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Comparative Study on Green Hydrogen Production via Solar vs Wind Electrolysis

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ABSTRACT

Green hydrogen is emerging as a key component of the global energy system's rapid decarbonization, which calls for clean, adaptable, and scalable energy carriers. Green hydrogen, which is created by electrolysing water with renewable power, is a sustainable substitute for hydrogen obtained from fossil fuels and has the potential to significantly reduce carbon emissions in transportation, industry, and energy storage. The two main renewable methods for producing hydrogen—solar-powered electrolysis and wind-powered electrolysis—are compared in this paper. The basics of electrolysis technologies and their energy needs are first described, followed by an examination of how solar photovoltaics and wind turbines can be integrated with electrolysers, emphasising new developments in technology, efficiency standards, and demonstration projects. The study highlights the unique advantages and disadvantages of each pathway: wind-driven systems, especially offshore, offer higher capacity factors and larger-scale deployment potential but are limited by infrastructure demands, wind resource variability, and higher capital costs. In contrast, solar-driven systems enjoy the advantages of rapidly declining photovoltaic costs and wide geographic applicability, but they also face challenges of intermittency, land intensity, and diurnal variability. Hybrid solar-wind systems that increase stability and utilisation are discussed in addition to a head-to-head comparison of efficiency, cost, scalability, and environmental impact. In order to determine future research objectives and position green hydrogen from solar and wind electrolysis as complementary options essential to reaching net-zero climate targets, the assessment concludes by looking at policy, economic, and commercial aspects.

Keywords: *Green hydrogen, Renewable electrolysis, Solar photovoltaics, Wind energy, and Decarbonization.*

Introduction

The drive to limit global warming and meet the targets of the Paris Agreement has created an urgent need to transform energy systems worldwide. Energy efficiency, electrification, and the quick growth of renewable energy are the main pillars of this transition [1, 2]. However, decarbonising several large-emitting industries, such as steel, cement, and some forms of transportation (such as shipping, long-haul trucking, and aviation), with electrification alone is either difficult or expensive [1].

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Therefore, to achieve deep decarbonization, energy carriers that can supply process heat, flexible storage, and high energy density are needed. Hydrogen's adaptability as an industrial feedstock and an energy vector for storage and transportation has made it a vital part of integrated decarbonization pathways and low-carbon futures. The production of hydrogen using water electrolysis with renewable electricity, or "green hydrogen," is becoming more widely acknowledged as a crucial component of the global energy transition [3, 4].

It provides nearly low lifecycle emissions in comparison to hydrogen obtained from fossil fuels and can decarbonise industries that are difficult to electrify, such as transportation and heavy industry, while also acting as long-duration energy storage [5]. This function is represented in significant worldwide assessments and integrated assessment studies that present hydrogen as an adjunct to electricity rather than a complete substitute for it [5]. Even if hydrogen has conceptual significance, production from fossil fuels nevertheless dominates the contemporary global hydrogen economy. The world's hydrogen demand was at 97 million tonnes in 2023, and fossil fuels provided nearly all of it. Low-emission hydrogen, such as green and blue hydrogen, nevertheless made up a very small portion of production. Transport, long-duration storage, and large-scale industrial decarbonization are some of the more recent uses of hydrogen, whereas the majority of its current use is focused on chemical feedstocks and refining. According to [6], these figures highlight the size of the current market as well as the significant gap that has to be closed if hydrogen is to make a significant contribution to climate goals.

Carbon intensity is a common way to classify hydrogen production pathways: "blue" hydrogen uses fossil fuels with carbon capture and storage (CCS); "green" hydrogen uses water electrolysis powered by renewable electricity, which produces hydrogen with almost zero operational greenhouse gas emissions; and "grey" hydrogen is hydrogen produced from fossil fuels without carbon capture [7]. Green hydrogen is significant for a number of reasons, including the fact that it can operate as a zero-carbon fuel in industries where batteries are not viable, substitute fossil hydrogen in industrial processes (cutting process emissions), and offer long-duration, seasonal storage to supplement variable renewables. Coupling electrolysis with low-carbon renewables is crucial to achieving the climate benefits of hydrogen since the emissions profile of hydrogen generation is largely dependent on the energy source [8]. Large pipeline projects and ambitious hydrogen targets have been proposed by the industry and international community, but actual capacity and deployment still lag behind planned plans. To lower production costs and close the competitiveness gap with hydrogen supplied from fossil fuels, government initiatives, industry roadmaps, and international evaluations all agree that a quick increase in electrolyser capacity and specialised, inexpensive renewable electricity are necessary. However, there are real short-term challenges as well, such as supply-chain pressures, infrastructure limitations, and project execution uncertainties (particularly for electrolyser production and essential materials) [9].

