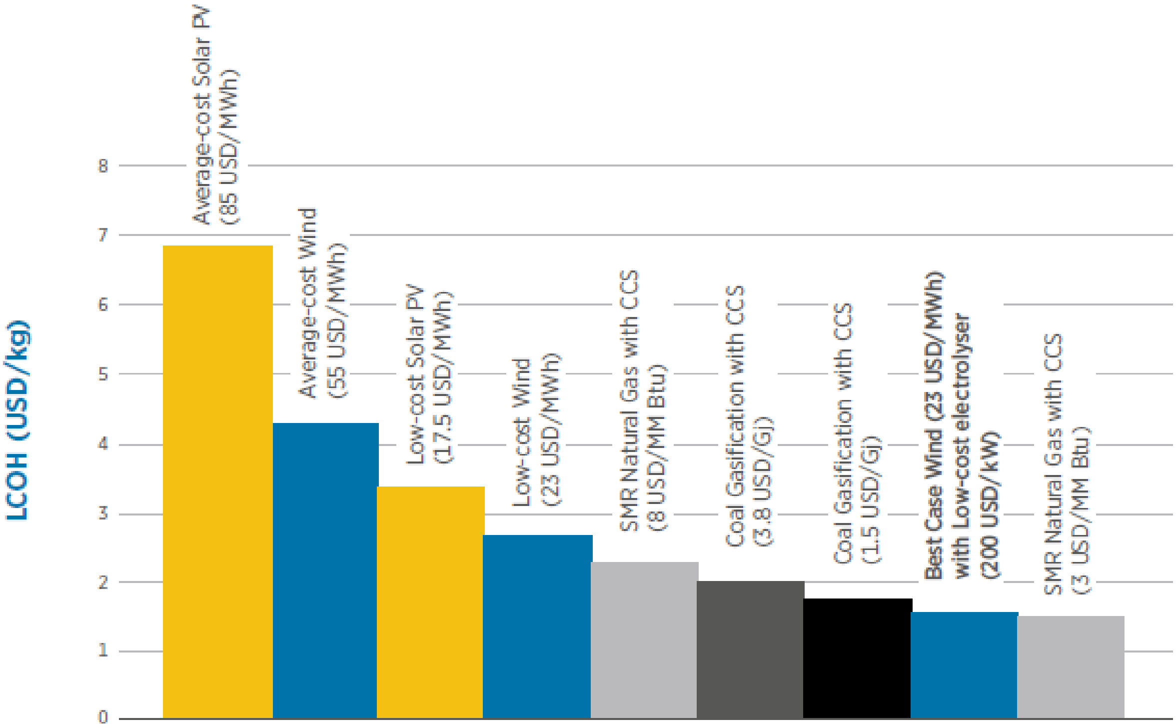


Figure 11. The influence of combustion and hydrogen production on carbon emissions [103]

The data illustrated in Figure 12 indicates that renewable electricity, both on average and in the best-case scenario, may present competitive supply costs when compared to fossil fuels with carbon capture and storage (CCS). This suggests that under specific circumstances, renewables could potentially emerge as one of the most economically feasible options for producing hydrogen, even in the current landscape. In this optimal scenario, a low-cost electrolyzer priced at USD 200/kW is considered, a milestone expected to be widely achievable by 2040, although some Chinese manufacturers claim its present feasibility. Furthermore, there are instances of low-cost renewable power, exemplified by wind projects in countries like Brazil and Saudi Arabia, where electricity costs are as low as USD 23/MWh [105]. Electricity, the primary output of renewable energy sources, is important for powering electrolysis units in hydrogen generation. Consequently, electricity price plays a significant role in determining the overall expense of hydrogen production. This cost is contingent upon various factors, including the installation of renewable energy infrastructure, geographical considerations, land costs, and the design and scale of renewable energy systems. Figure 13, which outlines the cost ranges associated with hydrogen production utilizing different renewable energy sources [106, 107], illustrates pertinent insights. It reveals that conventional energy sources like nuclear and coal generally offer lower production costs compared to renewables. However, their environmental impact, characterized by greenhouse gas emissions, poses notable concerns.



Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simplicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.
Source: IRENA analysis

Figure 12. The expenses associated with generating hydrogen from renewable sources and fossil fuels are currently being examined [105]

In contrast, despite the relatively higher costs associated with hydrogen production from green energy sources, there exists a prevailing global preference for their adoption due to their emission-free attributes. Efforts are actively underway to mitigate the costs associated with renewable energy sources. As delineated in Figure 13, renewable energy systems for hydrogen production typically entail higher expenses compared to conventional energy sources. Achieving optimal, reliable, cost-effective, environmentally sustainable, and efficient hydrogen generation presents a multifaceted challenge, as no single technique can satisfy all these objectives simultaneously. Hence, additional investigation is warranted to address the remaining complexities outlined as follows [108]. Given that hydrogen is not naturally occurring and must be synthesized, there is a pressing need to innovate manufacturing methods that consume less energy and facilitate large-scale production. Moreover, prioritizing water as a feedstock is advantageous due to its potential to mitigate environmental impact by eliminating CO_2 emissions. As hydrogen exists in a gaseous state at room temperature, it possesses a notably low volumetric density, necessitating a volume exceeding 3000 times that of typical liquid fuels to produce equivalent energy. Thus, it is pertinent to decrease the volume of hydrogen to streamline its storage and transportation processes. Due to hydrogen's increased flammability relative to other fuels, safety becomes a significant concern.

