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Review

Prospect of Green Hydrogen Generation from Hybrid Renewable Energy Sources: A Review

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Abstract: Hydrogen is one of the prospective clean energies that could potentially address two pressing areas of global concern, namely energy crises and environmental issues. Nowadays, fossil-based technologies are widely used to produce hydrogen and release higher greenhouse gas emissions during the process. Decarbonizing the planet has been one of the major goals in the recent decades. To achieve this goal, it is necessary to find clean, sustainable, and reliable hydrogen production technologies with low costs and zero emissions. Therefore, this study aims to analyse the hydrogen generation from solar and wind energy sources and observe broad prospects with hybrid renewable energy sources in producing green hydrogen. The study mainly focuses on the critical assessment of solar, wind, and hybrid-powered electrolysis technologies in producing hydrogen. Furthermore, the key challenges and opportunities associated with commercial-scale deployment are addressed. Finally, the potential applications and their scopes are discussed to analyse the important barriers to the overall commercial development of solar-wind-based hydrogen production systems. The study found that the production of hydrogen appears to be the best candidate to be employed for multiple purposes, blending the roles of fuel energy carrier and energy storage modality. Further studies are recommended to find technical and sustainable solutions to overcome the current issues that are identified in this study.

Keywords: green hydrogen; hybrid energy; solar energy; wind energy; fuel cell; renewable energy

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1. Introduction

Higher energy consumption and environmental pollution are key global challenges for sustainable development [1,2]. Recent studies show that global energy consumption has been growing faster than population growth in recent decades [3]. In addition, overall economic growth predominantly depends on fossil fuel consumption, significantly contributing to greenhouse gas emissions and global warming [4–6]. To address this issue, the increasing energy demand should be met by a clean and zero-emission energy source that is renewable, sustainable, and eco-friendly [7,8]. The recent literature reported that wind and solar energy have more potential than other renewable energy sources [9]. However, the key challenges for steady energy generated from these sources are their intermittent nature and dependency on weather phenomena. Therefore, an appropriate and reliable energy generation and storage system are needed for a consistent energy supply to balance energy generation and consumption [10–13]. Many techniques have been developed for an energy storage system, with some underpinning facts [11,12]. For instance, a lead–acid battery is one of the most popular, recently introduced techniques to store energy. However, this approach is facing many challenges, such as higher installation and maintenance costs, self-energy discharging properties, and the emission of harmful gases and soil contamination due to the discharge of harmful heavy metal (i.e., lead) into the environment [14].

Therefore, a hydrogen-based storage system is one of the alternative solutions that has shown growing interest from the international research community in recent days. So, this study will focus on the prospect of hydrogen energy generation from hybrid wind and solar energy sources to address the mentioned challenges [15].

According to the Australian energy resource assessment, Australia possesses some of the world's top renewable energy sources, notably sun and wind, with the capacity to generate nearly 5.29 giga-watts [16]. Applying these renewable energies can provide a sustainable solution for the isolated areas where power transmission is not cost-effective to meet the local power demand. In addition, the recent advancement of solar photovoltaic and wind turbine technology has fuelled significant global expansion in solar and wind energy harvesting. However, there is a flip side to producing energy from these sources due to their irregular nature and the dependency on climatic conditions. For example, the key environmental variables, such as wind speed, air density, solar radiation, air temperature, cloud coverage, etc., change with time, directly impacting energy generation. Therefore, a single system (either wind or solar) cannot provide a steady energy supply to the community. On the contrary, the energy demand is also independently varied over time. So, there is a need for a hybrid wind–solar energy system with an intelligent storage system capable of consistently supplying energy according to local demand.

Parrado et al. [17] have conducted a comprehensive study on hybridization with the addition of storage units attached to renewable power generation systems and found that this can be a feasible solution for peak and off-peak periods. In addition, the use of various storage technologies for renewable energy sources, such as chemical, electrochemical, mechanical, electrical, or thermal, is also studied by Ould Amrouche et al. [18]. In general, an energy storage device requires a storage medium, a power conversion unit, and a control unit, where the stored power preserves the efficiency of the grid by covering any energy deficits of renewable sources such as solar and wind plants. Though these storage technologies are widely being used in extensive applications, constraining factors, such as storage sizes, costs, and limited lifespan, are still causing problems in implementing these systems in stand-alone applications [19]. Moreover, during colder climatic conditions, charging stability for some storage is very poor, e.g., the self-discharge properties of electrical batteries [20]. Additionally, these batteries release harmful gases (i.e., CO_2, NO_x, and SO_x) in their lifetimes and dumping of these batteries after use will produce soil contaminated with harmful heavy metals (i.e., lead, zinc, nickel, and lithium). Therefore, to overcome existing storage problems, hydrogen generation through water electrolysis could be a model of industrial conversion of renewable electricity into chemical, storage, and transportable energy. Thus the possibility of unlocking zero emissions through hydrogen is attracting growing interest [21]. However, a stand-alone zero emissions hybrid renewable system based on hydrogen has yet to be completed for remote locations.

Producing clean and quality hydrogen with zero emissions is the main aim of this study, and the objectives such as solar-powered and wind-powered technologies are considered to achieve that aim. The previous review articles are mainly focused on quantitative hydrogen production through different hydrogen production technologies, including fossil-based sources. The main novelty of this study is to address the technological barriers and methods to obtain green hydrogen from solar and wind power. The prospective outcome and recommendation from this study is that the proposed technologies can be flexible approaches for producing green hydrogen in coastal areas.