An electrically powered chemical process called electrolysis separates water into hydrogen and oxygen. The carbon intensity of the power consumed almost totally determines its environmental performance. Hydrogen produced by electrolysis with little direct CO_2 emissions is known as "green hydrogen" when it is driven by renewable electricity, most frequently solar photovoltaics (PV) or wind turbines [10]. The two main contenders for large-scale green hydrogen production are solar and wind since they are currently the most developed, extensively used, and economically viable renewable energy sources [11]. They vary, nevertheless, in a number of key areas that impact electrolytic hydrogen systems, including geographic distribution and resource availability, typical capacity factors, temporal variability (diurnal versus stochastic wind patterns), implications for land and marine use, integration complexity, and cost dynamics [12]. Different electrolyser utilisation rates, hydrogen yields per unit of installed renewable capacity, and eventually the levelized cost of hydrogen (LCOH) for solar versus wind-driven systems are all directly impacted by these variations. Planning, investment, and policy decisions aiming at scaling green hydrogen must therefore take into account a thorough assessment of different approaches [13].

In this paper, two prominent methods for producing green hydrogen—solar-driven electrolysis and wind-driven electrolysis are compared. The foundation is laid out first, including the different ways that hydrogen can be produced, the different kinds of electrolysis technology, energy and efficiency standards, and the significance of combining electrolysis with renewable energy. The review then delves deeply into the workings, capabilities, case studies, technological developments, and difficulties of both wind-powered and solar-powered electrolysis. Both routes are compared, taking into account reliability, geography and scalability, energy efficiency, levelized cost of hydrogen (LCOH), and environmental effects. There is also discussion about hybrid systems that combine wind and solar power. Ultimately, the evaluation examines the commercial, economic, and governmental frameworks that impact deployment; pinpoints areas in need of further study; and makes judgments regarding whether a route is more appropriate in certain circumstances. In order to help academics, practitioners, and policymakers understand the relative advantages and disadvantages of each approach to bringing green hydrogen closer to commercial maturity and helping achieve global net-zero goals, the paper uses a comparative lens.

Fundamentals of Green Hydrogen Production

A variety of technological approaches can be used to manufacture hydrogen, a flexible energy source with varying effects on cost, scalability, and the environment. Around 95% of hydrogen produced now comes from coal gasification and steam methane reforming, which both release significant amounts of carbon dioxide into the atmosphere [14]. Fossil-based technologies currently account for the majority of global output. Despite being cheap, this traditional "grey hydrogen" uses a lot of carbon. To counteract emissions from fossil fuel-based production, "blue hydrogen" uses carbon capture and storage (CCS) technologies; however, life-cycle evaluations show that leakage rates and capture inefficiencies may undermine the climatic benefits of this technology [15]. Green hydrogen is the most environmentally friendly substitute; it is produced by electrolysing water using renewable energy. For industries that are difficult to decarbonise, such as steel, ammonia production, and heavy transportation, this route is considered a key component of deep decarbonization plans since it removes direct CO_2 emissions [16].

Green hydrogen is primarily made possible via electrolysis, which is the process of dividing water into hydrogen and oxygen using electricity. Alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs) are the three main types of electrolysers that predominate in research and implementation. Since they have been on the market for decades, alkaline systems are the most established [17]. They usually use liquid alkaline electrolytes, like potassium hydroxide, and function at low temperatures (30 to 90 °C). Although their reduced capital cost and relative simplicity make them appealing for widespread use, their flexibility under variable renewable inputs is limited by their slower dynamic reaction and lower current densities [18].

PEM electrolysis has become well-known due to its small size, high-purity hydrogen output, and quick reaction times. It uses a solid polymer electrolyte and operates at comparable temperatures [19]. Despite their need for expensive and rare catalysts like iridium and platinum, which raises worries about material availability and drives up costs, these features make PEM systems ideal for direct coupling with intermittent renewable energy [20]. Although SOEC technology is still in its early phases of commercialisation, it functions at temperatures between 500 and 1000 °C and has the potential to provide higher electrical efficiency when combined with waste heat sources in industrial operations. Long-term deployment of SOECs is limited by durability and material issues, notwithstanding this promise [21].

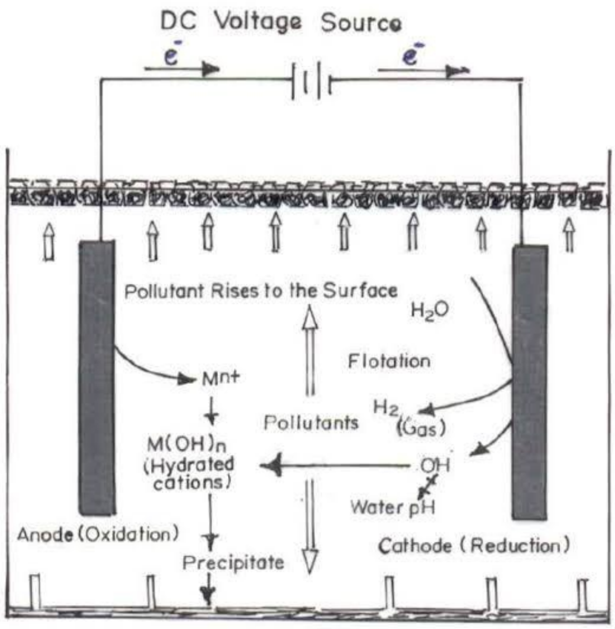

Figure 1. Principles of electrolysis
Source: *[22]*

When evaluating the feasibility of green hydrogen, the energy needs for electrolysis are crucial. Because of overpotentials, resistive losses, and auxiliary system demands, real systems usually use 50–60 kWh/kg H_2, even though the theoretical minimum energy input to split water is 39.4 kWh per kilogram of hydrogen (based on the lower heating value) 23]. Depending on the type of technology and operational conditions, this puts overall conversion efficiencies between 62 and 82% [24]. Although the necessity for high-purity deionised water adds to the purification expenses and logistical considerations, the water requirements are comparatively low in mass terms, ranging from 9 to 12 liters per kilogram of hydrogen [25]. To lower energy and water intensity, efforts are being made to improve electrolyser materials, stack architecture, and system integration.

