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Review

Innovative Strategies for Combining Solar and Wind Energy with Green Hydrogen Systems

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Abstract: The integration of wind and solar energy with green hydrogen technologies represents an innovative approach toward achieving sustainable energy solutions. This review examines state-of-the-art strategies for synthesizing renewable energy sources, aimed at improving the efficiency of hydrogen (H_2) generation, storage, and utilization. The complementary characteristics of solar and wind energy, where solar power typically peaks during daylight hours while wind energy becomes more accessible at night or during overcast conditions, facilitate more reliable and stable hydrogen production. Quantitatively, hybrid systems can realize a reduction in the levelized cost of hydrogen (LCOH) ranging from EUR 3.5 to EUR 8.9 per kilogram, thereby maximizing the use of renewable resources but also minimizing the overall H_2 production and infrastructure costs. Furthermore, advancements such as enhanced electrolysis technologies, with overall efficiencies rising from 6% in 2008 to over 20% in the near future, illustrate significant progress in this domain. The review also addresses operational challenges, including intermittency and scalability, and introduces system topologies that enhance both efficiency and performance. However, it is essential to consider these challenges carefully, because they can significantly impact the overall effectiveness of hydrogen production systems. By providing a comprehensive assessment of these hybrid systems (which are gaining traction), this study highlights their potential to address the increasing global energy demands. However, it also aims to support the transition toward a carbon-neutral future. This potential is significant, because it aligns with both environmental goals and energy requirements. Although challenges remain, the promise of these systems is evident.

Keywords: proton exchange membrane; solid oxide electrolysis; green hydrogen production; renewable energy; water electrolysis; alkaline electrolysis

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1. Introduction

The pressing need to prevent climate change and decrease dependency on fossil fuels is causing major shifts in the global energy environment. As affordable and sustainable substitutes for traditional energy, renewable energy sources, especially wind and solar, have emerged as key players in this shift. Large-scale integration of wind and solar energy into the energy system is significantly hindered by their intermittent nature, notwithstanding their enormous potential [1]. The idea of combining renewable energy with green hydrogen generation has drawn a lot of interest as a solution to this problem. Green hydrogen (H_2), generated through electrolysis with renewable energy, acts as a flexible energy carrier and storage medium, allowing for the dissociation of the generation and utilization of energy, as well as the storage of excess clean energy to be utilized during periods of minimal generation [2,3]. Current technological breakthroughs and increased investment in renewable energy systems have prompted the development of several solutions for integrating solar and wind energy with green H_2 systems. These techniques seek to improve the efficiency, dependability, and economic feasibility of renewable energy sources while also contributing to the larger aims of carbon reduction and energy security [4]. The combination of solar and wind energy with the generation of hydrogen not only addresses the variable nature of renewable energy sources but also has the potential to create hybrid energy systems that may function constantly and flexibly regardless of varying energy demands and supply conditions [5].

Faran Razi and Ibrahim Dincer [6] objectively examined several solar H_2 production processes in their research, with an emphasis on electrical, photonic, thermal, and hybrid energy choices. The paper went into detail about these methodologies, recent advancements, and key technology, as well as plant layouts that influence H_2 production prices. Environmental effect, cost, exergy and energy efficiency, and sustainability indices are all used to conduct a comparative study. The study discovers that high-temperature energy technologies that provide higher efficiency and yields while being less ecologically friendly, whereas biochemical and photonic routes are more sustainable but less effective. Mohammad et al. [7] evaluated the current state and recent advances in photovoltaic (PV)-powered green H_2 production, emphasizing the potential to considerably cut greenhouse gas emissions. The study explored the efficiency of electrolysis powered through different PV systems, with a special emphasis on solar-to-hydrogen (STH) conversion efficiency. The findings discovered a number of barriers, including safety concerns, production and storage challenges, commercial challenges, and concerns with weather fluctuation and PV cell cooling. Despite these obstacles, the study emphasizes PV-powered H_2 systems' potential as a viable substitute for traditional fuels. Abdulrahman et al. [8] proposed an intelligent multi-objective optimization strategy for H_2 energy storage systems (HESSs) in solar- or wind-powered reverse osmosis systems. The study evaluated three green H_2 storage methods: gas hydrogen storage (GH_2), liquid hydrogen storage (LH_2), and material-based hydrogen storage (MH_2). GH_2 had the highest overall life cycle cost (568,164.60 USD/year), whereas LH_2 had the greatest inherent risk due to explosion dangers. MH_2 outperformed GH_2 and LH_2 in terms of cost (18.92%) and safety (42.86%), although temperature control during H_2 emission posed issues. The findings offer an equitable strategy for constructing sustainable HESSs that takes into account both economic and safety factors. Marcel et al. [9] investigated the optimization of green H_2 synthesis from solar and wind energy to give high-temperature heat to Europe's hard-to-abate production industries. They used geospatial analysis to improve the sizing of plant components such as PV and wind capacity, electrolyzers, and hybrid storage that combines compressed H_2 and lithium-ion batteries. The study indicated that the levelized cost of H_2 (LCOH) varied between 3.5 and 8.9 EUR/kg, with wind-rich regions having the lowest costs. Optimal H_2 storage might satisfy industrial demand for two to three days. Furthermore, a consistent demand profile lowered costs by about 11%, and the majority of scenarios fulfilled EU emission targets.

Mohammad Zoghi et al. [10] conducted an analysis of the energy, exergy, and exergy-economic (3E) performance of various systems aimed at green hydrogen production, namely wind, solar pond, and ocean thermal energy conversion (OTEC) systems. They employed a trilateral cycle (TLC) to enhance heat matching, combined with a thermoelectric generator (TEG) for efficient waste heat recovery. The findings indicated that wind systems yield the highest exergy efficiency ranging between 5.8% and 10.47% at wind speeds of 8 to 12 m/s while simultaneously maintaining the lowest cost rate at 66.08 USD/h. However, the salinity gradient solar pond (SGSP)-based system emerges as the most cost-effective option for hydrogen production, with costs fluctuating between 42.78 and 44.31 USD/GJ. This reveals significant economic implications for the future of sustainable energy. Although the performance metrics of wind systems are commendable, the overall economic advantage provided by the SGSP system cannot be overlooked.

Qusay et al. [11] conducted a comprehensive analysis of renewable energy capabilities across 27 EU nations and the UK specifically examining solar, wind, hydro, and green hydrogen. The research identified Austria, Belgium, and Germany as frontrunners in renewable energy production; however, Germany stands out as the foremost producer. Green hydrogen, particularly in Germany and France, serves a crucial function as an alternative fuel. Regions such as Northern Sweden and Germany are recognized as potential hubs for green electricity (this is significant, because it highlights emerging markets). The study underscores the necessity of balancing supply and demand while emphasizing the EU and UK's notable progress and commitment to sustainability objectives in the energy sector. Although challenges remain, the findings paint a promising picture for future energy strategies.

Temitayo et al. [12] investigated recent advancements in the generation of green hydrogen (GH) utilizing water electrolyzers powered by renewable energy sources. Their emphasis spans solar, wind, and hybrid systems. They conducted a comprehensive examination of various electrolyzer types, placing particular focus on proton exchange membrane (PEMWE) and alkaline water electrolyzers (AWEs). Notably, PEMWE can achieve an extraordinary hydrogen purity level of 99.9999% alongside superior current densities. Cost analyses indicate that the levelized cost of hydrogen (LCOH) derived from wind energy for PEMWE fluctuates between USD 5.3 and USD 9.29 per kilogram; in contrast, AWE ranges from USD 7.49 to USD 7.59 per kilogram. Moreover, solid oxide electrolyzers (SOEs) exhibit costs varying from USD 6 to USD 9.34 per kilogram, with the possibility of a significant reduction to USD 1.9 per kilogram by 2050. This analysis underscores that wind speed significantly influences the production costs of GH. However, the interaction of various factors complicates the overall scenario, because it creates a multifaceted landscape that requires careful consideration.

Shibna et al. [13] explored the synergy between solar photovoltaic (PV) and wind systems in order to provide energy for a green building located at Rajasthan Technical University in Kota, India. By employing the iHOGA algorithm, the researchers optimized a hybrid system that yields 6988 kWh/year of energy, which effectively meets the building's demand of 6759 kWh (with minimal surplus). The system, however, reduces energy loss to 276 kWh/year and mitigates an impressive 5273.14 kg of CO_2 emissions annually. Furthermore, the integration of these renewable sources significantly decreases other pollutants—most notably, 9601.512 kg of SO_2 and 32,424.32 kg of NOx each year—thus underscoring the environmental advantages of this approach. Although the results are promising, the study invites further investigation into optimizing such systems, because the potential for greater efficiency and sustainability remains.

Jabraeil et al. [14] introduced a system based on solar and wind energy for the production of liquid hydrogen and ammonia—two sustainable energy carriers—addressing urban demands for electricity, cooling, heating, and freshwater. The research evaluates three scenarios: the exclusive production of liquid hydrogen, ammonia and a dual production approach. An artificial neural network facilitates predictions, while a genetic algorithm optimizes the entire system. When utilizing 40% of net power in the electrolyzer, the system achieves energy and exergy performances of 56.78% and 44.69%, respectively, producing 13.2 MW of net power. This is coupled with substantial outputs of liquid hydrogen, ammonia, freshwater, and cooling load. Exergy analysis reveals high destruction rates in the Rankine cycle and electrolyzer. However, the optimal production rates and efficiencies are identified for the dual production scenario, which highlights the complexity of the system. Although the findings are promising, further research is necessary to enhance performance and sustainability.

This review paper shows a thorough evaluation of the novel approaches used to combine wind and solar energy with green H_2 systems. The article classifies and examines existing techniques, emphasizing their technological and economic benefits, as well as the problems they face. It also looks at the most recent technological advances that are being researched to address these difficulties and improve the efficiency of integrated renewable energy systems. This review is unique in that it takes a comprehensive approach to the integration of wind and solar energy with green H_2 systems, providing a full examination of both established and new techniques. Unlike prior evaluations, which frequently focus on either wind or solar energy integration with H_2 generation in isolation, this research conducts an unbiased study of various hybrid configurations and possible synergies. Additionally, the paper presents a novel paradigm for evaluating the sustainability and effectiveness of these integrated systems, taking into consideration the most recent advances in materials science, design of systems, and energy management systems. By presenting a roadmap for future research and development, this review intends to bridge the gap between theoretical study and practical application, eventually contributing to the growth of sustainable energy systems.

This paper is structured to provide a review of renewable energy integration, green hydrogen production, and novel hybrid systems. Section 2 investigates the current state of solar and wind technology, improvements in green hydrogen production, and the benefits and problems of hybrid systems. Section 3 discusses options for optimizing energy conversion, storage, and grid integration. Section 4 includes extensive case studies that examine hybrid systems in a variety of scenarios. Section 5 discusses the major findings, tackles obstacles, and proposes options for future research. The study concludes with a summary in Section 6.