Additionally, as an asphyxiant gas, it can result in suffocation by depleting oxygen levels in the atmosphere. Consequently, meticulous attention to various safety and security protocols is essential when handling or storing hydrogen. Once hydrogen is prepared for utilization, it should be employed with utmost efficiency to generate heat or power. Due to its production process rather than natural occurrence, hydrogen commands a cost threefold higher than fossil fuels. Moreover, storage considerations may exacerbate expenses, particularly with the utilization of high-pressure technologies. A projection of production costs for renewable hydrogen can be extrapolated and juxtaposed against fossil fuel alternatives integrating carbon capture and storage (CCS). A portion of CO_2 remains unsequestered in CCS facilities, prompting consideration of carbon pricing, as delineated in Figure 14. Forecasts indicate that hydrogen production from low-cost solar and wind photovoltaic (PV) projects is poised to attain competitiveness with fossil fuels within the upcoming five years, particularly in comparison to steam methane reforming (SMR) from natural gas with CCS, assuming a natural gas price of USD 8 per million British thermal units (Btus). In the case of low-cost PV projects, this equilibrium is anticipated within eight years. Subsequently, from 2030 to 2040, renewable hydrogen costs are projected to fall below those of fossil fuels with CCS across all scenarios.

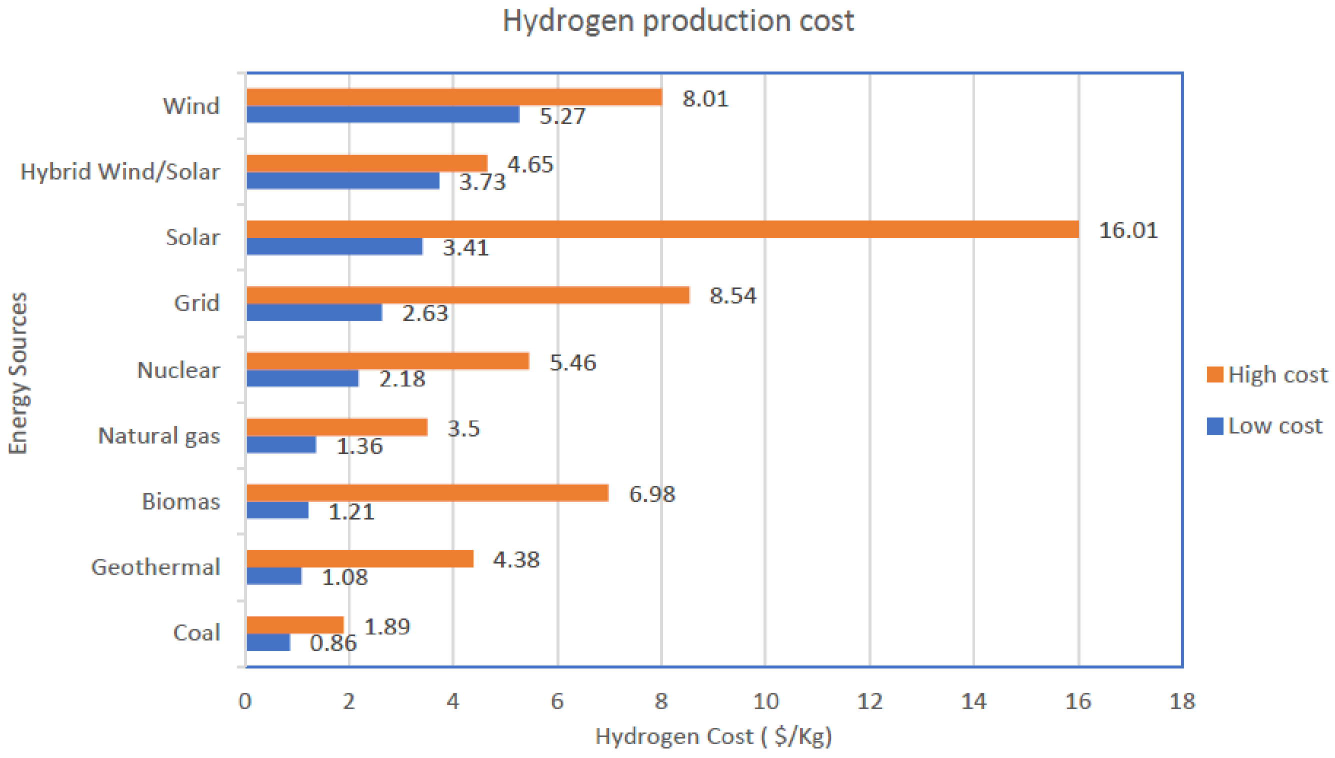
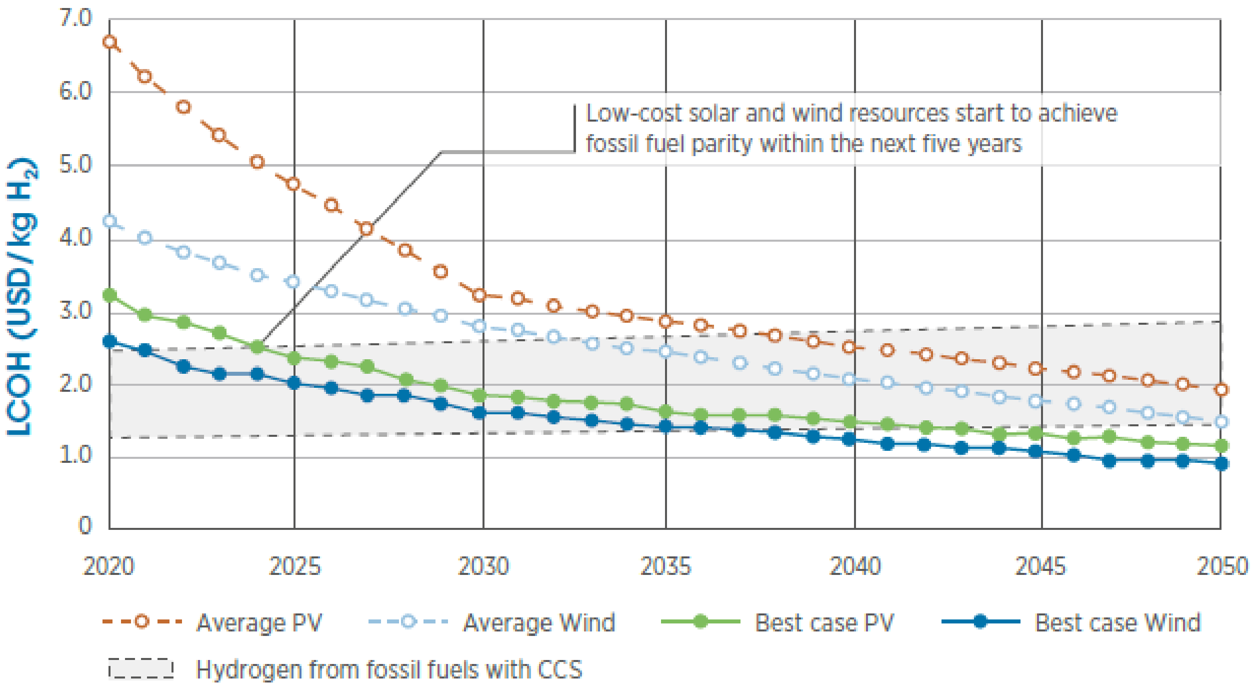