2. Hydrogen as a Future Fuel

In recent decades, hydrogen energy has shown significant interest as a potential future fuel. It can be used for different purposes, e.g., as an energy carrier or storage medium. It provides carbon-free alternatives to conventional fuels [22]. Hydrogen is a combustible and safe fuel, which produces water and a negligible amount of nitrogen oxides upon reaction. As a fuel, hydrogen has unique properties, including a fast-burning speed and no toxicity or ozone-forming ability [23]. As shown in Figure 1, hydrogen energy content is

142 megajoules per kilogram (MJ/kg), which is more than double that of liquified natural gas (55.2 MJ/kg), about 2.5 times more than that of transport fuels (45.8 MJ/kg), and more than 4 times that of coal (31.4 MJ/kg) energy content [24]. Hydrogen is derived conventionally from a mixture of clean coal and fossil fuels, nuclear power, and large-scale renewables, increasing its potential to become a dominant future fuel.

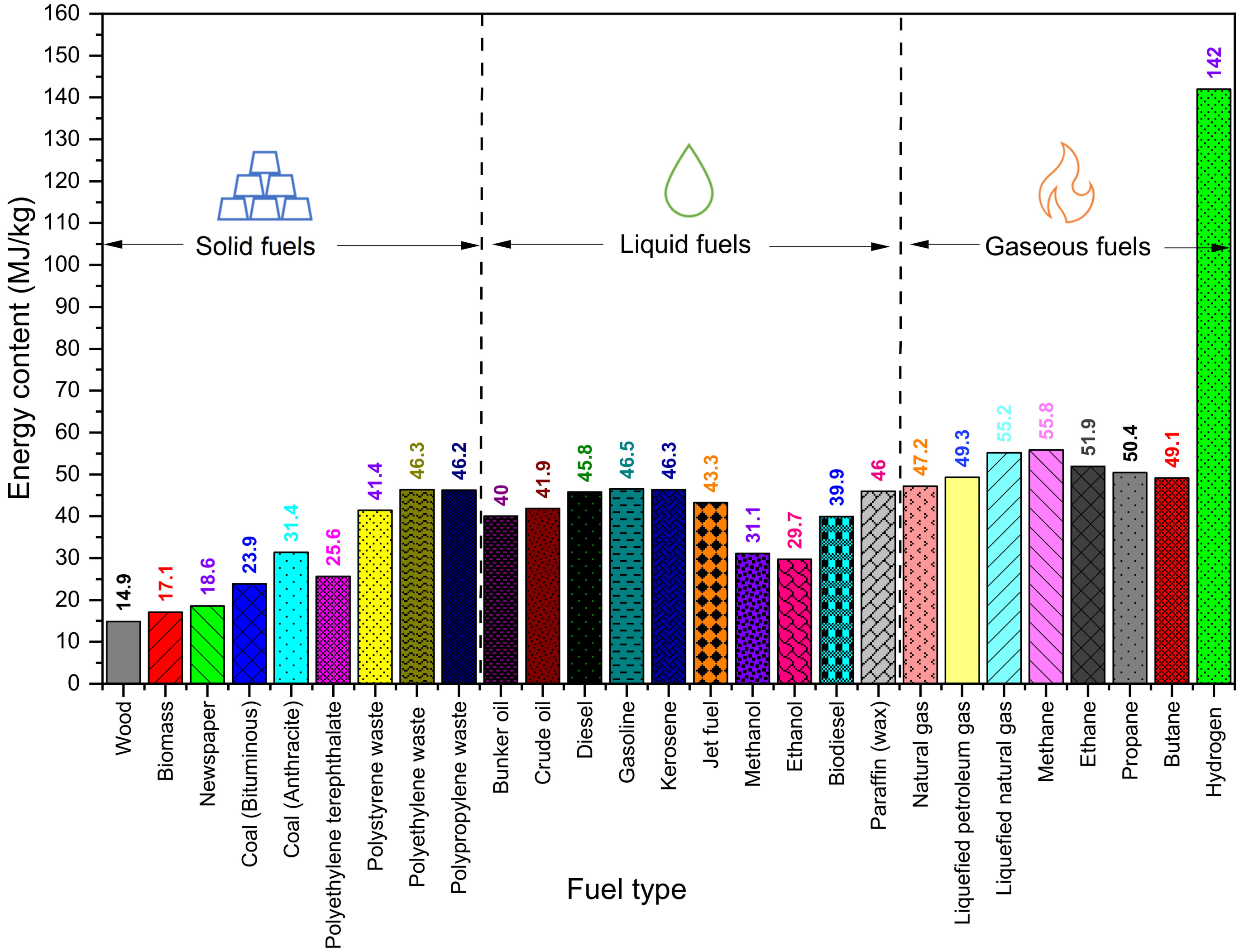

Figure 1. Energy contents of different fuel types, including hydrogen [24–26].

The literature reveals that the large-scale development of hydrogen production is feasible for a fuel cell to produce electricity in the future [27]. Scientists have developed a set of computer codes to simulate the unsteady combustion of hydrogen fuel in rocket engines [28]. In addition, Akdeniz et al. [29] conducted energy, exergy, and sustainability analyses on the aviation engine using hydrogen fuel. Their study reported that the engine exergy efficiency reduced from 26.9% to 24.3%, while the ecological effect factor increased from 3.712 to 4.113 [29]. Similarly, Salvi and Subramanian [30] investigated the effects of hydrogen–hydrocarbon dual fuel mixes on theoretical spark ignition engine (SIE) performance parameters. According to their findings, the engine's performance is significantly influenced by the mixture's hydrogen, methane, butane, and propane ratios.