2. Renewable Energy Integration

2.1. Overview of Renewable Energy

As the global energy demand surges and traditional resources become increasingly depleted, the imperative to advance clean energy solutions intensifies. This underscores the critical need to explore and develop alternative renewable energy sources that can effectively address the rising energy requirements [15]. Recent advancements in renewable energy technologies, such as solar, wind, and bioenergy, have opened up new possibilities for sustainable energy generation. These innovations hold the potential to transform the energy landscape by providing viable and eco-friendly alternatives to conventional fossil fuels [4,16]. This review aims to explore how these emerging technologies can be integrated into the current energy infrastructure to meet the growing global demand while minimizing the environmental impact. By harnessing the full potential of these renewable sources, we can work towards a more sustainable and resilient energy future. Figure 1 provides a visual representation of energy consumption trends both in the US and globally.

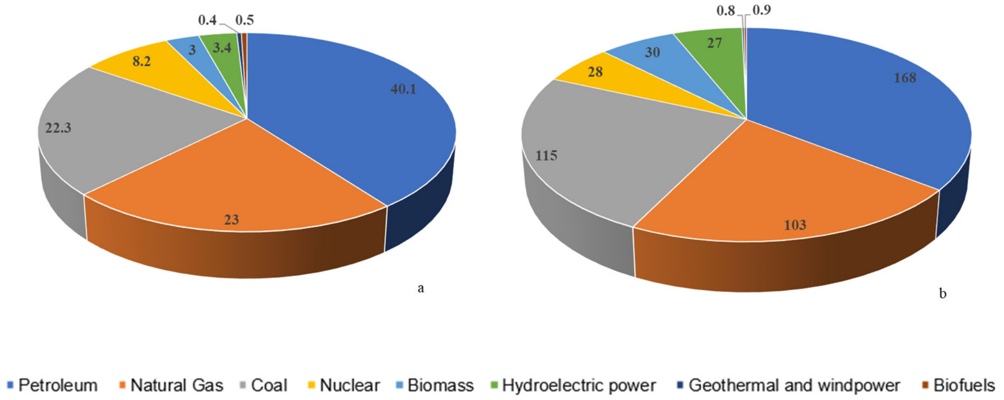

Figure 1. Fossil and solar energy consumption in the (**a**) US and (**b**) worldwide in BTU (quads = 10^{15} BTU) (USCB 2007).

2.2. Current State of Solar and Wind Energy Technologies

2.2.1. Significance of Solar and Wind in Advancing Sustainable Energy Transition

To reach the goal of a clean energy society and address the global climate challenges by 2050, as envisioned by the United States Department of Energy, it is essential to develop sustainable and efficient clean energy systems [17,18]. This path underscores the necessity for a fundamental shift, driven by the pursuit of sustainable and environmentally friendly alternatives to the traditional reliance on fossil fuels. Solar and wind energy are crucial in the transition to a sustainable energy system, offering significant environmental, economic, and technological benefits. These sources—mainly solar and wind—are harnessed from the Earth's ongoing natural processes. The sun's radiant energy and the continuous movement of wind provide inexhaustible power that can meet humanity's energy needs indefinitely. Technological advancements and research have further bolstered the adoption and integration of these renewable energy sources, making them increasingly efficient, cost-effective, and accessible [19]. According to a UN report, the prices for renewable energy technologies are declining swiftly. Between 2010 and 2020, the cost of electricity from solar power dropped by 85 %, while onshore and offshore wind energy costs decreased by 56 % and 48 %, respectively. These decreasing prices enhance the appeal of renewable energy across the board, particularly for low- and middle-income countries, where most of the new electricity demand is expected. With these cost reductions, there is a significant opportunity for a substantial portion of the new power supply in the coming years to be generated from low-carbon sources [20]. These renewable energy sources play a vital role in lowering greenhouse gas emissions and combating climate change, as they produce electricity without relying on fossil fuels. Among them, solar energy stands out for its immense potential to generate renewable power. Additionally, unlike other renewable sources like biomass, which can have some negative environmental impacts [21], solar energy production is known to have no harmful effects on the environment [22]. This lack of emissions also reduces air and water pollution, leading to cleaner environments and improved public health.

The integration of both solar and wind energy systems is gaining momentum as a strategy to balance the intermittent nature and geographical limitations of these renewable sources. This approach addresses the challenges of unpredictability and the technical constraints associated with each system, making them more reliable and viable on a larger scale. For example, the use of wind energy is limited at certain sites due to low wind speeds [23]. Hybrid solutions will therefore maximize their efficiencies and reliability [24].

2.2.2. The Evolution of Solar Energy Technologies

The advancement of solar technologies, especially in the generation of electricity, has been impressive. These developments have greatly improved efficiency, lowered costs, and expanded the range of applications for solar energy [25]. Initially, the first-generation silicon PV cells consisting of semiconductive materials like silicon, which was developed in the mid-20th century, laid the foundation for solar energy by converting sunlight directly into electricity with efficiencies around 15–20%. These cells, however, were costly and primarily used in specialized markets such as space exploration. Next was the development of thin-film solar cells in the late 20th century. This phase offered a less expensive alternative with greater versatility, though with slightly lower efficiencies of 10–15%. These thin-film technologies enabled new applications, such as building-integrated photovoltaics (BIPVs) and portable solar systems, by reducing material usage and production costs. However, research has shown that the most effective way to further reduce costs is to enhance the power conversion efficiencies of the PV cells, and that is where the third phase was critical. The third phase of PV cells were produced using advanced semiconductors, including nanocrystalline materials, polymers, dye-sensitized solar cells, and concentrated solar cells with efficiencies up to 40% [26]. Current state-of-the-art solar technologies for energy generation have advanced significantly, offering higher efficiency, cost-effectiveness, and versatility. Leading the innovation are perovskite solar cells, which have shown remarkable efficiency gains and potential for low-cost production, challenging traditional silicon-based photovoltaics. Their efficiencies exceed 25%, surpassing traditional silicon PV cells while being cheaper and easier to manufacture. Next in line was the arrival of Tandem cells. These cells blend perovskite with silicon or other materials, exceeding 30% efficiency by harnessing a broader spectrum of sunlight. Further advancements in solar technology include bifacial solar panels, which collect light from both sides, and concentrated solar power (CSP) systems, which use mirrors to concentrate sunlight onto a central receiver. CSP systems are being refined for large-scale energy production and offer the advantage of thermal energy storage for a consistent power supply. Furthermore, advancements in solar tracking systems and transparent solar cells are enhancing energy capture and opening up new possibilities for integrating solar power into buildings and everyday objects. These cutting-edge technologies, coupled with improvements in energy storage, are driving the solar industry towards greater efficiency and broader adoption, making solar energy a more viable and sustainable solution for global energy needs. These developments, alongside innovations such as building-integrated photovoltaics, transparent solar cells, and advanced energy storage solutions, highlight the significant strides made in solar technology [27]. This progress is crucial for the global transition to sustainable energy. As research and development continue, solar power is poised to become an even more integral component of the global energy landscape.

2.2.3. Wind Energy Technologies

As the demand of clean energy continues to grow, wind, a form of solar energy that is caused by the differential heating of the surface of the Earth by the sun, has a known capability of supplying several MW of energy. According to a report published by Statista in 2024, the global generation of wind energy for the past two decades has shown a percentage increment of 379% with an exponential growth rate of 0.12% (see Figure 2). Traditional wind energy generation has primarily depended on onshore wind turbines, which have become a common feature in areas with strong and steady winds. These turbines harness the kinetic energy of the wind, converting it into electrical energy as their blades rotate [28]. According to Greenpeace, wind power has the potential to meet global energy demands, providing up to 30% of the world's electricity by 2050, while also creating over 2 million new jobs and reducing CO_2 emissions by 113 billion tons by that time.

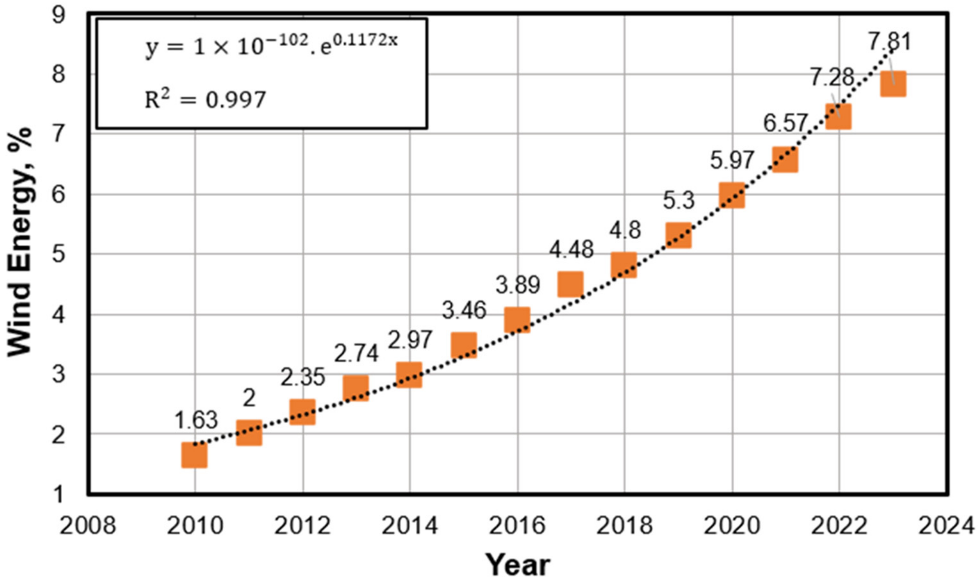

Figure 2. Wind energy global generation according to Statista.

With the growing demand for sustainable energy, wind generation technology has advanced significantly, leading to cutting-edge developments that have greatly expanded the potential of wind power [29]. One of the most notable advancements is the shift from onshore to offshore wind turbines, which marks a significant leap forward. Offshore turbines can harness stronger and more consistent winds over oceans and large bodies of water, allowing them to generate more electricity than their onshore counterparts due to the higher wind speeds found offshore [30]. Additionally, floating wind turbines, a ground-breaking innovation, allow for the installation of turbines in deep waters where fixed foundations are impractical, opening up vast new areas for wind energy generation [31]. Another emerging technology is the Vertical Axis Wind Turbine (VAWT), which features a design that rotates around a vertical axis. This allows VAWTs to capture wind from any direction, making them ideal for urban settings or areas with turbulent wind conditions [32,33]. These innovations and many more are propelling wind energy towards a more efficient and sustainable future (see Figure 3).

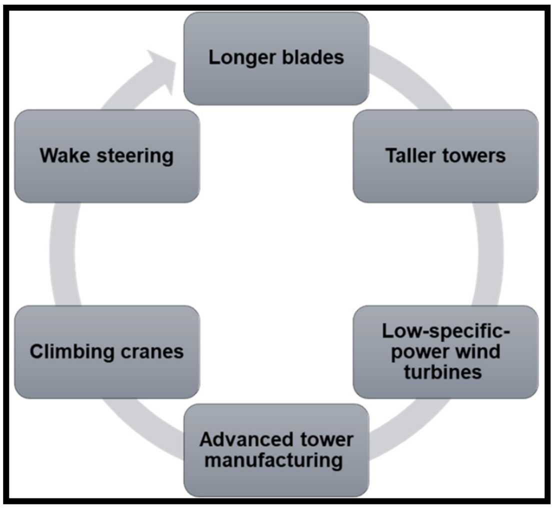

Figure 3. Wind energy technological innovations studied by NREL.