Figure 13. The expense of generating hydrogen fluctuates depending on the energy source used [63]



Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

Figure 14. The expenses related to generating hydrogen from wind and solar energy are compared to those from fossil fuels [109]

6. Conclusion

The transition to utilizing renewable energy sources, like wind and solar, for hydrogen production is a pivotal step toward achieving sustainable energy objectives. Cutting-edge technologies, including water electrolysis and biomass conversion, offer efficient pathways to produce environmentally friendly hydrogen. Emphasizing the potential for energy storage and reliable supply underscores the strategic importance of this approach. Future initiatives are focused on optimizing electrolysis systems and enhancing biomass conversion techniques to accelerate the transition to a cleaner energy landscape. In tandem with renewable energy production, hydrogen offers diverse storage options, ranging from compressed gas to liquid and solid-state storage. Each method presents unique advantages and challenges related to energy usage and safety. Ongoing efforts are directed toward enhancing storage technologies to minimize energy consumption and ensure broader acceptance. The versatility and scalability of hydrogen position it as a promising candidate for integrating renewable energy solutions, thus fostering sustainability across various sectors. Recognized as a cornerstone of sustainable global development, hydrogen is increasingly valued for its multifaceted applications. Projections indicate a substantial rise in its role in meeting energy demands by 2050, particularly as renewable energy adoption accelerates. Its versatility extends to electricity generation, synthetic fuel production, and beyond, with fuel cell electric vehicles offering enhanced efficiency and range.

Additionally, hydrogen holds promise in reducing CO_2 emissions, particularly when derived from renewable sources. To fully capitalize on its potential, ongoing efforts are essential to advance production, storage, and utilization technologies, ensuring maximum efficiency and sustainability. Despite the complexities associated with hydrogen production costs, renewable energy sources offer promising avenues for achieving competitive pricing. Addressing challenges such as innovative manufacturing, storage optimization, and safety protocols is paramount for cost-effective and efficient hydrogen generation. Future endeavors should prioritize research into enhancing electrolysis efficiency, storage, and transportation alongside advancements in renewable energy technologies. These collective efforts will facilitate the widespread adoption of hydrogen as a renewable energy solution, thus contributing to a greener and more resilient energy landscape.

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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