According to Shivaprasad et al. [31], a hydrogen-powered spark-ignition engine outperformed a gasoline-powered counterpart in terms of thermal efficiency. Olabi et al. [27] also experimented on a single-cylinder spark-ignition engine using varying volumetric dilution ratios of hydrogen to gasoline. They found that more excellent hydrogen ratios produce higher efficiency values and better environmental benefits. Correspondingly, Xia et al. [32] investigated the effects of biodiesel blends and hydrogen in a compression ignition engine. A series of tests were carried out in a water-cooled, single-cylinder, constant-speed engine under varied loading conditions. They concluded that adding hydrogen enhanced both combustion and emission rates due to the absence of carbon atoms in the increased hydrogen. According to Cai and Zhao [33], adding more H_2 to diesel fuel improves thermal efficiency but increases nitrogen oxide (NO_x) emissions. Similarly, Akal et al. [34] studied a compressed-ignition engine using a hydrogen/diesel fuel combination and found that adding hydrogen improved performance while reducing pollutants and making the engine run quieter (less noise). So, hydrogen has considerable potential as a future sustainable fuel. However, hydrogen production is a challenging issue that needs some processes before its implementation as a fuel [35].

3. Advances in Green Hydrogen Production

Thermochemical reforming [36–38], electrolytic conversion [39,40], direct solar water splitting [41,42], and biological methods [43,44] are widely used to produce hydrogen in large quantities. Depending on the production process and energy source, the obtained hydrogen is classified as grey, blue, and green as represented in Figure 2. The hydrogen obtained from steam methane reforming and thermal cracking is categorized under grey hydrogen [45]. As shown in Figure 2, large amounts of CO_2 are produced through methane steam reforming, but these CO_2 vapors are collected in containers and stored in safe places. The hydrogen produced from natural gas, biogas, and syngas is categorized under blue hydrogen, where the formed CO_2 gases cannot be stored and will be sent to the atmosphere. Compared to grey hydrogen, blue hydrogen, which is produced from natural gas, can reduce CO_2 emissions significantly by capturing and reusing carbon. As shown in Figure 2, both grey and blue hydrogen production processes generate CO_2 as the by-product, but in the case of green hydrogen production technologies, zero carbon emissions are noted. Mostly, solar and wind technologies are used to produce green hydrogen. However, there are other catalytic reforming technologies that have the capability to produce green hydrogen. For example, biomass gasification and nuclear thermal/chemical pathways also have the potential to reduce carbon emissions; however, major challenges such as production technology costs, system durability, reliability, infrastructure, and safety are the further concerns [46]. It is estimated from the life cycle assessment that hydrogen production through biomass gasification has showed less greenhouse gas emission (405 to 896.61 g CO_2/Kg H_2) compared to wind driven electrolysis (600 to 970 gCO_2/Kg H_2) [47]. However, biomass gasification has not been scaled up thus far and it can be expected that their input to global energy production would help to attain full potential soon [48]. In addition, higher moisture content, low hydrogen production, and high operating costs are the major drawbacks associated with biomass gasification, as shown in Table 1. On the other hand, the solar- and wind-powered electrolysis techniques are the well-established renewable power sources that can produce hydrogen through electrolysis [40]. Table 1 presents the advantages and disadvantages of different hydrogen production technologies.

According to Yan et al. [49], current global H_2 production is around 75 Mt per year, with 76% being blue hydrogen coming from natural gas (205 Gm^3, or 6% of current global natural gas use) and 23% being grey hydrogen coming from coal (107 Mt, or 2% of current global coal use). However, this production generates about 830 Mt CO_2 emissions per year, which are then emitted into the atmosphere as greenhouse gases (2% of global annual emissions). However, there is still a growing international consensus that low-carbon hydrogen will play an essential role in the world's transition to sustainable energy. Therefore, a necessary prerequisite for the hydrogen economy is an inexpensive, low-carbon hydrogen source and a simple, low-cost process for producing that hydrogen energy [45]. For example, Alirahmi et al. [50] appraised a multi-generation system for green hydrogen from thermodynamic and economic viewpoints. Their system uses geothermal energy to create electricity, hydrogen, oxygen, and cooling in the Sabalan geothermal wells in Iran. The system can meet the annual energy needs of 160 homes by producing 4696 MWh. Similarly, Sukpancharoen and Phetyim [51] modelled an optimised process concerning biogas to generate green hydrogen and electrical power incorporating the Aspen Plus simulation tool. The outcome of the parameter adjustment was 211.46 kmol/h of green hydrogen generation and 2311.68 kWh of electric power production using 100 kmol/h of biogas.