2.2.4. Integrating Solar and Wind Renewable Energy Systems

The integration of wind and solar energy technologies has become a focal point in the push for more reliable and sustainable energy generation. Traditionally, wind and solar energy have operated independently, each contributing to the renewable energy mix according to their unique strengths—wind turbines capturing kinetic energy from wind and photovoltaic panels converting sunlight into electricity. However, recent innovations have led to the creation of hybrid energy systems that integrate wind and solar technologies, offering a more stable and reliable energy supply. Figure 4 shows a typical component of a hybrid energy system consisting of solar and wind energies.

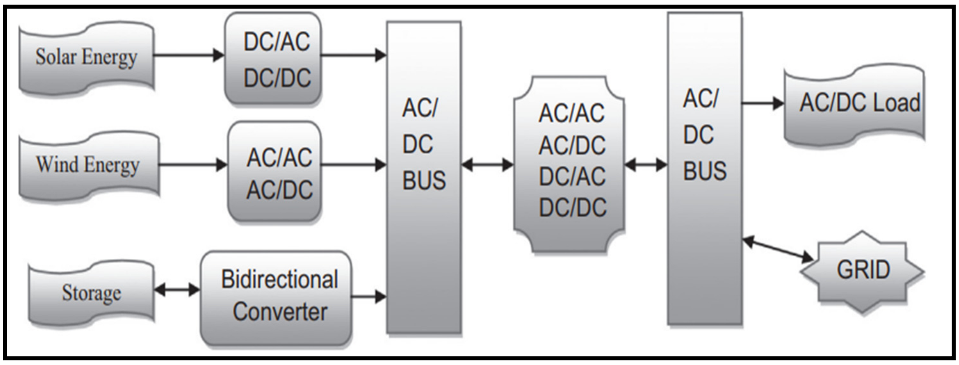

Figure 4. Fundamental components of a standard solar–wind hybrid energy system.

A combination of these renewable energy sources will ensure a steadier supply, minimizing the chances of power shortages during challenging weather conditions [34]. These systems leverage the complementary strengths of wind and solar energy, with solar power usually reaching its peak during the day, while wind power tends to be more reliable at night or in varying seasons [24]. Current technologies incorporate advanced energy storage solutions like lithium-ion batteries to store the surplus energy produced during peak times to be used when demand surges or when wind and solar resources are unavailable. Also, smart grid technologies further enhance these systems by using real-time data analytics to optimize the distribution and usage of generated power, ensuring a stable and efficient energy supply [35]. Floating solar panels, combined with offshore wind farms, represent another cutting-edge innovation, maximizing the use of available space and resources [36]. These integrated systems have charted the route for a resilient and adaptable infrastructure capable of meeting the growing global demand for clean energy. For example, Figure 5 highlights a schematic diagram of a basic power system that integrates various renewable energy sources.

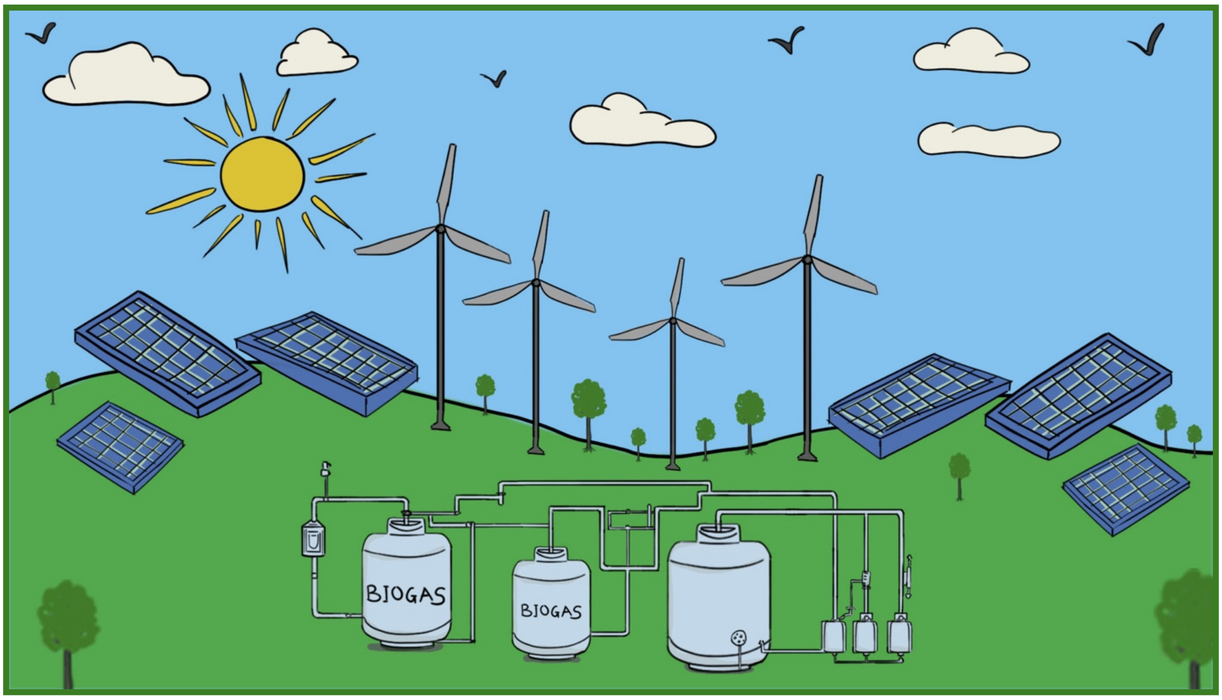

Figure 5. Current state-of-the-art hybrid renewable energy technologies. Highlighted are integrated solar and wind energy sources and a biogas unit.

3. Innovative Strategies

3.1. Optimized Energy Conversion and Storage

Solar and wind energy offer abundant and clean power sources, yet their variability leads to both excesses and shortages in energy generation. Green hydrogen systems provide a viable solution to these challenges by converting surplus renewable energy into hydrogen through electrolysis. This hydrogen can be stored and later used to supply power during periods of low renewable energy production. By integrating solar, wind, and hydrogen technologies, a more robust and reliable energy infrastructure can be achieved. This section examines innovative technologies for optimizing hydrogen conversion and advanced storage solutions based on the current literature.

3.1.1. Techniques for Efficient Energy Conversion

Maximizing energy conversion from solar and wind sources is essential for optimizing their output. Improvements in solar photovoltaic (PV) cells and wind turbines are critical to effectively capturing and converting energy. Key advancements include power-to-gas technology, advanced electrolytes, and high-efficiency PV technologies. Integrating these technologies with green hydrogen systems necessitates advanced control strategies to efficiently convert excess energy into hydrogen through electrolysis. A brief overview of these technologies is provided below.

Power-to-gas (P2G) technology provides a solution for large-scale, long-term electricity storage by connecting the power grid with the gas grid. This technology involves converting surplus electricity into hydrogen through water electrolysis, which is then transformed into methane (CH_4) or substitute natural gas (SNG) by reacting with carbon monoxide (CO) or carbon dioxide (CO_2) in a methanation reaction. The produced methane can be injected into the existing gas distribution network or stored for future use, effectively bridging renewable energy generation with conventional gas infrastructure (see Figure 6).

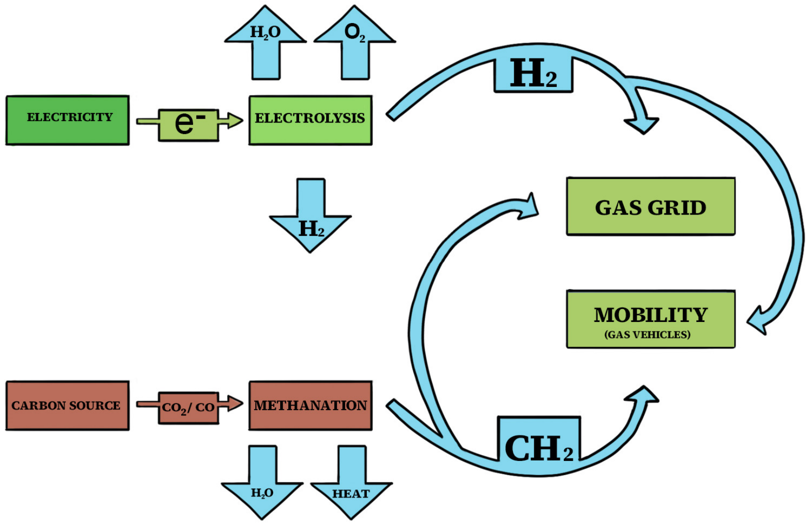

Figure 6. Power-to-gas (P2G) technology process.

Electrolyte systems for water electrolysis are pivotal in the efficient production of hydrogen and oxygen from water. The main types include proton exchange membrane (PEM), alkaline water electrolysis (AWE), and solid oxide electrolysis (SOE), each with distinct efficiencies, flexibilities, and lifespans, as outlined by Götz et al. [37], These systems are compared in Table 1, highlighting their operational characteristics.

Table 1. Operational characteristics of the electrolytes in Ref [37] with significant modifications.

Key Parameters	**Alkaline Electrolysis**	**PEM Electrolysis**	**Solid Oxide Electrolysis**
State of development	Commercial	Commercial	Commercial
Cell temperature in °C	40–90	20–100	800–1000
Electrolyte	Alkaline solution	Solid polymer membrane	ZrO_2 ceramic doped with Y_2O_3
Charge carrier	OH^-	$H3O^+/H^+$	O^{2-}
System power consumption (future) in kWh/m^3 (Hs)	4.3–5.7	4.1–4.8	Not Available
Cell voltage in V	1.8–2.4	1.8–2.2	0.91–1.3
H_2 production in m^3/h (STP, per system)	<760 ≈ 2.7 MW	Up to 450 ≈ 1.6 MW	Not Available
Cold start time	Minutes–hours	Seconds–minutes	Not Available

From the table, it is evident that PEM electrolysis has a lower system consumption but with a higher cost than alkaline water electrolysis. It is primarily due to PEM's higher efficiency and advanced design. PEM technology operates at lower temperatures, uses thinner proton-conductive membranes (20–300 μm), and allows for faster response times and higher current densities (above 2 A/cm^2), making the overall process more efficient. This leads to reduced power consumption compared to alkaline electrolysis.

However, the higher cost of PEM electrolysis arises from the use of expensive noble metals like platinum and palladium for the hydrogen evolution reaction and iridium oxide (IrO_2) or ruthenium oxide (RuO_2) for the oxygen evolution reaction at the electrodes. These materials, while effective, are much more costly than the materials used in alkaline electrolysis, which rely on less expensive catalysts. Additionally, the advanced components and compact design of PEM systems contribute to the overall cost, making PEM electrolysis more expensive than alkaline water electrolysis, despite its efficiency advantages [38].

In connecting to the grid, there is a need for fuel cells as a power generation technology. Fuel cells are devices that convert chemical energy directly into electrical energy through electrochemical reactions between fuels (typically hydrogen) and oxidizing agents (like oxygen). They consist of two electrodes—an anode and a cathode—separated by an electrolyte. Hydrogen is introduced at the anode, where it splits into protons and electrons, generating electricity as the electrons flow through an external circuit. The protons combine with oxygen at the cathode to produce water and heat. Fuel cells are used in various applications, including powering electric vehicles, providing backup power, and serving as stationary power sources. Different types, such as polymer electrolyte membrane fuel cells (PEMFCs) and molten carbonate fuel cells (MCFCs), can operate on various fuels, enhancing their flexibility and environmental benefits. A comparison between different fuel cells, which include alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), and phosphoric acid fuel cells (PAFCs) is addressed in Table 2. They are particularly appealing for renewable energy generation and cogeneration systems, where both electricity and thermal energy are produced to improve efficiency [39]. PEMFCs are among the most promising power generation technologies for achieving carbon neutrality. They are characterized by high power density, rapid start-up times, excellent efficiency, lower operating temperatures, and safe handling [40].