Combining electrolysis with renewable energy is crucial for making sure that the production of hydrogen makes a significant contribution to climate goals. If electrolysis is fueled by fossil fuels, it may paradoxically increase emissions in the absence of renewable inputs [26]. The most scalable and quickly growing renewable energy sources are solar and wind, which make them ideal electrolysis partners. Due to supply fluctuations, their integration presents difficulties. While wind is unpredictable and frequently a supplement to solar power, solar power is limited by seasonal and diurnal cycles. The levelized cost of hydrogen (LCOH) and electrolyser usage rates are impacted by these variations. In this situation, flexible electrolyser technologies in particular, PEM systems are beneficial because they can adjust their operation in response to changes in the electrical supply [27]. Furthermore, hybrid renewable systems that include wind and sun can improve system capacity factors, reduce intermittency and lower overall costs [28].

Table 1. Comparison of hydrogen production pathways
Source: *[29, 30]*

Production Pathway	Feedstock	CO_2 Emissions	Technology Maturity	Cost Range (USD/kg H_2)
Grey Hydrogen	Natural gas via SMR	~10 kg CO_2/kg H_2	Mature	1.0–1.5
Blue Hydrogen	Natural gas + CCS	~1–3 kg CO_2/kg H_2	Emerging	1.5–2.5
Green Hydrogen	Water electrolysis + RES	~0	Growing	3–7

Ultimately, the fundamentals of green hydrogen production underscore its role as both a technological and systemic challenge. Advances in electrolyser performance, reductions in renewable electricity costs, and improved system integration are essential to making green hydrogen economically competitive [31]. As global energy systems transition toward decarbonization, the close coupling of renewable energy with electrolysis will determine whether hydrogen evolves from a niche solution into a cornerstone of net-zero strategies.

Table 2. Efficiency ranges of different electrolyzer technologies
Sources: *[32, 33]*

Electrolyzer Type	Operating Temp (°C)	Efficiency Range (%)	Key Advantages	Key Challenges
Alkaline	60–90	60–70	Mature, cheap catalysts	Lower dynamic response
PEM	50–80	65–75	Compact, flexible	High cost, scarce materials
SOEC	600–800	80–90	Very high efficiency	Not yet commercial

Powered Electrolysis

Solar-powered electrolysis creates hydrogen in a carbon-free process by combining photovoltaic (PV) electricity generation with electrolysers. The basic process is using photovoltaic (PV) modules to convert sunlight into direct current (DC) energy, which is then supplied to an electrolyser to split water into oxygen and hydrogen. Conversion and transmission losses, as well as the efficiency of the PV module and electrolyser, all affect system efficiency [34]. There are two primary ways to design PV integration: stand-alone systems for hydrogen generation, especially in remote locations with high solar irradiation, and grid-connected systems, which redirect excess solar electricity to electrolysis during times of low demand [35].

Conversion efficiency, hydrogen yield, and system dependability under varying irradiance circumstances are the performance parameters of solar-driven electrolysis. Advanced tandem and perovskite-silicon cells have laboratory efficiencies surpassing 30%, whereas commercial crystalline silicon PV modules attain 18–22% efficiency [36]. Overall solar-to-hydrogen (STH) efficiency when combined with electrolysers usually falls between 10 and 15 per cent in commercial systems, but research prototypes can reach up to 20 percent in the right lab settings. Intermittency continues to be a major problem: weather variations and diurnal cycles lead to extremely variable hydrogen output, which, if storage or hybridisation are not used to alleviate it, can lower electrolyzer utilisation rates and raise the levelized cost of hydrogen (LCOH) [37].

The chances of producing hydrogen from solar electricity have risen due to recent technological advancements. Bifacial and perovskite-silicon tandem cells are two examples of high-efficiency PV modules that are lowering land-use intensity while increasing efficiency [38]. Direct solar-to-hydrogen methods, such as photoelectrochemical (PEC) water splitting, integrate light-absorbing semiconductors straight into catalytic devices, avoiding the PV–electrolyzer contact. Direct solar-to-hydrogen methods, such as photoelectrochemical (PEC) water splitting, integrate light-absorbing semiconductors straight into catalytic devices, avoiding the PV–electrolyzer contact. Despite the fact that PEC is still in its infancy, demonstration systems have demonstrated stability under simulated sunlight and STH efficiencies exceeding 19%. Furthermore, dynamic electrolysers especially PEM systems, which can ramp flexibly in response to changing irradiance and changeable solar inputs can now be coupled more smoothly thanks to power electronics and smart inverters [39].