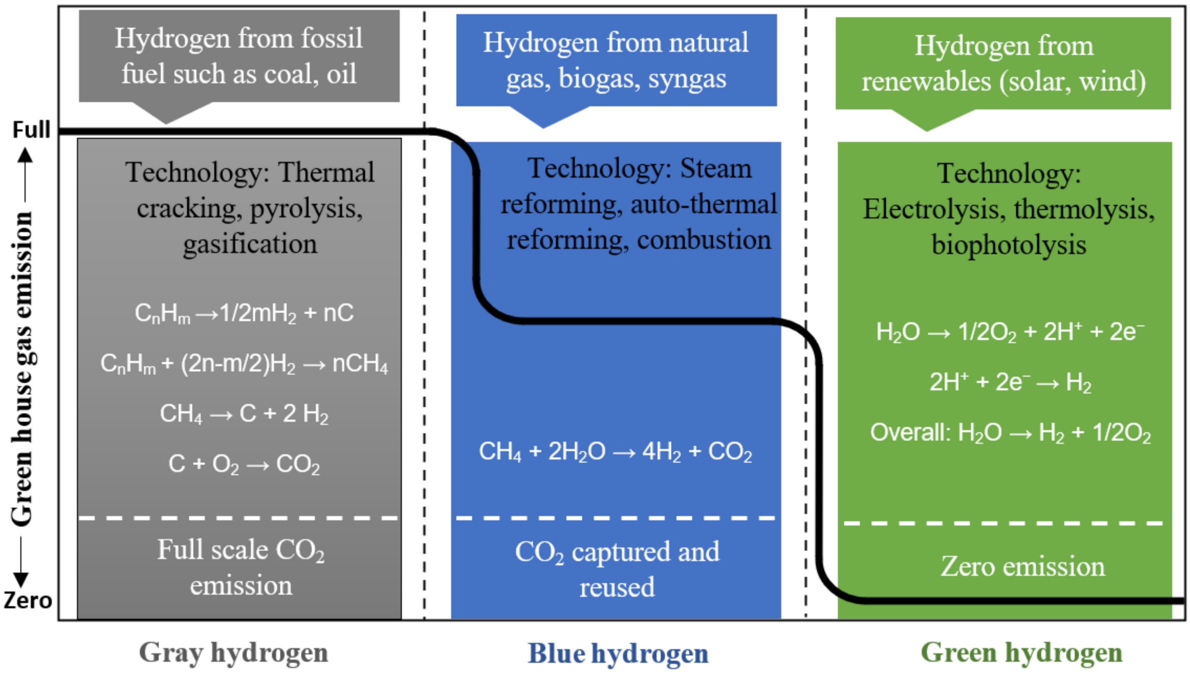

Figure 2. Category of hydrogen, their feedstocks, and technologies [52,53].

Table 1. Advantages and disadvantages of different hydrogen production technologies.

Hydrogen Production Process	Advantages	Disadvgantages	References
Steam methane reforming	Higher hydrogen yield, higher hydrogen to carbon ratio, clean hydrogen production, environmentally friendly processes, abundant steam, and no oxygen needed.	Higher greenhouse gas emissions, a lower conversion rate, increased operating costs, increased energy consumption, and required constant heat supply.	[54]
Biomass Gasification	Reliable in operation, easy and fast in maintenance, and very easy in operation.	Low heating value, high moisture content, and generation of solid tar.	[55]
Proton exchange membrane electrolyser	Good compactness and efficiency and fast response.	More expensive and lower durability.	[56]
Thermolysis	Clean and reliable with oxygen as by-product.	High capital cost, corrosion, and toxicity.	[57]
Photolysis	Clean and oxygen as by-product.	Low efficiency, low reliability, and required sunlight.	[58]

In another study, researchers explored hydrogen production by reforming green ammonia. They revealed that a scalable 12-faceted reactor produced over 66 L min^{-1} of hydrogen with state-of-the-art ammonia reforming efficiency of 83.6% [59]. Furthermore, Gerloff [60] examined alkaline electrolysis, polymer electrolyte membrane electrolysis, and solid oxide electrolysis cell (SOEC) to assess the environmental implications of greener hydrogen production. They revealed that only renewable sources such as wind and solar energy in the alkaline electrolysis process produce green hydrogen with minimum or nearzero carbon emissions. Moreover, Singlitico et al. [61] evaluated the economic feasibility of hydrogen production from offshore wind power hubs using a variety of electrolyser placements, technologies, and operating modes. The results indicated that prices of green hydrogen production offshore can be as low as 2.4 EUR/kg, which is competitive with the current cost of hydrogen produced by natural gas. Water electrolysis becomes a preference when green hydrogen production from renewable sources is a consideration relating to the abundancy of water sources. This priority is based on both quantitative and qualitative aspects. In addition, Tarhan and Cil [62] concluded that water electrolysis is the most efficient method among the current commercial methods. In spite of this, the use of hybrid renewable sources (solar and wind) in water electrolysis is not yet sufficiently developed for hydrogen generation.

Figure 3 illustrates the schematic for hydrogen production. In the first stage, electricity is generated from a hybrid renewable source (a combination of wind turbine and solar PV); an electrolyser is used in the second stage. In the electrolyser, water is split into hydrogen gas as the principal product and oxygen gas is released as a by-product. The hydrogen gas is further passed through a compressor for storage purposes. This compressed hydrogen can be transported for commercial purposes. In terms of operation, electrolyser-produced green hydrogen can be used to meet the electricity shortfall of hybrid solar and wind electricity.

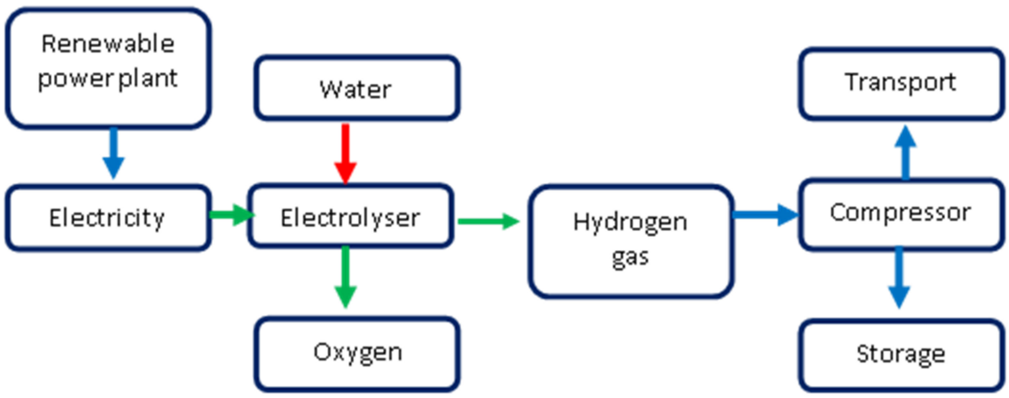

Figure 3. Schematic diagram of green hydrogen production.