Table 2. Comparison of different fuel cell types in Ref [39] with significant modifications.

Fuel Cell Type	**PEMFC**	**AFC**	**DMFC**	**PAFC**	**MCFC**	**SOFC**
Operating temp (°C)	30–100	90–100	50–100	160–220	600–700	500–1000
Fuels	Hydrocarbons or methanol	Pure hydrogen	Methanol	Hydrogen from natural gas	Natural gas, biogras, others	Natural gas or propane, hydrocarbons or methanol
Electrolyte	Solid polymeric membrane	Aqueoussolutionof potassium hydroxide soaked in a matrix	Solid organic polymer poly-perfluorosulfonic acid	100% phosphoric acid stabilized in an alumina-based matrix	Li_2CO_3/K_2CO_3 materials stabilized in an alumina-based matrix	Solid, stabilized zirconia ceramic matrix with free oxide ions
Energy conversion efficiency (heat and power) (%)	85–90	85	85	85–90	85	Up to 90
Electrical efficiency (%)	30–40	60	20–25	40–42	43–47	50–60
Typical stack size	<1–100 kW	10–100 kW	up to 1.5 kW	50–1000 kW (250 kW module typical)	<1–1000 kW (250 kW module typical)	5–3000 kW
Operational life cycle	40,000–50,000 h (stationary) Up to 5000 h (mobile)	Up to 5000 h	10,000–20,000 h	Up to 40,000 h	Up to 15,000 h	Up to 40,000 h

Advancements in water electrolysis have further improved hydrogen production processes. Techniques such as sacrificial-agent-assisted water electrolysis utilize small molecules to replace the oxygen evolution reaction (OER), thereby degrading pollutants and enhancing efficiency. Organic upgrading-assisted electrolysis incorporates organic reactions to replace the OER, producing high-value chemicals along with hydrogen. Self-powered electrolysis systems combine water splitting with metal-based batteries or fuel cells, enabling hydrogen production without additional electricity input. Self-catalyzed electrolysis systems leverage spontaneous metal oxidation at the anode, facilitating hydrogen production at the cathode [41].

Photovoltaic (PV) technology advancements have significantly boosted solar energy utilization by improving the efficiency and adaptability of PV systems. These systems convert solar energy directly into electricity, while photothermal variants use reflectors to generate heat for steam turbines. Modern PV technologies incorporate high-performance panels and intelligent inverters that dynamically optimize the system performance. Research into Cu-doped ZnCdS-based photocatalysts has demonstrated that copper doping enhances the conversion of solar energy into thermal energy, thereby increasing the overall efficiency of hydrogen production through improved photocatalytic processes [42,43].

3.1.2. Advanced Storage Solutions for Hydrogen

Storage is a crucial factor of the green hydrogen ecosystem, facilitating the management of hydrogen produced during phases of high renewable energy generation. Advanced storage technologies are essential to ensure that hydrogen can be stored and retrieved safely and cost-effectively. Various hydrogen storage methods include compressed gas tanks, hydrogen tanks, cryogenic liquid, physical storage metal hydride storage, and underground storage [43]. This section provides an in-depth analysis of three of these storage solutions. A comparative analysis of these hydrogen storage techniques is provided in Table 3.

Table 3. Comparison of hydrogen storage methods in Ref [43] with significant modifications.

Storage Method	**Hydrogen Content (wt.% H_2)**	**Volumetric Density (g/L)**	**Volumetric Energy Density (MJ/L)**
Compression			
1 bar, RT	100	0.0814	0.01
350 bar, RT	100	24.5	2.94
700 bar, RT	100	41.4	4.97
700 bar, RT, (inlc. Type IV tank)	5.7	40.8	4.9
Liquid Hydrogen			
1 bar, −253 °C	100	70.8	8.5
1 bar, −253 °C (inlc. tank)	14	51	6.12
Metal Hydrides			
MgH_2	7.6	110	13.2
$FeTiH_2$	1.89	114	13.7

Compressed Hydrogen Storage: Compressed hydrogen storage is the most common method used for both stationary and mobile applications. This well-established technology enables rapid hydrogen filling and release without requiring additional energy for release. However, compressing hydrogen to high pressures consumes approximately 13–18% of its lower heating value, impacting the overall cost-effectiveness of the process. Increasing pressure results in only a marginal increase in the power requirements for compression. Typically, hydrogen is stored in cylindrical vessels, because spherical vessels are less practical for mobile applications. These vessels must be lightweight, durable, and capable of withstanding high pressures while resisting hydrogen diffusion and potential embrittlement. The four types of compressed hydrogen storage vessels—Type I, Type II, Type III, and Type IV—are detailed in [8]. Underground geological caverns also offer a long-term storage solution, though concerns about hydrogen purity due to potential contaminants in the caverns may arise.

Liquid Hydrogen Storage: Storing hydrogen in its liquid form (LH_2) provides a much higher density compared to gaseous storage, enhancing the volumetric energy density. At −253 °C, the density of liquid hydrogen is about 71 g/L, making it more energy-dense than compressed hydrogen. Liquid hydrogen storage is a well-established technology that allows for high rates of hydrogen release and low adiabatic expansion energy under cryogenic conditions. In its liquid state, hydrogen is non-corrosive, and storage generally involves stainless steel and aluminum alloy vessels with adequate insulation. However, the cost and energy demands for liquefaction are significant [43].

Solid-State Storage: Solid-state hydrogen storage involves hydrogen chemically reacting with metals or metal alloys to form metal hydrides. In this process, hydrogen molecules dissociate into atomic hydrogen on the metal surface, diffuse into the bulk material, and become chemisorbed within the metal or alloy structure. This interaction can cause the metal lattice to expand by approximately 20–30% of its initial volume. Metal hydrides are formed either through direct reactions between hydrogen and the metal or via the electrochemical dissociation of water molecules. The reaction mechanisms are as expressed in Equations (1) and (2):

$$\text{Direct Hydrogen Reaction} \qquad M + x/2H_2 \leftrightarrow MHx \tag{1}$$

$$\text{Electrochemical Dissociation of Water} \qquad M + x/2H_2O + x/2\,e^- \leftrightarrow MHx + x/2\,OH^- \tag{2}$$

where M is a metal or alloy.

The formation of metal hydrides releases heat due to chemisorption, while desorption—where hydrogen is released for use—requires an equivalent amount of energy to be supplied externally. This reversible reaction can be triggered by reducing pressure or increasing temperature. Understanding the thermodynamics of these reactions is crucial for optimizing metal hydride storage systems. Metal hydrides provide higher hydrogen storage capacity compared to compressed and liquefied hydrogen and operate at moderate temperatures and pressures, making them a safer alternative to the more extreme conditions required for gas compression and liquefaction. They can also undergo multiple cycles of hydrogen loading and release if impurities do not interfere. Generally, many metal hydrides require moderate energy inputs ranging from 20 to 55 kJ/mol H_2 for hydrogen release [43]. However, metal hydrides present challenges such as slower sorption and desorption kinetics, higher temperatures required for hydrogen release, and potential formation of undesirable gases during discharge. Table 4 lists various metal hydrides and their hydrogen storage capacities.

Table 4. Hydrogen storage characteristics of metal hydrides in Ref [43] with significant modifications.

Metal Hydride	**H_2 Capacity (wt.%)**	**Desorption Temperature (°C)**	**Desorption Enthalpy (kJ/mol H_2)**
MgH_2	7.6	>300	75
MgH_2–$LiBH_4$	11.4	>350	45
MgH_2–$LiAlH_4$ (1:1 M)	9.4	>250	45
$FeTiH_2$	1.89	>30	28
$LaNi_5H_6$	1.4	>100	31
Mg_2NiH_4	3.59	>280	65
MgH_2–$NaAlH_4$ (1:1 M)	7.6	>175	-
Mg_2FeH_6	5.5	>300	77.6

3.2. Grid Integration and Management

3.2.1. Strategies for Integrating Hybrid Systems into the Grid

Integrating hybrid systems that combine solar, wind, and green hydrogen into the existing energy grid involves careful planning and execution. The process requires the development of advanced grid management systems to handle the variability and intermittency of renewable energy sources, ensuring effective real-time monitoring and control to balance energy supply and demand. Fluctuations in renewable energy supply are best managed by leveraging the complementary nature of each source. Solar power peaks during daylight hours, while wind generation varies with different weather conditions. Hydrogen, as a green energy solution, can serve as a long-term storage mechanism, providing a consistent supply to the grid. By utilizing predictive modeling to forecast weather patterns, operators can anticipate fluctuations in solar and wind energy and adjust hydrogen production accordingly. This approach helps maintain a stable and reliable energy supply, optimizing the integration of renewable resources into the grid [24].

Advanced energy management software is crucial for optimizing hybrid system operations by coordinating various energy sources, managing storage, and adjusting production rates based on demand. Flexible grid architectures are essential for the seamless integration of renewable energy and hydrogen technologies, allowing the grid to adapt to changes in energy supply and demand, thus enhancing stability and reliability. Hybrid systems are designed to complement traditional energy sources, offering additional stability and reliability to the grid while managing the variability of renewables and optimizing hydrogen contributions. Addressing challenges in energy transmission and distribution is also vital to ensure the efficient incorporation of these hybrid systems into the existing grid infrastructure.

Research highlights the importance of electrolyzers and fuel cells in integrating hydrogen technologies into the grid, as they can adjust hydrogen production based on demand signals and operate during periods of low electricity prices or excess renewable output [44,45]. Studies have shown that hybrid energy storage systems using renewable energy sources and hydrogen can provide reliable power to remote areas and reduce costs by 20% [46]. Simulation studies have explored hybrid storage systems with fuel cells, electrolyzers, hydrogen tanks, and batteries and have shown that increasing hydrogen production flexibility can reduce costs and CO_2 emissions [47,48]. Various optimization techniques, including ensemble learning frameworks, have been investigated to improve the design of integrated renewable energy-powered hydrogen systems [49]. Economic analyses of grid-connected electrolysis technologies, such as proton exchange membrane electrolysis (PEMEC) and solid oxide electrolyzers, have revealed potential cost reductions with scaling and subsidies [50]. Additionally, electrolyzers contribute to the demand response and ancillary services like voltage regulation and frequency control, enhancing grid flexibility and potentially reducing hydrogen production costs [51].

3.2.2. Smart Grid Technologies and Management Practices

Two crucial components for advancing towards sustainable energy sources are smart grid technology and hydrogen energy systems (HESs). The shift to smart grids marks a major advancement from traditional electricity distribution systems, essential for optimizing green hydrogen production and utilization within a comprehensive energy framework. Smart grids enhance coordination and operational efficiency, addressing the challenges related to intermittent renewable energy sources and ensuring effective hydrogen production and distribution. Smart grids involve several key elements to facilitate green hydrogen production, including real-time data monitoring and analysis for tracking energy production and consumption; predictive analytics for anticipating energy needs and adjusting hydrogen production; and automated control systems for managing hydrogen production, storage, and integration with other energy resources. Advanced metering infrastructure (AMI) supports real-time energy consumption monitoring and control, while energy management systems (EMSs) optimize the operation of hybrid systems, ensuring efficient energy distribution and utilization. Incorporating artificial intelligence (AI) into these systems can transform green energy grid management by enhancing the monitoring, control, and communication capabilities.