The real-world application of solar-powered electrolysis is demonstrated by several case studies and pilot projects. A 10 MW solar-powered PEM electrolyzer at the Fukushima Hydrogen Energy Research Field (FH2R) in Japan can produce up to 1,200 m^3/h of hydrogen for use in transportation and industry (New Energy and Industrial Technology Development Organisation [1]. Large-scale projects with dedicated PV farms are being proposed in Australia's solar-rich regions, including Western Australia and Queensland, to support export-oriented hydrogen hubs [2]. High-irradiance zones are geographically suitable for competitive solar hydrogen production, as evidenced by pilot installations in MENA desert regions [3].

Even with these developments, there are still many obstacles to overcome. Electrolysers operate under partial loads due to the unpredictability of solar energy, which, if not properly controlled, can impair performance and shorten system lives [3]. Another issue is land use since massive PV arrays need a lot of surface area, which could put them in competition with natural ecosystems or agriculture. Even with their steady decline, PV module costs still account for a sizeable portion of the overall system cost, especially for standalone installations [4]. Another significant limitation is the availability of water in dry areas with high solar potential, necessitating the purchase of desalination or water purification equipment [5].

Table 3. Selected solar electrolysis demonstration projects

Sources: *[6, 7]*

Project	Location	Capacity (MW)	Technology	Highlights
Hydrogen Park South Australia	Australia	1.25	PEM	PV + grid mix
Mallorca Green H_2	Spain	2.5	PEM	PV + battery + electrolyzer
NEOM Project (under development)	Saudi Arabia	2000+	PEM/Alkaline	World's largest PV + H_2 hub

Wind-Powered Electrolysis

Another leading renewable energy source for electrolysis is wind, which has benefits that solar-based systems can also benefit from. Wind-powered electrolysis works by using wind turbines to transform the kinetic energy of flowing air into electrical power, which can then be sent directly to electrolysers or indirectly through grid connections. Wind resources are more variable than solar ones. Unlike solar, which is limited to the day, wind frequently displays seasonal and diurnal patterns that can supplement solar availability, which makes it a desirable option for hybrid renewable hydrogen systems [8].

Both onshore and offshore configurations are possible for wind-to-hydrogen integration; offshore wind offers especially high capacity factors and less land-use constraints, but at higher capital costs [9]. System scalability, electrolyser efficiency, and turbine capacity factors all influence wind-driven electrolysis performance indicators. In comparison to solar PV, modern onshore wind turbines usually reach capacity factors of 30–45%, while offshore wind projects surpass 50%. These wind projects offer a more reliable source of power for electrolysis [10]. With efficiencies ranging from 62 to 82%, the power produced is sent to alkaline or PEM electrolysers, making levelized prices of hydrogen (LCOH) more competitive in areas with abundant wind [10]. Crucially, compared to solar-only projects, the comparatively high utilization rate of wind-powered electrolyzers enhances capital amortisation and reduces expenses. Wind speed fluctuations still result in sporadic hydrogen production, though, therefore storage or hybridization are required for a steady supply.

Wind-to-hydrogen applications are becoming more widespread due to recent technology advancements. With floating wind platforms connected to offshore electrolyzers, offshore wind-hydrogen integration has accelerated. These platforms can either produce hydrogen on-site or supply electricity for onshore electrolysis through subsea cables [11]. Offshore electrolysis is being studied in a number of projects to lower transmission losses and take advantage of the abundance of seawater resources; however, this presents problems with corrosion-resistant materials and seawater desalination. In order to increase efficiency and prolong electrolyser lifetimes, hybrid wind-electrolyser systems are also being designed to incorporate flexible PEM electrolyzers that can ramp in response to varying wind output [12]. Large-scale wind-to-hydrogen facilities are now even more economically viable thanks to developments in digital monitoring, smart controls, and predictive maintenance [13].

Case studies demonstrate the intricacy and potential of wind-powered hydrogen generation. The goal of the H_2Mare flagship project in Germany is to create large-scale offshore hydrogen hubs that incorporate power-to-X and seawater desalination technologies by directly integrating offshore wind turbines with electrolysers [14]. In the UK, ERM is leading the Dolphyn Project, which is funded by the UK Government's Hydrogen Supply Competition. The project is testing floating offshore wind-to-hydrogen platforms that use PEM electrolysis and seawater desalination, with pipelines delivering the hydrogen to the coast [15, 16]. In order to facilitate industrial decarbonization and grid balancing, Denmark's Green Hydrogen Hub project combines onshore wind power with extensive electrolysis and subterranean hydrogen storage. In the meantime, Equinor's Hywind floating offshore wind farms in Norway and the UK are being assessed for their potential integration with hydrogen production systems to decarbonize ammonia manufacturing chains and sea transportation [17]. When taken as a whole, these projects show that wind-powered hydrogen is not only economically viable but also strategically compatible with national and regional decarbonization programs.