3.1. Hydrogen Generation from Solar Energy

The electricity generated by solar photovoltaic (PV) modules could be used to electrolyse water for hydrogen generation, as shown in Figure 4. This system is one of the cleanest hydrogen-generating technologies. However, the current downsides of PV-based hydrogen production are its high installation costs and lesser efficiency than fossil fuels [63].

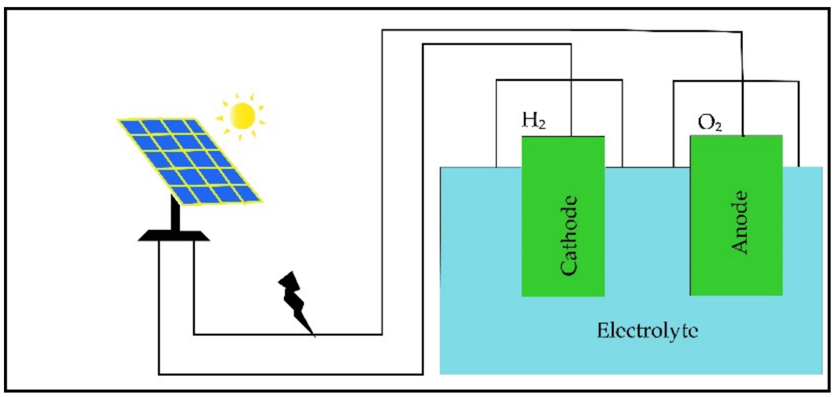

Figure 4. Hydrogen production from solar based electrolysis.

Purnami et al. [64] scrutinized the current status of solar-powered water electrolysis along with some of the innovative applications used to enhance the overall efficiency of such systems. Such approaches include applying magnetic, light energy, ultrasonic, and pulsating electric fields. This study also provides insight into new applications for enhancing electrolysis efficiency. Toghyani et al. [65] analysed the energy and exergy performance of the hydrogen refuelling station under different working conditions, where the station's efficiency significantly increased for electric grid connection in the system. In another study, the solar-driven production of hydrogen (S-DPOH) achieved a cumulative production of hydrogen (CPOH) during 50 h of solar irradiation of 43.75 mmol produced H_2 of 38.66 $\pm$ 0.655 mmol/hg, which is 1.5 folds higher than the maximum rate reported for pure TiO_2-based photocatalyst [66].

Although solar is a clean and abundant energy source, the power extracted from photovoltaic solar cells is around 20%. This is because of factors such as a shadow, dust, and operating temperatures [67]. As a result, solar PV hardly meets the required electricity demand. Furthermore, solar electricity is only available during the day, limiting its accessibility. Therefore, hybrid systems with different renewable energy sources and storage technologies can address this shortcoming. However, the cost per kWh of PV generation is steadily decreasing. Other energy sources can be used to boost efficiency and extend the system's operational hours.

3.2. Hydrogen Generation from Wind Energy

Water electrolysis by wind energy uses the same principle (Figure 5) as solar, described earlier. Wind energy is the easiest and cleanest way to produce hydrogen. Compared to other renewable sources, it is cheaper and more efficient in producing hydrogen. However, producing hydrogen from wind energy requires a mature wind turbine structure, an electrolyser, and an appropriate hydrogen storage system [63].

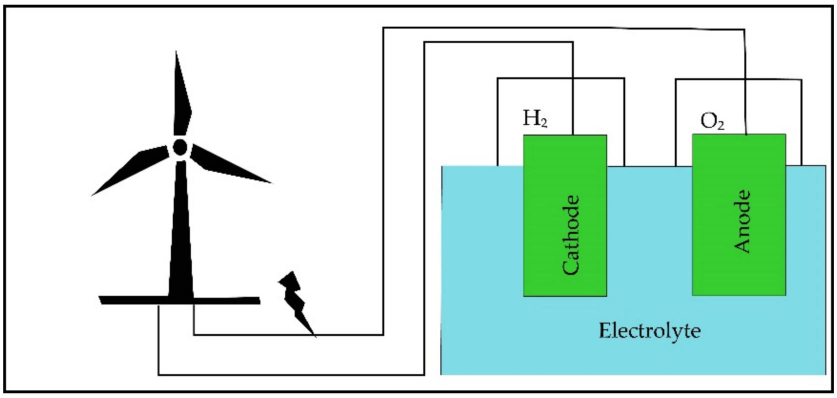

Figure 5. Hydrogen production from wind-based electrolysis.

Almutairi et al. [68] revealed that the highest wind energy of Iran's Bahabad and Halvan stations could produce 19.844 and 19.429 tons/year of hydrogen, respectively. Another study in Ukraine achieved a capacity of 688 GW from the combined wind power plants on its territory, which can provide an average annual production of 43 million tons of green hydrogen through electrolysis [69]. In South Africa, the feasibility of the application of wind turbines was performed by Ayodele and Munda [70]. They reported that the highest wind potential site produces hydrogen from 6.51 to 226.82 metric tons, depending on the turbine's capacity, while the best turbine cost is 0.23 AUD/kWh. Similarly, Abdel-Basset et al. [71] also argued that wind electrolysis is the key to sustainable hydrogen production shortly, where proper predictions for precise energy calculation are needed.