Machine learning (ML) plays an increasingly important role in integrating HESs, optimizing energy management, and improving grid stability. ML, a subset of AI, allows systems to learn from data, recognize patterns, and make decisions autonomously, addressing the variability of renewable energy sources, demand fluctuations, and efficient energy distribution. ML models are particularly useful for energy forecasting by analyzing historical consumption data and weather patterns to predict future energy needs and for demand response initiatives, improving real-time grid operations and optimizing energy transfer within smart infrastructures [52]. Deep learning (DL) models further enhance energy prediction accuracy by analyzing a wide range of variables, including historical data and meteorological conditions. DL models are effective in predicting the energy supply, particularly for renewable sources like wind and solar, and in capturing temporal and spatial dependencies to refine supply forecasts [53]. Optimization algorithms, fundamental to AI, are critical for real-time decision-making, efficient resource allocation, and optimized energy flows within smart grids and HESs [54]. The substantial volume of data from weather reports, production logs, and consumption patterns requires advanced analytics. Blockchain technology has emerged as a key tool in the green hydrogen production ecosystem, offering significant benefits in terms of transparency, traceability, and efficient trading of green hydrogen.

Blockchain technology brings several advantages to green hydrogen production, particularly in enhancing traceability and transparency. By documenting each stage of hydrogen production on a decentralized ledger, blockchain ensures compliance with the standards related to renewable energy sourcing and carbon emissions. This level of transparency is crucial for both certification and verification processes. Moreover, blockchain facilitates direct peer-to-peer trading of green hydrogen via smart contracts, eliminating the need for middlemen and securing efficient transactions. It also aids in the seamless integration of renewable energy sources into hydrogen production by providing real-time monitoring of energy generation, usage, and storage, thereby optimizing resource utilization. Additionally, the combination of blockchain with advanced power management systems boosts the efficiency and sustainability of hydrogen production, storage, and consumption. This technology significantly enhances data access performance, further strengthening the overall effectiveness and sustainability of the green hydrogen ecosystem. Figure 7 summarizes the impact of blockchain on data access performance in hydrogen production [55].

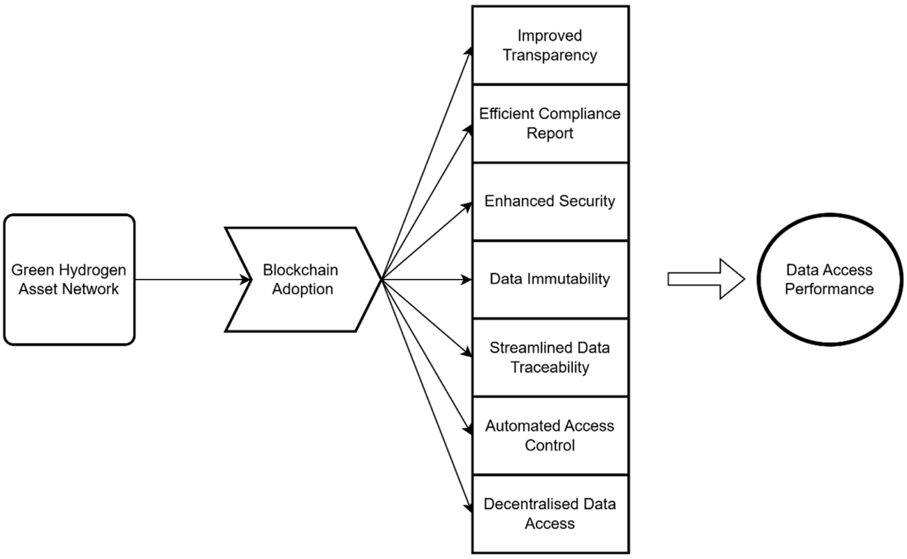

Figure 7. Influence of blockchain in hydrogen production in Ref [55] with significant modifications.

In summary, the paper presents several key innovations aimed at enhancing renewable energy integration and infrastructure reliability mentioned in the literature. These include the integration of solar, wind, and hydrogen technologies, where surplus power is used for hydrogen production and storage, addressing renewable energy intermittency. Advanced electrolysis techniques, such as sacrificial agent-assisted and organic upgrading-assisted methods, improve hydrogen production efficiency while enabling the coproduction of valuable chemicals. Hydrogen storage innovations, including compressed, liquid, and solid-state metal hydrides, offer safer and more cost-effective solutions. Additionally, smart grid integration through machine learning and deep learning enhances real-time energy management and grid stability. Lastly, blockchain technology is introduced to improve transparency and traceability within the hydrogen ecosystem, facilitating peer-to-peer transactions and efficient resource use.

4. Case Studies and Applications

Energy efficiency and carbon emissions can be improved by integrating wind and solar power with green H_2 systems, a technique that has drawn a lot of interest. Under three distinct scenarios: regional applications, urban vs. rural regions, and industrial applications, this section showcases the real-world deployment of such hybrid systems.

4.1. Case Study 1: Regional Implementation

The EU aims to attain carbon neutrality by 2050, as detailed in the 2020 European Green Agreement [56]. Expanding renewable energy sources is crucial for achieving this ambitious goal. The European Union's market is expected to experience an increase in energy demand for hydrogen and electricity [57]. Other sectors are electrifying, which is causing a significant increase in electricity demand. On the other hand, hydrogen is especially important in difficult-to-electrify regions. Hydrogen can be used or converted into methanol, methane, ammonia, or Fischer–Tropsch fuels for shipping and aviation, as well as feedstocks in the chemical sector and steelmaking. The integration of offshore wind farms with green H_2 generation is increasingly centered around the North Sea area, specifically in offshore Germany, the Netherlands, and the UK. This area is perfect for producing wind energy on a large scale due to its high wind speeds. Additional help for the combination of renewable energy and H_2 generation comes from the presence of coastal areas and pre-existing facilities. Hydrogen is produced by electrolyzers powered by excess electricity produced by wind farms in the Northern Germany region, especially in Schleswig-Holstein. Once delivered or stored, this hydrogen can be used for a variety of purposes, such as industrial activities and transportation [57].

Many believe that the European North Sea, with its relatively shallow waters, presents a suitable location for offshore wind energy and has the potential to become an energy hub in order to meet this growing need. Due to this, the governments of the nation's bordering the North Sea have pledged to build offshore wind farms in the region capable of producing at least 300 GW by 2050. For various reasons, including its seasonal synchronization with demand, its abundant supply in Europe, its affordability, its role in energy security and tactical autonomy, and the existence of a competitive EU wind sector, wind energy is crucial in this context. Offshore wind has the potential to be significant, particularly for green H_2 and its derivatives. By 2030, the North Sea's anticipated cost-effective wind capacity of 635 GW could supply a significant amount of Europe's electricity needs. With 200 million people living in high-demand areas and 20% of Europe's GDP, the prospect is not only enormous but also well located [58].

The slow growth of onshore wind energy due to societal acceptance challenges [59] highlights the relevance of offshore wind energy, which has minimal acceptance issues [60]. The projected technological onshore wind capacity in Europe is 13.4 TW [61], while the European wind industry expects to deploy 1 TW by 2050. To effectively exploit the North Sea's wind potential, floating wind turbines must be deployed. Floating wind turbines enable the utilization of wind resources in deep oceans with relatively high capacity factors, constituting the next frontier in the offshore wind sector [62]. Pilot projects in Spain and Scotland have demonstrated the practicality of floating wind. Even though industrial floating wind installations are rare in Europe, the business is rapidly growing, with many projects scheduled to be functional by 2030 [63]. In the United Kingdom, for instance, shallow water seabeds are already totally reserved for fixed-bottom turbines. As a result, floating wind appears to be the only viable alternative for exploiting the rest of the offshore seabed. As a result, the UK has launched auctions for seabed licenses designed specifically for floating wind projects.

Integrating North Sea wind energy into the onshore energy grid presents considerable hurdles due to the need for additional long-range transmission facilities. Transmission system operators (TSOs) have shown a desire to develop similar facilities in the North Sea. Offshore transmission lines typically connect wind farms to the shore by radial connections or connections from point to point [64]. Novel hybrid interconnectors link wind farms and permit inter-country transmission. The hybrid systems correspond with the mutual interests of North Sea nations and the European Commission. While not all North Sea nations embrace hybrid interconnectors, the European TSOs' Ten-Year Network Development Plan (TYNDP) 2024 has hybrid projects in consideration [65]. Another expansion of hybrid interconnectors would be the construction of a more meshed offshore grid with terminals connecting different countries. Figure 8 displays various offshore connection types.

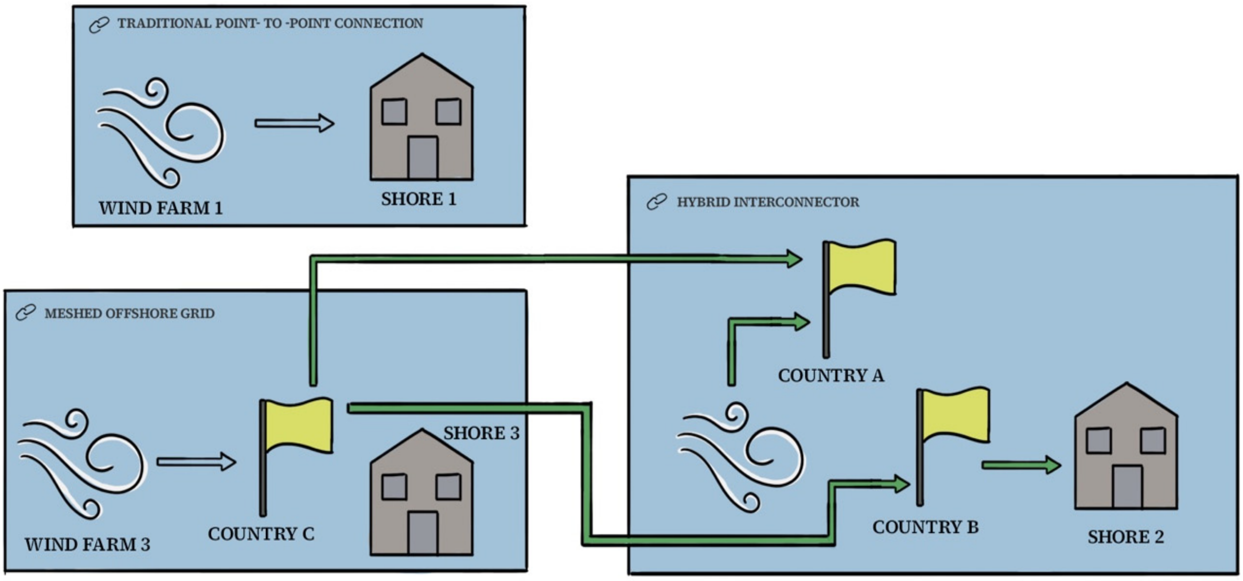

Figure 8. A schematic representation of the various types of offshore connections.