However, wind-to-hydrogen systems have a lot of obstacles to overcome. Wind speed variability lowers electrolyser use, necessitating hydrogen storage or larger capacity to provide a steady supply. Costs and technological complexity are increased by offshore integration, particularly when it comes to corrosion-resistant materials, desalination for electrolyser feedwater, and remote platform maintenance. Transmission and grid connection facilities continue to be major obstacles, with offshore wind-to-hydrogen projects necessitating large pipeline or cable investments. Furthermore, to guarantee sustainable deployment, a thorough evaluation of the life-cycle environmental implications is required, especially concerning marine ecosystems and seabed infrastructure [18].

Table 4. Selected wind-to-hydrogen demonstration projects
Sources: *[19]*

Project	Location	Capacity (MW)	Technology	Status
H2Mare	Germany	100+	Offshore PEM	R&D phase
Dolphyn Project	UK	Floating offshore wind + PEM	Pilot stage	
Hywind Tampen	Norway	88 MW	Offshore wind powering oil platforms, with hydrogen studies	Operational

Comparative Assessment: Solar vs. Wind Electrolysis
The comparative performance of solar- and wind-powered electrolysis has drawn more attention due to the growing demand for low-carbon hydrogen worldwide. Both methods offer carbon-free ways to produce hydrogen, but they differ greatly in terms of efficiency, costs, and implementation viability depending on infrastructure, resource availability, and geographic location [20]. Therefore, comparative analysis is essential for determining the best deployment plans, influencing policy, and directing investment choices. Wind electrolysis benefits from high capacity factors and the scalability of contemporary wind turbines, particularly offshore, whereas solar electrolysis takes advantage of fast-declining photovoltaic (PV) costs and ample irradiance in many places [21]. The relative benefits and drawbacks of the two strategies are critically examined in this part, along with their effects on the environment, system reliability, scalability, cost-effectiveness, and efficiency.

Energy Efficiency
Both electrolyzer performance and primary energy conversion efficiency affect energy efficiency in renewable electrolysis. For commercial crystalline silicon modules, solar PV systems usually attain conversion efficiencies of 18–22%; record tandem perovskite–silicon devices surpass 30% [22]. When combined with alkaline electrolyzers or proton exchange membranes (PEM) that operate at 62–82% efficiency, the overall solar-to-hydrogen (STH) efficiency is between 10 and 15% in real-world scenarios. Wind turbines, on the other hand, have capacity factors of 30–45% onshore and greater than 50% offshore, converting kinetic energy into electrical power [23]. Improved electrolyser utilisation results from wind's stronger and more steady energy yield, which in turn produces hydrogen more reliably. Overall power-to-hydrogen conversion efficiency for integrated wind-electrolysis systems ranges from 12 to 18%. Therefore, wind typically offers superior year-round energy yield and electrolyzer working stability, even though PV can give higher peak efficiencies under perfect conditions [24].

Cost-Effectiveness (LCOH)
One of the key determinants of technology competitiveness is the Levelized Cost of Hydrogen (LCOH). The price of PV modules, which have decreased by more than 80% since 2010, has a significant impact on solar hydrogen costs [25]. By 2030, LCOH values are expected to reach USD 1.5–2.0/kg in areas with high solar irradiation (≥2000 kWh/m^2/year) [26]. Intermittency, however, raises the cost contribution from capital-intensive equipment by decreasing electrolyser capacity factors [27]. Higher capacity factors and longer yearly operation hours are advantages of wind-powered electrolysis that lower the electrolyser's cost burden. In areas with abundant wind resources, offshore wind projects can generate hydrogen at competitive prices despite their high capital requirements. By 2030, LCOH values are expected to be between USD 2.0 and USD 2.5/kg, and by 2035, offshore wind-to-hydrogen could be comparable with blue hydrogen produced from natural gas [28].

Scalability and Geographic Suitability
When deciding which technology is better suited, geography is crucial. Desert regions with abundant sun irradiation and relatively high land availability, like North Africa, the Middle East, and Australia, are ideal for solar electrolysis [29]. On the other hand, wind-powered electrolysis is most competitive in coastal wind-rich areas of East Asia, North America, and Europe, where offshore wind deployment is also supported by robust legislative frameworks [30]. In terms of scalability, solar projects need bigger land footprints to produce equivalent amounts of hydrogen, whereas wind projects, particularly offshore, offer higher per-project capacity (hundreds of MW to GW scale) with less land-use conflict [31]. In areas where solar and wind are complementary, hybrid projects that combine the two are increasingly seen as the most scalable option.

Environmental Impacts
Environmental factors for wind and solar electrolysis are different. According to [32], solar projects necessitate large land tracts, which frequently raises issues about ecological disruption, agricultural displacement, and water demand in arid places. Additionally, the production of PV modules uses a lot of energy and materials, including vital minerals like silicon, silver, and indium [33]. Although wind projects especially those located offshore avoid land competition, they present environmental problems concerning seabed disturbance, bird and bat mortality, and marine ecosystems. Desalinating seawater for electrolysis is another requirement for offshore hydrogen projects, which raises questions about brine disposal and environmental effects [34]. Although site-specific effects vary significantly, life-cycle assessments often indicate that both solar and wind hydrogen systems deliver a >70% reduction in greenhouse gas emissions when compared to fossil-derived hydrogen [35].