As wind power is highly volatile and erratic, exact wind speed prediction can enhance the system's safety while also helping to streamline despatch and cut down on lost revenue. In the past, scientists ignored virtual components' impact and failed to identify wind speed characteristics effectively. Therefore, the prediction was unreliable, which led to ineffective results. Zhang et al. [72] proposed an energy theory method to bridge these gaps. This method outperformed other forecasting methods, reduced fluctuation risk, and increased system stability. Another hindrance was generation variability, which was widely acknowledged as a major barrier to the greater use of renewable energy sources. It is well understood that combining generations from geographically (or technologically) diverse sources can reduce generation intermittency. Therefore, Han and Vinel [73] constructed an optimised model for intelligently employing a wind energy portfolio for a given harvesting region, and this pooling model significantly reduced wind energy generation forecasting errors.

In contrast, Murcia et al. [74] validated atmospheric reanalysis data sets to simulate onshore wind generation time series for large-scale energy system studies. However, as expected, in terms of wind speed simulation, no model can fully describe the auto-correlation function of wind speed at a single point. Therefore, wind source is unreliable for a sustainable energy generation system.

3.3. Hydrogen Generation from a Hybrid Renewable Energy System

Recently, a hybrid renewable energy system (HRES) has emerged as a promising solution to address the issues with individual energy sources [75]. Usually, a hybrid green energy system uses various renewable energy sources, such as wind and solar, as shown in Figure 6. The benefits of HRES rely on multiple renewable energy sources to supply consistent and uninterruptible energy. Therefore, this energy availability will compensate for the unreliability of single renewable energy sources and reduce greenhouse gas emissions [76]. Such systems are typically located very close to the place of demand. Thus, the chance of damage to the transmission wire is decreased and quick access in terms of repair and maintenance is facilitated. As greenhouse gas emission constitutes a significant issue regarding global warming, renewable sources will offer a prospective solution due to their low emissions. Thus, many ongoing research projects worldwide aim to obtain the best and most reliable renewable energy generation system [77].

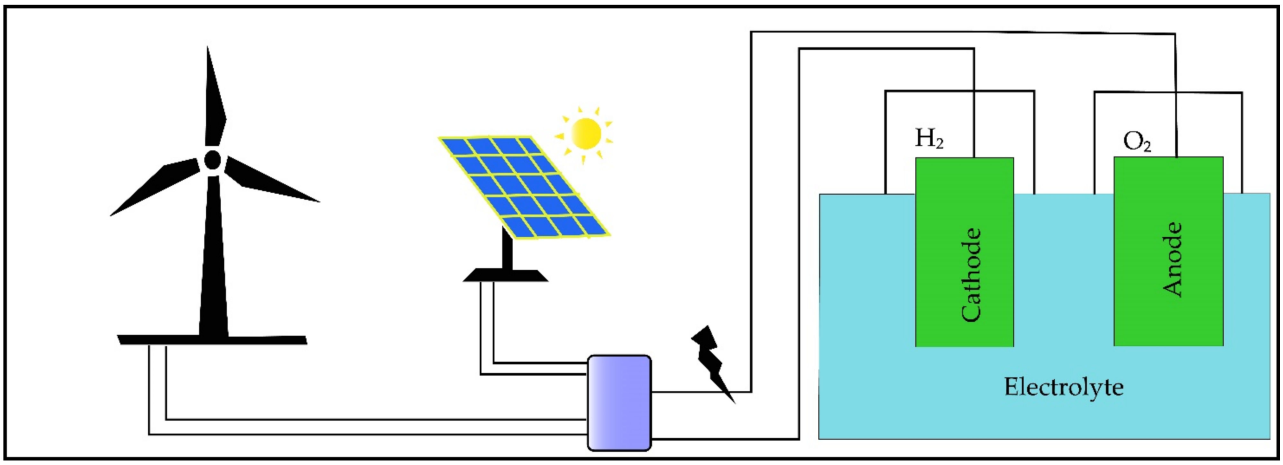

Figure 6. Hydrogen production from hybrid energy-based electrolysis.

In recent times, many studies have focused on using hybrid renewable energy for different applications. For example, Uwineza et al. [78] examined the feasibility of combining hybrid renewable energy with large-scale reverse osmosis desalination. The latter energy system comprises photovoltaic panels, wind turbines, microturbines, batteries, converters, thermal load controllers, and a boiler. The optimal system has a net present value of AUD 1.54 M and an energy cost of 0.089 AUD/kWh. Another hybrid power system, an alternative device to isolated power demand, was developed to combine renewable and fossil sources with energy storage devices. Using this system, energy losses and also intermittent behaviours of the sources and demands can be easily treated [79]. A different study demonstrated a wind and wave hybrid system as a cost-effective solution to the offshore power supply. This novel wind–wave hybrid power generation system was modelled with AMESim and MATLAB/Simulink. This study revealed that the energy coupling efficiency of this hybrid system ranges from 80.34 to 99.12% [80]. Another hybrid renewable power system was assessed for its technical and economic feasibility on remote Huraa Island in the Maldives. That hybrid power system used diesel, solar PV, wind, and battery storage and achieved maximum renewable penetration (RP) of 96% with 1800 kW PV, 1000 kW wind, and 4000 kWh battery storage [81]. In a separate study, a grid-connected stand-alone hybrid renewable power system that comprised a solar photovoltaic/wind turbine sold back the generated excess power to the grid [82]. This study reported the lowest cost of electricity (70 AUD/MWh) with the highest renewable percentage (94.3%) for this hybrid system. This hybrid system emitted the lowest carbon dioxide emissions (44.1 kg CO_2/year) [82].