Concerns regarding legal and regulatory obstacles, such as the ambiguity of project responsibility, have been raised, despite the various advantages of hybrid projects. According to ENTSO-E, a consortium of European TSOs, an interconnected offshore grid can promote energy security, possibilities for trading, standards, and minimize the demand for total assets [66].

The North Sea Wind Power Hub is a prime instance of an offshore facility project. A coalition of TSOs and gas TSOs is driving the initiative, which seeks to build a significant offshore wind hub in the North Sea and link it to the onshore grid using high-voltage direct current (HVDC) cables. In addition to electric interconnectors, the hubs are expected to contain H_2 manufacturing facilities and pipelines linking to them onshore [57].

More closely examining offshore H_2 production, the H_2Mare project intends to compare the cost-effectiveness of offshore and onshore electrolysis. It investigates a variety of ideas, including manufacturing H_2 offshore and bringing it onshore via pipelines, sending power onshore for electrolysis, or producing and storing H_2 offshore in floating tanks for pickup by ships. The H_2Mare project is an innovative effort aimed at investigating the feasibility and promise of offshore green H_2 production that is fully independent of grid connections [67]. This significant project, led by a coalition of 33 top industrial and scientific partners and supervised by Siemens Energy, has the potential to transform our understanding of renewable energy and its applications, especially in the setting of offshore wind energy.

The H_2Mare project is focused on manufacturing green H_2 and other power-to-X (PtX) products directly at sea. Unlike traditional approaches that rely on transporting power produced by offshore wind turbines to the mainland grid, the H_2Mare project envisions a system in which the electricity produced is instantly used to manufacture H_2 by water electrolysis directly at the source [67]. This technique not only eliminates the need for substantial and costly grid infrastructure, but it also provides the possibility of establishing a self-sustaining, emissions-free energy production cycle in the offshore area [68]. The project's vision goes beyond simply creating H_2. It also intends to manufacture other PtX products, such as synthetic fuels and chemicals, which are required for a variety of industrial operations. This program is in line with worldwide efforts to decarbonize hard-to-abate sectors and transition to a sustainable energy market.

4.2. Case Study 2: Environmental Siting of Hydrogen Production Hubs

The combustion of hydrogen has proven to be a clean, versatile, and efficient energy carrier (see Equation (3)).

$$H_{2\,(g)} + ½\,O_{2\,(g)} = H_2O_{(Liquid)} + \text{Energy} \tag{3}$$

Hydrogen helps in energy generation through fuel cells, direct combustion, and various industrial applications, and hydrogen can produce electricity, provide high-temperature heat, and support a wide range of energy needs without the carbon emissions associated with fossil fuels (see Figure 9).

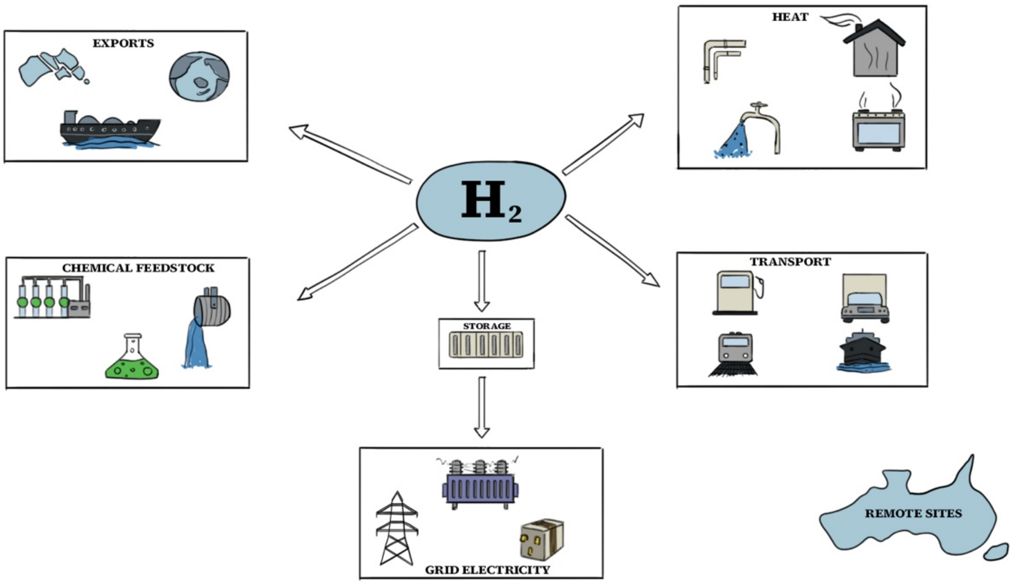

Figure 9. Uses of hydrogen (State of Hydrogen 2022 Report).

This makes hydrogen a crucial component in the transition to a sustainable and decarbonized energy system. At present, the world consumes around 65 million tons of hydrogen each year, with almost 95% of it produced through carbon-intensive methods. For example, the most common source of hydrogen is by reacting methane from natural gas with steam ($CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$). Although, a cheaper and well-established process, the release of CO_2 is still a challenge not contributing to the clean energy sustainable goals of 2050. There is therefore a global call for alternative ways for hydrogen production using renewable energy sources. Numerous research studies have explored the performance and cost of hydrogen production using green energy sources like solar and wind. Renewable energy sources such as solar and wind significantly reduce the environmental impact of hydrogen production by powering the electrolysis process, in which water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) using electricity. When this electricity is generated from renewable sources, the hydrogen production process becomes almost entirely carbon-free. However, there is a limited amount of research on the application of renewable energy sources specifically for hydrogen production. Currently, Chile and Argentina, with their world-class variable renewable energy (VRE) resources, have significant potential to become leading producers and exporters of renewable energy stored in hydrogen-rich chemicals.

Comparison of Hybrid Systems in Different Environments

The setup of hybrid renewable systems at varying environments requires utmost study to achieve potent results when deplored in certain environments. Ref [69] hinted that the location of hydrogen production is a key factor in determining the final cost, as it influences the capacity factor of a plant harnessing renewable energy. Furthermore, factors such as (a) geographical climatic factors, (b) infrastructure and logistics, (c) economic and technical challenges, (d) environmental and land use concerns, (e) technical integration, and many others are great determiners of cost. Herein, we reviewed several case studies that explored the use of solar and wind energy for hydrogen production in rural, urban environments, or in industrial regions. The initial evaluations indicate that Australia ranks among the countries with the greatest potential for green hydrogen production.

Currently, Australia has committed to decarbonizing its mineral processing, fertilizer production, and oil and gas industries and utilizing them domestically to produce hydrogen [70]. For example, the Gladstone Hydrogen Project located in Gladstone, Queensland, Australia (an industrial region), invested USD 3 billion in their Electrolyzer Manufacturing Plant, making it one of the biggest hydrogen plants in the world. Gladstone's location is advantageous for hydrogen production, thanks to its established industrial base, port facilities, and access to nearby renewable energy resources. However, one significant challenge in Gladstone is that the capital expenditure, along with operational and maintenance costs for solar and onshore wind energy production in that area, are twice as high compared to hydrogen production from sources like brown coal [71]. One major reason is that the city itself is an industrial region that lacks abundant solar and wind resources, which are more abundant in the rural and regional areas. Another challenge to sighting the location of hydrogen production hubs is the available of water. Hydrogen production requires a significant amount of water, sometimes exceeding the combined capacity of Australia's six major municipal desalination plants in Adelaide, Gold Coast, Melbourne, Perth, and Sydney, which together have an approximate capacity of 480 GL per year. Water scarcity remains a critical issue for farming and communities in regional Australia, with ongoing efforts to improve water risk assessment frameworks. Although Gladstone is not typically considered a water-scarce area, the substantial water demand for hydrogen production could present challenges, especially during droughts or periods of increased industrial activity. Effective water resource management and favorable climatic conditions are crucial for maintaining the sustainability of hydrogen production in the region [72].

One out of the seven hubs identified by the Council of Australian Governments is Pilbara in Western Australia. This pilot project will involve a phased development project aimed at large-scale hydrogen production in the remote region utilizing solar and wind energy [73]. However, producing hydrogen in Pilbara presents substantial challenges due to the region's isolation and arid conditions. The key challenges include the difficulty in transporting hydrogen to markets, as the area lacks the infrastructure necessary for large-scale production and distribution. Water scarcity is another significant issue in Pilbara [74]. Given Pilbara's limited freshwater resources, which complicates the electrolysis process and could make it costly if desalination is required, the high initial capital costs for establishing hydrogen production facilities, coupled with the expenses related to renewable energy, water procurement, and transportation, pose major economic viability concerns. The technical hurdles of integrating intermittent renewable energy sources like solar and wind into a consistent hydrogen production process, along with the challenges of maintaining operations in such a harsh and isolated environment, further complicate the project. Successfully addressing these obstacles will require substantial investment, innovative solutions, and collaboration among stakeholders.

5. Discussion

5.1. Renewable Energy Sources

Wind and solar energy are employed as renewable energy sources to generate electricity to power electrolysis for H_2 synthesis [75]. Solar energy has been used in applications such as photovoltaic systems (PVs), concentrated solar power (CSPs) systems, and wind energy to power electrolysis equipment. A converter (DC/DC or AC/DC) is required for establishing the power of renewable energy sources with electrolysis input. Rather than the high expense of power transmission, renewable energy sources are being used to provide electricity in remote places [76]. The excess energy generated by green energy sources has been utilized to power electrolysis for H_2 generation. The electrolysis is powered by PV panels, a solar charger, and a DC/DC converter via an electrical circuit known as a maximum power point tracker. In the event of low solar radiation, the battery is thought to serve as energy storage. The PV/H_2 system has several advantages over other renewable energy sources, including the utilization of DC voltage and verified parts that require minimal maintenance. The CSP/H_2 system uses heat instead of electricity to power the electrolysis system and convert water to steam via the SOE [77]. Thermal storage in the CSP/H_2 system enables continuous H_2 generation. Research was undertaken [78] to compare the efficiency of each system under identical operating conditions. The results revealed that the CSP/H_2 system performs better than the PV/H2. Furthermore, wind energy was employed to power the electrolysis (wind/H_2) unit by supplying electricity through an AC/DC converter. Wind energy is available 24 h a day, not just during the day, like solar energy; however, it is an uneven energy source owing to its nature.

5.1.1. Solar-Powered Hydrogen Production System

PV/H_2 technology is a green H_2 generation method powered by the solar system, which creates electricity to fuel the electrolysis unit. The PV/H_2 system is the most commonly employed technique for producing green H_2 due to its low cost, superior efficiency, and ease of implementation. This technology has been experimentally tested in several places and weather situations. Another research investigation found that utilizing a photovoltaic tracking system provided the best results but at a higher cost than a conventional PV system, while using a concentrated PV system increased efficiency when compared to a classical PV system. Another model-based investigation yielded similar results to an empirical investigation. A review of a photovoltaic system-based maximum power point tracking (MPPT) revealed that the performances were nearly identical to those of a PV system with or without MPPT, although the cost was somewhat higher when employing MPPT. Furthermore, it was established that the rate of H_2 production was proportional to MPPT efficiency [79].