Reliability and Intermittency Management
Controlling intermittency is essential to the hydrogen supply. While wind production is unpredictable, but frequently complements solar diurnal patterns, solar electrolysis experiences predictable but severe daily cycles with nearly zero output at night. By balancing intermittencies, hybrid solar-wind systems can reach higher capacity factors (up to 70% in some countries) [36]. Flexible PEM electrolysers and storage technologies (such as compressed hydrogen, subterranean salt caverns, or batteries for electrical buffering) are essential for controlling fluctuations. Although it presents issues with additionality and carbon accounting, grid integration also provides a mechanism to stabilise supply [36].

Comparative Case Studies and Techno-Economic Analysis
Regional trade-offs are demonstrated by a number of comparative projects. Although they confront land and water issues, solar-rich hydrogen projects in Australia, such as the Asian Renewable Energy Hub, are intended to take advantage of the abundant desert solar resources [37]. Offshore wind-electrolysis initiatives in Northern Europe, including the UK's Dolphyn project and Germany's H_2Mare, place a strong emphasis on scalability, integration with current gas

infrastructure, and accessibility to industrial demand centres [38]. According to techno-economic assessments, offshore wind electrolysis will be more competitive in industrialised coastal regions, whereas solar electrolysis may dominate exports in solar-rich developing countries [39].

Hybrid Systems: Solar-Wind Electrolysis Integration

Although solar and wind energy separately offer promising avenues for electrolysis powering, both resources are intrinsically sporadic. Wind energy output fluctuates with seasonal and diurnal wind patterns, while solar irradiance is limited to daytime hours and is weather-dependent. A complementary production profile that lowers overall intermittency and raises the capacity factor of coupled electrolysers is produced by hybridising solar and wind inputs. Research indicates that when compared to single-source systems, hybrid solar–wind systems can attain greater utilization rates, with electrolyzers running more consistently and effectively [14]. Hybridization lowers system costs by reducing the demand for large storage capacity by smoothing out renewable energy.

The increased interest in hybrid renewable-to-hydrogen systems is demonstrated by a number of large-scale demonstration projects. The Asian Renewable Energy Hub (AREH) in Australia combines electrolyzers for the manufacture of hydrogen and ammonia for export markets with solar and wind power, surpassing 26 GW [15]. In order to supply European markets, hybrid solar-wind hydrogen projects are being constructed in Morocco to take advantage of the nation's abundant solar insolation and Atlantic wind resources [16]. Hybridised renewable hydrogen hubs, which are frequently connected to ammonia plants and industrial clusters, are also being investigated in pilot projects in China and India [1]. The techno-economic benefits of integrating variable resources to guarantee electrolyser operation around-the-clock are empirically demonstrated by these projects. Compared to single-resource models, hybrid solar–wind hydrogen systems have several advantages.

They first reduce the Levelized Cost of Hydrogen (LCOH) by raising electrolyzer load factors. By decreasing generation gaps, improving grid integration, and lowering the curtailment of excess renewable power, they also contribute to system stability. Third, because shared transmission lines, substations, and electrolyser facilities lower capital expenditures, hybrid systems maximise the use of land and infrastructure [2].

Additionally, the combination makes it possible for hydrogen production to be flexible, allowing projects to adapt to changing export schedules or patterns of demand. Hybrid systems have operational and technical difficulties despite their potential. Advanced energy management systems, such as digital optimisation tools, predictive forecasts, and smart inverters, are necessary to coordinate variable renewable outputs. Although more flexible than alkaline systems, proton exchange membrane (PEM) electrolysers nevertheless experience efficiency losses during frequent ramping, making it difficult to match variable input power with electrolyser dynamics [3]. Water availability for electrolysis in arid areas, transmission integration, and the best location for co-located solar and wind farms are among the infrastructure concerns. Coupling with battery storage for short-term balancing, sector coupling with grid services, and employing hydrogen storage to absorb generation peaks are some of the hybridisation options being studied [4].

In the end, one of the most promising setups for attaining high utilization, steady operation, and economically viable green hydrogen at scale is hybrid solar–wind electrolysis. Realising its potential would require supportive policy frameworks and ongoing innovation in systems integration.