A hybrid energy management strategy, known as Action Dependent Heuristic Dynamic Programming (ADHDP), was developed to reduce hydrogen consumption to improve the performance of a hybrid system. The results showed that the ADHDP networks converged well under various operating conditions [83]. There are a variety of optimisation techniques, including classical methods and metaheuristics. However, drawbacks of various optimisation approaches are common, such as the computational burden, immaturity of convergence, being stuck in local energy optima, inaccuracy of results, and others. Optimising this system can improve the efficiency and operation of renewable hybrid power systems. There is an argument that the optimisation approach used here has these essential characteristics, and simulation results back this up [75]. Nowadays, the research optimisation approach is concerned with the storage issue. As most hybrid systems are engaged using common storage such as a battery, it is evident that the battery also emits gas, and its self-discharging property makes it an unreliable storage medium. Therefore, other storage systems, such as compressed air, flywheel storage, hydro storage, ammonia storage, hydrogen storage, etc., are now becoming popular. Among them, hydrogen is the most popular storage due to its low critical temperature (33 K), and liquid hydrogen can be stored in open systems. The volumetric density of liquid hydrogen is 70.8 $kg{\cdot}m^{-3}$, and large volumes, where the thermal losses are small, can cause hydrogen to reach a mass system ratio close to 1 [84].

Current research reveals that 11% of total energy needs will be met by hydrogen energy by 2025 and 34% by 2050 [62]. It is also stated that coal use will decrease by 36.7% depending on hydrogen energy production, and oil use will decrease by 40.5% by 2030. More than 50 million tons of hydrogen are produced annually globally [62]. According to the International Energy Agency, hydrogen energy generated from wind and electrolysis will be cheaper than natural gas by 2030 [85]. In an experimental study in Colorado, USA, Abdin and Mérida [86] integrated PV, WT, a battery bank, an electrolyser, and a hydrogen tank with a cost of AUD 0.50 kWh. They found that the minimum COE was 0.78 AUD/kWh without a battery bank at the exact location. Another study revealed that the best solution from a technical viewpoint consists of a hybrid system that combines hydrogen with short-term energy storage technologies such as batteries and supercapacitors [87]. Mehrpooya et al. [88] developed a unique hybrid system based on the solar thermochemical water-splitting hydrogen production cycle. The outcome showed that concentrated solar power could provide 5.88 MW of heat for the thermochemical cycle with a fuel cell efficiency of about 63%. This hybrid system produced 13.63 MW of electricity with 85% efficiency [88]. On the other hand, Walsh et al.'s [89] economic model assessed regional factors to identify areas of high economic potential for hydrogen production. This analysis discovered that a number of regions around Australia are ranked in the 95th percentile or greater for hydrogen production. Despite these ample energy sources, a hybrid renewable source (solar and wind) is rarely applied in water electrolysis for hydrogen generation. Therefore, this research will focus on green hydrogen generation using a solar–wind hybrid renewable energy source for a sustainable solution.

4. Potential of Renewable Energy Sources to Produce Hydrogen

Weibull distribution is a widely used function for analysing solar radiation and wind speed data in a given location over time. The Weibull parameters can be estimated using the following methods: the energy pattern factor method (EPF); graphical method (GM); maximum likelihood method (MLM); moment method (MM); and modified maximum likelihood method (MMLM). However, the two-parameter Weibull distribution is a special case of the generalized gamma distribution [90–92].

According to Bureau_of_meterology [93], Australia has the highest solar irradiation in the world, receiving on average up to 35 megajoules per square metre per day (MJ/m^2/day) or 9.7 kilowatt-hours per square metre per day (kWh/m^2/day) [94]. Theoretically, if only 0.1 per cent of incoming energy could be converted into usable energy at an efficiency of 10 per cent, all of Australia's energy needs could be met only with solar energy. Therefore, energy from a 50 square km solar farm would be adequate to meet all of Australia's electricity needs [95]. However, the BOM report [96] notes that coastal areas, particularly in the south, have a higher atmospheric moisture content, which contributes to the region's increased cloud cover. Therefore, variations in solar exposure are to be expected seasonally. Kam et al. [97] conducted a study using Weibull distribution methods to compare how well the global solar irradiance model could estimate PV energy output and the size of PV installations. They concluded that the MM accuracy (7%) is higher than both the GM (13.5%) and the MLM (15.25%). In Iran, Fereidooni et al. [98] assessed hydrogen production using solar facility. The study estimated that around 373 tons of hydrogen could be generated annually from a PV plant having capacity of 20 kW.