Research has shown that combining the PV/H_2 system with PEM electrolysis has yielded promising results, with efficiency steadily improving over time. In 2008, just 6% performance was reported utilizing the PV/H_2 combination, with a high production cost of approximately 40 USD/kg [80]. Research aims to improve PV/H_2 efficiency, productivity, and cost-effectiveness. In reality, in 2010, the efficiency was increased to 12.4% by adopting direct connectivity between the photovoltaic system and the electrolytic unit. The production cost of H_2 has lowered from 40 USD/kg in 2008 to 3.4 USD/kg in 2022. The outcome is because of the operating voltage system, which is constantly accessible from the PV system to power the electrolysis. Several studies have found that PV/H_2 systems are better suited for remote places than electrolysis. Furthermore, because PV panels are more efficient than horizontal panels, they have an impact on H_2 production. The PV/H_2 system can generate both H_2 and power through a fuel cell, making it ideal for nighttime or wintertime use [81].

When there is little or no solar radiation to generate the electricity required for electrolysis, a fuel cell can be acquired to power an electrolysis machine. Utilizing grid/H_2 for H_2 generation is less expensive than utilizing grid/PV/H_2 or PV/H_2, according to a study of the costs of various green sources for electricity production. In actuality, the expenses for grid/H_2, grid/PV/H_2, and PV/H_2 are, respectively, 5.5, 6.1, and 12.5 USD/kg [82]. Because power transportation is relatively expensive, PV systems and wind energy are advantageous in rural places where the traditional grid is not deployed. The initial cost has been determined to be dependent on the cost of the land and the installation of the PV system. A high output of H_2 can be provided by increasing the efficiency of the PV/H_2

system, which is particularly appropriate in remote places due to the significant potential of solar energy in these areas. This has led to the introduction of bifacial solar panels, which first increase H_2 generation and subsequently improve efficiency [83]. As a result, H_2 generation increased to 4.2 g/h/m^2 from 3.7 g/h/m^2 in the case of monofacial solar panels, while the efficiency of bifacial solar panels reached 13.5% as opposed to 11.55%.

5.1.2. Wind-Powered Hydrogen Production System

Wind energy is not more efficient than solar energy owing to the wind's unpredictable nature. As a result, the amount of electricity generated by wind turbines varies over time. Excess electricity might be stored as H_2 gas utilizing wind energy in a W/H_2 system, as illustrated in Figure 10. During low wind speeds, the produced H_2 can be converted to energy using a fuel cell; during high wind speeds, a portion of the H_2 may be sold or stored, while the remainder is converted to electricity [84]. Thus, a wind turbine's efficiency can be enhanced by integrating it with an electrolytic unit and a fuel cell to create a sufficient green energy source [85].

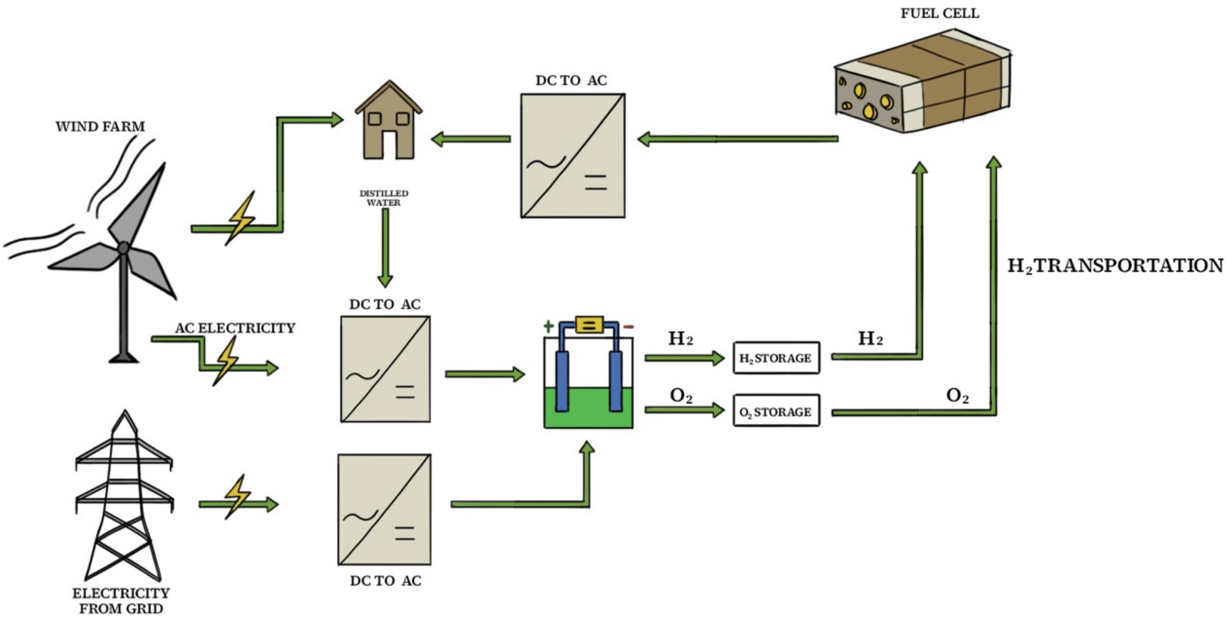

Figure 10. Wind/H2 system for hydrogen and electricity production.

There is theoretical and numerical research on the wind/H_2 system, in addition to the experimental investigations. In actuality, a model for electrolysis has been created utilizing four numerical models [86]. The suggested models have demonstrated good performance under the wind speed outcome conditions. Additional studies have looked into how to use a novel approach and control technique to enhance the wind/H_2 system's efficiency [87]. To reduce the cost of producing H_2 under the wind/H_2 system, many strategies and procedures have been developed. It has been noted that the expenses are influenced by both the original outlay and the locations of the wind and H_2 systems. A sample of some global locations and the associated costs of an electricity-based wind energy system and H_2 generation are provided in Table 5.

Table 5. Wind energy system based on hydrogen production and electricity costs.

Country	Electricity Cost (USD/Kwh)	H_2 Production Cost (USD/Kg)	References
Turkey	NA	3.10	[88]
Pakistan	NA	4.02	[89]
Algeria	NA	1.214	[90]
Iran	0.0325–0.0755	1.375–1.59	[91]
Iran	0.068–0.115	2.1008–3.5602	[92]
Morocco	NA	2.36–2.66	[93]
South Africa	NA	6.34–8.97	[94]
Afghanistan	0.063–0.079	2.118–2.261	[91]
Kuwait	NA	13.28–11.52	[95]

When H_2 is generated using renewable energy sources, it is stored and transferred. High-pressure tanks are used to properly store H_2 [56]. The most serious issue that can arise is the escape of compressed gas at high pressure, which could result in an explosion. On the other hand, the storage system is one of the most important elements influencing H_2 production costs. Various installation strategies for wind and H_2 systems have been studied to lower production costs [88]. The cost of producing H_2 and transporting it by pipeline is around 5.71 USD per kilogram. A study was carried out on the integration of H_2 and methane generation, which allows for an increase in the system's overall efficiency [89]. A low-cost H_2 manufacturing method was discovered employing a wind turbine in the location with the highest potential wind power in Southern Algeria [90]. The lowest price of roughly 1.214 USD/kg was found in Adrar City.

5.1.3. Hybrid Solar and Wind Energy System for Hydrogen Production

PV systems are most effective for producing electricity in rural locations where there is no grid. Furthermore, creating H_2-based wind and solar energy to power electrolysis units is extremely appealing, especially in the case of excess energy, which can be traded in, stored, or transformed into electricity through fuel cells [78]. To increase the effectiveness of the H_2 production system, it is necessary to integrate wind and solar power in order to create an efficient hybrid H_2 production system, which allows for lower H_2 costs and constant production, since two green energy sources are used [96]. Figure 11 depicts the PV-wind/H_2 system concept. The PV-wind/H_2 system outperforms the PV/H_2 and wind/H_2 systems due to its high potential for electricity. The PV/H_2 and wind/H_2 systems combine to generate the hybrid system [97]. Hybrid systems are more efficient than single systems like PV/H_2 or wind/H_2 [98]. The efficacy of the PV-wind/H_2 system is improving as the input electricity to the electrolysis unit rises, as does the temperature of the water within the electrolysis.

To improve the efficiency of the solar–wind/H_2 system, numerous more experiments have been carried out utilizing various methodologies. The results shown below serve as examples [4,99–101]:

- Refueling automobiles at H_2 stations, where a kilogram of H_2 may be produced at a price of 13.12 USD.
- Batteries increase the system performance and enable uninterrupted constant operation of the solar–wind/H_2 system.
- The hybrid system has a higher efficiency factor than the single system.
- Supplying homes with power with fuel cells that run on hybrid systems that produce H_2.
- Supplying cars with H_2 for as little as 9.28 USD/kg.
- At an efficiency of about 61%, the production of 239 kg/h has been attained.

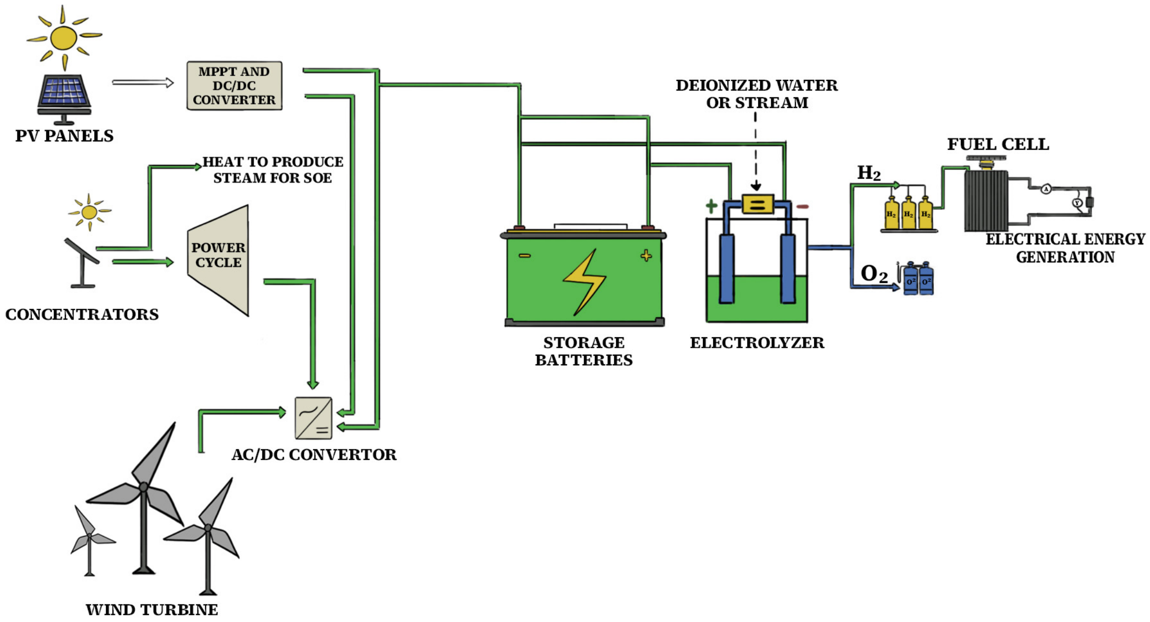

Figure 11. Concepts of solar and wind-powered hydrogen production systems.

Thus, the H_2-generating system's solar and wind energy can be used for desalination, electricity, cooling, and heating in addition to producing hydrogen. A summary of the features of a few hybrid solar–wind hydrogen systems is shown in Table 6.

Table 6. Technical specifications for solar, wind, and H_2 production systems.