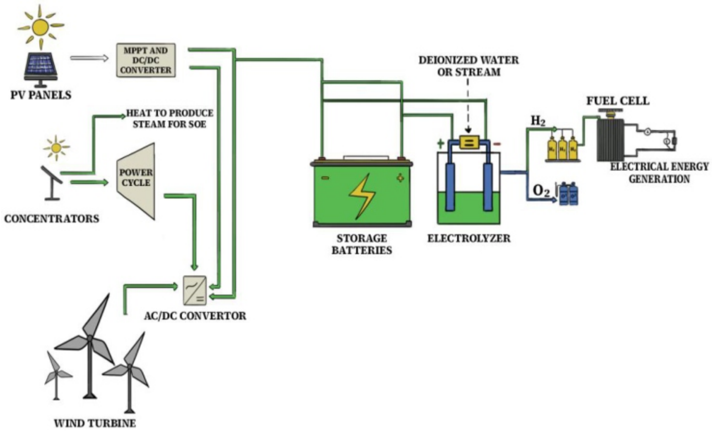

Figure 2. Concepts of solar and wind-powered hydrogen production systems
Sources: *[5]*

Policy, Economic, and Market Perspectives

Green hydrogen market development is heavily influenced by policy frameworks. Many nations have included hydrogen in their long-term decarbonization plans, encouraging investment and establishing capacity goals. Underpinned by the European Green Deal and Fit-for-55 package, the European Union's Hydrogen Strategy seeks to achieve 40 GW of electrolyser capacity within the EU and an additional 40 GW in bordering regions by 2030 [6]. Through its National Hydrogen Strategy, Germany has committed €9 billion to hydrogen projects, with a focus on imports from nations with abundant renewable energy sources [7].

With the help of provisions in the Inflation Reduction Act that provide tax credits of up to USD 3/kg for low-carbon hydrogen, the Department of Energy in the United States launched the Hydrogen Energy Earthshot initiative, which aims to bring the price of clean hydrogen down to USD 1 per kilogram within ten years [8]. Asian economies are also making rapid progress. For example, South Korea's Hydrogen Economy Roadmap calls for 15 GW of fuel cell capacity by 2040, and Japan's updated Basic Hydrogen Strategy calls for a 12 million ton annual supply of hydrogen by that time [9]. With an emphasis on integrating renewable energy sources and expanding domestic electrolyser production, China, the world's largest producer of electrolysers, has included hydrogen in its 14th Five-Year Plan [10].

Both the necessity for industrial decarbonization and climate legislation are driving the growth of the hydrogen marketplaces. By mid-2023, over 1,000 projects in 40 countries had been identified, and global state investments in hydrogen had surpassed USD 240 billion [11]. The Middle East, Australia, and Latin America; regions with a wealth of renewable energy sources are establishing themselves as exporters of hydrogen by using solar and wind power to generate inexpensive hydrogen and its byproducts, including ammonia [12]. With energy giants, utilities, and IT companies investing in gigawatt-scale projects, the private sector is becoming more involved. Growing trust in market scalability is evident in projects like Australia's export-focused hydrogen corridors, Saudi Arabia's NEOM project, and offshore wind-to-hydrogen projects in Northern Europe [13].

Fiscal incentives and subsidies are essential for closing the cost difference between fossil fuel-based and green hydrogen. The EU invests billions of euros in electrolyser scaling and hydrogen infrastructure through initiatives like the Innovation Fund and Important Projects of Common European Interest (IPCEI) [14]. Additionally, carbon pricing is becoming more significant. According to [15], the EU Emissions Trading System (ETS), which raised carbon costs above €90 per ton in 2023, makes green hydrogen more competitive when compared to hydrogen sourced from natural gas. Adoption of renewable hydrogen is being mandated. For instance, by 2030, 42% of industry must use renewable hydrogen, and 1% of transportation fuels must use it, according to the EU Renewable Energy Directive (RED II) [16]. In addition to generating demand, such actions also motivate private investment in cost-cutting and technology scaling. Despite quick advancements, there are still major obstacles to overcome.

Cost is the biggest obstacle: the Levelized Cost of Hydrogen (LCOH) from renewable electrolysis currently ranges between USD 4 and USD 6/kg, while the Levelized Cost of Hydrogen (LCOH) from natural gas-based hydrogen without carbon capture is USD 1-2 kg [17]. Closing this gap requires increasing system efficiency, decreasing the cost of renewable energy, and scaling up electrolyser output. Market expansion is also limited by infrastructure constraints. There aren't many dedicated hydrogen pipelines, storage caverns, or export terminals, and they cost a lot of money up front [18]. Another barrier is the availability of water, particularly in desert areas where solar hydrogen projects are being pursued. Additionally, cross-border commerce and long-term investment planning are hampered by legislative uncertainties, fragmented markets, and a lack of standardised certification requirements [19].

Table 5. Selected national hydrogen strategies
Sources: *[20]*

Country/Region	Target year	Capacity Goal (GW)	Policy Tool
EU	2030	40 GW	EU Hydrogen Strategy, carbon pricing
Germany	2030	10 GW	National Hydrogen Strategy
Japan	2030	3 Mt H_2	Subsidies, import hubs
USA	2030	Multi-GW	Hydrogen Shot Initiative

Future Directions and Research Gaps

Technological advancements, cost reductions, and systemic integration into the larger energy shift will be key factors in the future of green hydrogen production using solar and wind-powered electrolysis. Even though these renewable energy sources have shown encouraging promise, there are still important research gaps that need to be filled in order for green hydrogen to become commercially viable and scale globally [21]. The development of electrolyser technology is one of the main areas of attention. High capital costs, efficiency losses under variable renewable inputs, and short lifespans are problems with current systems, especially proton exchange membrane (PEM) and alkaline electrolyzers. By using high-temperature heat, solid oxide electrolysers (SOECs) provide increased efficiency; nevertheless, their commercial readiness is still limited [22]. It is generally agreed that achieving cost reductions below USD 200 per kilowatt, enhanced load flexibility, and longer operating lifetimes are crucial criteria for scaling up implementation [23]. Renewable hydrogen is unlikely to be able to compete on price with fossil fuel-based alternatives anytime soon without such innovations.