Integrated Solar and Wind Systems for H_2 Production	Cost Analysis: H_2 Production (USD/kg) Vs. Electricity Generation (USD/kWh)	Performance Metrics and Specifications	References
Synergized Solar-Wind Hybrid for H_2 Production	The cost of generated electricity ranges from 0.06 to 0.55 $/kwh. H_2 production costs range from $3.73 to $4.65 per kg.	Utilized in the electrification process. Production of H_2 exceeds that of PV and wind. Used as a method for desalination. Utilized as a cooling mechanism utilized as a system of heating. Enhanced effectiveness.	[89,92,93,96,97]
Wind-Driven H_2 Production	H_2 production costs range from 5.27–8.01. The cost of electricity produced in USD/kg ranges from 0.08 to 0.55 USD/kwh.	An AC/DC converter is required to power the electrolysis. Extreme wind speed settings. Efficiency is about 5–14%.	[84–87,102]
Solar Photovoltaics and H_2	The cost of producing H_2 ranges from 3.41 to 16.01 USD/kg, whereas the cost of generated electricity ranges from 0.06–0.38 USD/kWh.	The most commonly used technology for green H_2 production. Requires minimal maintenance. Increases H_2 output. Lowers production costs. Achieved efficiency of 12.4% in 2010 and 21% by 2020.	[50,79,81,103–105]

5.2. Challenges and Limitations

Given that hydrogen can serve as an alternative energy source and offer flexibility to the power market. It is crucial to prioritize sustainable production methods through the integration of renewable energy systems, often referred to as green hydrogen energy systems. The advancement in green hydrogen systems in terms of techno-economic capabilities, competitive advantage, and optimization strategies are extensively reviewed and found to be the major drives in the renewable energy field to address issues associated with the extensive use of wind-based electricity and takes a central role in future net-zero carbon drives. It goes without saying that some challenges are hindering the accelerated adoption of these technologies. This section focuses on the challenges that need to be carefully considered to realize the full potential of green hydrogen technology.

i. **Intermittency and Variability:** The inherent fluctuation of solar and wind energy is a substantial obstacle to achieving consistent hydrogen generation. Variations in renewable energy production can result in ineffective electrolysis processes and unreliable hydrogen provision [106,107]. Hybrid solar–wind–hydrogen systems employ multi-layered control strategies to manage renewable energy fluctuations across various timescales. Short-term responses (seconds to minutes) utilize power electronics, battery storage, and fuel cells for rapid adjustments. Medium-term strategies (minutes to hours) incorporate predictive algorithms, energy management systems, and flexible electrolyzer operation. Long-term approaches (hours to days) leverage hydrogen storage, seasonal forecasting, and grid interconnections. Advanced control methods, including adaptive systems, model predictive control, and hierarchical structures, coordinate these components. This comprehensive approach ensures continuous system stability by balancing energy production, storage, and consumption, effectively addressing the intermittent nature of renewable sources in an integrated and efficient manner.
ii. **High capital cost:** The equipment required for electrolysis, hydrogen storage, and fuel cells remains expensive. These high initial investments can be a significant barrier to entry for many potential adopters, particularly in regions without strong policy support. Also, developing the necessary infrastructure for large-scale hydrogen storage and distribution requires substantial investment and technological advancements [108–113].
iii. **Market Uncertainty and Regulatory hurdles:** The embryonic state of the green hydrogen market introduces ambiguity for investors, potentially constraining financing for extensive projects and impeding industry expansion. Also, a lack of standardized regulations and codes for hydrogen systems in many regions can slow down project development and increase compliance costs [107,114–116].
iv. **Material degradation:** Prolonged exposure to hydrogen can degrade certain materials in electrolyzers and fuel cells, potentially reducing the system lifespan and increasing maintenance costs. Therefore, accurately predicting the performance degradation of fuel cells is both theoretically significant and practically important, highlighting the need for further research in this area [117].
v. **Safety issues:** Hydrogen is extremely combustible and necessitates cautious handling. Integrating strong safety measures and protocols increases the overall complexity and cost of the system, especially in densely populated regions.
vi. **Fuel cell efficiency:** The process of converting electricity into hydrogen through electrolysis and subsequently converting it back into electricity using fuel cells is characterized by a relatively poor overall efficiency, often ranging from 30% to 40%. This decrease in efficiency can render the system less economically feasible as compared to the direct utilization of renewable electricity or alternative energy storage technologies [118–121].

The challenges associated with the solar and wind energy-integrated green hydrogen production systems highlighted in the previous section can be mitigation by several correction measures, such as:

i. **Automated forecasting and control systems:** The integration of solar and wind resources with hydrogen production can be optimized with the use of intelligent control systems and advanced weather forecasting technologies. The influence of intermittency can be reduced by using machine learning algorithms to forecast the output of renewable energy and modify electrolysis processes appropriately.
ii. **Cost reduction strategies:** One way to lower the capital costs of hydrogen systems is to use less expensive materials, increase the output, and enhance manufacturing

processes. The use of carbon pricing mechanisms, government incentives, and subsidies may contribute to the increased economic viability of these systems.

iii. **Standardization and market policy support:** Regulatory hurdles can be reduced through the development and implementation of international standards for hydrogen systems. Government policies that incentivize green hydrogen production and use can help create a more stable market environment and attract investment. This can include feed-in tariffs for green hydrogen, mandates for hydrogen use in certain sectors, and support for research and development.

iv. **Development of advanced materials:** Research into more durable and hydrogen-resistant materials can extend the lifespan of system components and reduce maintenance costs. This includes developing new catalysts, membranes, and structural materials for electrolyzers and fuel cells.

v. **Efficiency improvements:** The overall efficiency of the system can be raised by continuing research into more effective electrolysis technologies, such as high-temperature electrolysis and sophisticated proton exchange membrane (PEM) electrolyzers. Hydrogen-based energy storage can also become more viable through creating reversible fuel cells and increasing fuel cell efficiency.

Some of the highlighted potential solutions for addressing the barriers hindering the widespread adoption of these green hydrogen technologies have been proven to mitigate the challenges. While some are just hypothetical solutions that could be implemented and improved with time, ongoing research and development are steadily improving the viability of these integrated systems.

5.3. Future Directions

The advent of technological advancements has created room for significant improvements in green hydrogen production and is shaping the future of integrated solar, wind, and green hydrogen systems. The adoption of hydrogen-based technology presents substantial opportunities for economic growth, improvement in human well-being, and addressing pressing environmental concerns. Recently, there has been a growing interest in the method of water electrolysis for hydrogen generation, driven by technological advancements and the accessibility of cost-effective power sources. Emerging trends such as floating offshore renewable energy platforms, advanced AI-driven control systems, and solid-state electrolysis technology are opening up new possibilities for more efficient and cost-effective hydrogen production. The expansion of hydrogen applications beyond energy storage to include industrial processes, synthetic fuel production, and transportation is creating new markets and improving the economic case for green hydrogen. Also, through hydrogen-based energy storage for grid stabilization, large-scale hydrogen storage systems can provide long-duration energy storage to stabilize grids with a high penetration of renewable energy. The incorporation of hydrogen in steel production as a reducing agent could significantly reduce carbon emissions and the overall energy consumption.

The hydrogen market's growth depends on future hydrogen prices, technology advancements, potential greenhouse gas restrictions, and alternative energy costs. Hydrogen shows promise as a future fuel due to various social, economic, and environmental factors, potentially reducing oil imports and vehicle emissions. The current research focuses on hydrogen synthesis from diverse sources and improving storage and transportation methods. While the experimental results are promising, their large-scale feasibility needs careful evaluation. The urgent need for clean energy is clear, but transitioning from fossil fuels faces significant political and economic challenges. The shift to renewable energy, including hydrogen, will be gradual due to the extensive restructuring required in global energy infrastructure, which underpins the world economy and power dynamics.

6. Conclusions

This research extensively discusses the advancement of integrated solar and wind energy with green hydrogen systems for efficient hydrogen production, storage, and consumption. It highlights recent technological developments, such as improved electrolyzers and enhanced energy storage. Various instances of the implementation of the system in real-world applications were critically examined. The need for integrated renewable energy and green hydrogen systems to help us achieve a sustainable, low-carbon future is growing as the urgency to address climate change decreases. Even if there are still obstacles to overcome, the continuous progress in technology, along with the increasing governmental and social backing for sustainable energy solutions, point to a bright future for these creative approaches. The success of combining solar and wind energy with green hydrogen systems will ultimately depend on a coordinated effort across multiple domains—technological innovation, policy support, market development, and public engagement. As research progresses and costs continue to decrease, these integrated systems have the potential to play a pivotal role in the global energy transition, contributing significantly to the decarbonization of various sectors and the creation of a more sustainable and resilient energy landscape.

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Abbreviations

Anion Exchange Membrane	AEM
Alternating Current	AC
Alkaline Electrolysis	ALK
Alkaline Fuel Cell	AFC
Alkaline Water Electrolysis	AWE
Advanced Metering Infrastructure	AMI
Artificial Intelligence	AI
Balance of Plant	BOP
Building-integrated Photovoltaics	BIPV
Carbon dioxide Capture and Utilisation	CCU
Carbon dioxide Capture and Storage	CCS
Concentrated Solar Power	CSP
Carbon monoxide	CO
Carbon dioxide	CO_2
Copper	Cu
Direct Current	DC
Direct Methanol Fuel Cell	DMFC
Deep Learning	DL
European Power Exchange	EPEX
Energy Management Electrolysis	EMS
Fossil abiotic depletion potentials	F-ADP
Fuel cell electric vehicles	FCVEs
Gas hydrogen storage	GH_2
Gigawatts	GW
Greenhouse Gas	GHG
Green Hydrogen	GH
Hybrid renewable energy systems	HRES
Hydrogen evolution reaction	HER
Hydrogen energy storage systems	HESSs
High Voltage Direct Current	HVDC
Levelized cost of hydrogen	LCOH
Life Cycle Assessment	LCA
Liquid hydrogen storage	LH_2
Low Heating Value	LHV

Machine Learning	ML
Material-based hydrogen storage	MH_2
Maximum Power Point tracking	MPPT
Methane	CH4
Megawatts	MW
Metric Tonnes	MT
Molten Carbonate Fuel Cells	MCFC
Natural Gas	NG
Ocean Thermal Energy Conversion	OTEC
Oxygen Evolution Reaction	OER
Phosphoric Acid Fuel Cell	PAFC
Photo-electrocatalysis	PEC
Photovoltaic	PV
Polymer Electrolyte Membrane Fuel Cells	PEMFC
Power Management System	PMS
Power-to-Gas	P2G
Power-to-X	PtX
Proton Exchange Membrane	PEM
Proton Exchange Membrane Electrolysis	PEMEC
Renewable Energy Sources	RES
Salinity Gradient Solar Pond	SGSP
Solar-to-hydrogen	STH
Solid Oxide Electrolysis	SOE
Steam Methane Reformer	SMR
Substitute Natural Gas	SNG
Terawatts	TW
Ten-Year Network Development Plan	TYNDP
Thermoelectric Generator	TEG
Transmission System Operators	TSOs
Trilateral Cycle	TLC
United Nation	UN
Variable Renewable Energy	VRE
Western Interconnection	WI
Wind Turbine	WT
Zinc Cadmium Sulphide	ZnCds

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