Another important area of research is materials innovation. Large-scale deployment is hampered by PEM electrolysers' need for pricey and limited platinum-group metals, especially ruthenium and iridium. For instance, without notable improvements in catalyst efficiency or substitution, the yearly worldwide supply of iridium is incredibly scarce and insufficient to enable gigawatt-scale electrolyser development [24]. The creation of abundant and highly effective transition metal oxides, carbides, and perovskite-based catalysts, as well as the creation of robust membranes and electrode assemblies that can withstand the varying load cycles imposed by hybrid solar–wind systems, are promising research avenues [25]. Resolving these material limitations will improve supply chains' sustainability while also reducing costs.

Along with technological advancements, electrolysis systems' integration with smart grids and digital optimisation tools is becoming more widely acknowledged as a critical enabler for deployment in the future. Due to the inherent intermittency of renewable-powered electrolysis, digital solutions like artificial intelligence (AI), machine learning, and digital twins are useful for real-time performance optimisation.

By using these technologies, electrolyzers can decrease efficiency losses, increase component lives, and dynamically adapt to changing inputs. Additionally, by acting as variable loads through smart grid integration, electrolysers can provide grid-balancing services and absorb excess electricity during times of oversupply. The business case for green hydrogen is strengthened by this dual role, which also improves integration of renewable energy sources [26].

In the future, the construction of extensive green hydrogen hubs presents a calculated route to lower costs and expand the worldwide market. Hydrogen hubs can eliminate infrastructure duplication and provide economies of scale by combining downstream industries, electrolysers, storage, and renewable resources. This growing strategy is shown by landmark projects like the Asian Renewable Energy Hub in Australia and the NEOM Green Hydrogen Project in Saudi Arabia, which seek to manufacture hydrogen or derivatives like ammonia for export markets at competitive costs [27]. To improve hub design, evaluate cross-sectoral integration with industry and transportation, and analyse socio-environmental effects, such as land use and water consumption in resource-constrained places, more research is necessary [28].

Table 6. Research gaps and potential solutions

Research gaps	Potential Solutions
High electrolyzer cost	Scale-up manufacturing; <$200/kW target [29]
Scarce catalysts (Ir, Pt)	Non-precious metal catalysts, perovskites [30]
Durability under variable loads	Advanced membranes, dynamic control [31]
Renewable intermittency	Hybrid solar–wind; AI optimization [32]

Conclusion

The potential of solar and wind-powered electrolysis for the production of green hydrogen has been contrasted in this paper, with an emphasis on the advantages, disadvantages, and prospective areas for further study of each method. Both solar and wind-powered electrolysis have great promise to advance green hydrogen, but system integration and resource availability will determine if they are suitable. Despite intermittency and land-use issues, solar systems are aided by advanced photovoltaic technology and declining costs. Although they require expensive infrastructure and grid integration, wind systems, especially offshore ones, offer better and more reliable capacity factors.

Large-scale hydrogen hubs could reduce prices through economies of scale, while hybrid solar-wind systems increase usage and dependability. All things considered, growing green hydrogen and establishing it as a pillar of the worldwide net-zero transition will require innovation in electrolysers, material substitution, and digital optimisation.

Table 7. Summary of key findings

Dimensions	Summary of Key Findings
Energy Efficiency	Solar-powered electrolysis achieves PV-to-hydrogen efficiencies of ~15–20%, but performance is constrained by diurnal variability. Wind-powered systems provide steadier capacity factors, though efficiency depends on wind fluctuations and turbine reliability [33, 36].
Cost-Effectiveness (LCOH)	Declining PV module costs make solar-driven hydrogen competitive in high-irradiance regions. Wind-based systems have higher upfront costs, especially offshore, but scaling and integration with offshore platforms could reduce costs significantly [34, 35].
Scalability and Geographic Suitability	Solar electrolysis is best suited for arid and high-irradiance regions (e.g., MENA, Australia), while wind-based hydrogen is favorable in coastal and offshore regions (e.g., North Sea, U.S. East Coast). Regional resource availability strongly shapes deployment [36].
Environmental Impacts	Solar requires large land areas, raising concerns over land competition and biodiversity impacts. Wind has lower land footprint but offshore development raises concerns about marine ecosystems and visual impacts [37].
Reliability and Intermittency	Both technologies face variability: solar suffers from daily and seasonal cycles, while wind varies with weather conditions. Hybrid solar–wind systems improve stability and hydrogen output consistency [38].
Demonstrations and Projects	Solar electrolysis pilots are growing in Australia and Spain, while large-scale wind-to-hydrogen projects such as H2Mare (Germany), Dolphyn (UK), and Hywind Tampen (Norway) are testing offshore integration [39].

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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