Wind energy use is becoming increasingly popular because of its environmental benefits and smaller carbon footprint compared to fossil fuels. In contrast, wind speed forecast accuracy is the critical challenge for achieving long-term sustainability in development. Wind speed data is the sole focus of many studies, ignoring all other meteorological characteristics, resulting in erroneous weather predictions. According to BOM [99], from January to February, Northern Australia faces a lower breeze than average. For the months of March to August, Tasmania and South Australia receives lower wind energy, around nearly 2 km/h, while average breezing remains the same in other Australian regions. The September to December period is the hottest time, where a few regions feel breezes of around 10 to 15 km/h. From the wind direction pattern, it is evident that, in winter, the southern hemisphere and the western winds are more regular on the Australian continent than in summer. Meteorological factors such as the monsoon regime, tropical cyclones, sea or mountain breezes, frontal systems, and convective activity influence wind intensity and direction on regional and local scales. Ivy et al. [100] concluded that wind and solar power plants have a lot of potential for hydrogen production, which may be used by fuel stations in the United States. Ni et al. [101] assessed hydrogen production potential from wind, solar, and biomass energy sources and revealed that the produced hydrogen can cover 40% of power consumption in the transportation sector in Hong Kong. Hence, from the conducted literature, it is observed that the renewable energy methods, such as solar- and wind-powered electrolysis techniques, have great potential to meet the global hydrogen energy demands.

5. Energy Conversion Techniques from Green Hydrogen

Energy can be extracted from hydrogen either using a steam turbine or a fuel cell. A steam turbine uses a three-step process to generate electricity, the first phase of which is generating heat with the reaction of hydrogen and oxygen. This reaction is the starting point for the process. The subsequent process comprises steam production with the heat generated by a boiler; this steam is then directed via a turbine, resulting in mechanical energy formation. This mechanical energy is used to run the electrical generator, which is finally converted into electrical energy.

In contrast, the fuel cell is a single-stage energy conversion system, where hydrogen reacts with oxygen in a closed chamber to generate electricity and water as a by-product.

Because of the single direct conversion process, fuel cells can achieve much higher conversion efficiencies than the traditional steam turbine electricity generation method. Additionally, fuel cells positively contribute to environmental aspects and other climate challenges. They are considered safe, silent, and pollution-free (or nearly zero emissions) operational units, depending on the type of fuel cell. In the case of operating with hydrogen, the only by-product is water or water vapour; there are no emissions. Fuel cells have the highest efficiency compared to other energy conversion systems [102]. However, fuel cells require pure oxygen and hydrogen to produce the necessary power for transport and electricity generation.

A fuel cell uses KOH solution as the electrolyte. Hydrogen reacts with hydroxyl ions on the anode side to form water and release electrons ($2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$). On the cathode side, oxygen reacts with water to form hydroxyl ions ($2H_2O + O_2 + 4e^- \rightarrow 4OH^-$). According to the overall reaction ($O_2 + 2H_2 \rightarrow 2H_2O$), a fuel cell produces electric power and thermal power [77]. To determine the fuel cell's output power and electrical efficiency, the cell voltage must first be determined as follows: $V_{Fuel\ Cell} = E - V_{Loss}$, where E and V_{Loss} represent the equilibrium potential and voltage losses, respectively [103].

Similarly, Zhang et al. [104] conducted an experiment comprising interdigitated fields with varying outlet channel widths to study cell performance and active electrochemical area (ECA). They concluded that the ECA and cell performance increase significantly with narrower outlet channels at the expense of ohmic resistance. The study revealed that pressure drop in the fuel cell is less within a 3-channel serpentine configuration than in other serpentine channel configurations. They also concluded that pressure drop in the single channel requires more pumping power with higher flow rates for blowing species gases [105]. On the other hand, Bacquart et al. [106] studied a specimen comparison of hydrogen refuelling station (HRS) nozzles. The analysis reveals that, at 70 MPa nozzle pressure, hydrogen in a refuelling station showed a good understanding of all contaminants. Another study on hydrogen fuel conducted by ohi. et al. [107] revealed that high-quality fuel with a purity of 99% hydrogen is required to produce electricity.

Simulation and modelling are secure and effective ways to initiate a solution for real-world problems. It offers valuable methods of research that are simple to verify, interact with, and comprehend. Simulation and modelling offer useful insights into complex interactions across industries and disciplines. These include increasing productivity, power, reliability, durability, performance, and utilisation, among other things [108]. The most widely used simulation tool for investigating any hybrid system is HOMER (Hybrid Optimization Model for Electrical Renewable). As HOMER can perform hybrid system dimensioning with energy requirements, it also determines the optimal size of each system component. Apart from dimensions, simulation can also specify the component type and size. The tool then analyses the system's behaviour in detail. However, acceptable sizing requires identifying the key variables and then running the simulation repeatedly, manually adjusting the variables. It can simulate photovoltaic generators, batteries, wind turbines, AC generators, fuel cells, electrolysers, hydrogen tanks, AC–DC bidirectional converters, and boilers in hybrid systems. Other simulation applications and their shortfalls are described in Table 2.

Table 2. Simulations and optimisation applications for hydrogen from hybrid energy systems.

Software Name	Provider	Scope	References
HomerPro	NREL (National Renewable Energy Laboratory), USA	This system can optimise and simulate most of the available hybrid systems including electric vehicles.	[109]
HYBRID2	University of Massachusetts	The hybrid systems can analyse three types of electrical loads, multiple wind turbines, generators, storage, and conversion device.	[110]
iHOGA	University of Zaragoza (Spain).	This system can optimise hybrid systems consisting of generators, batteries, turbines, fuel cells, electrolysers, hydrogen tanks, rectifiers, and inverters.	[111]

Table 2. *Cont.*

Software Name	Provider	Scope	References
TRNSYS	The University of Wisconsin, University of Colorado (USA)	It was developed to simulate thermal systems and does not allow the carrying out of optimisations.	[112]
HYDROGEN	Institute for Energy Technology (IFE, Norway)	GenOpt programme is necessary to perform economic optimisation using the lineal simplex optimisation process.	[113]
INSEL	University of Oldenburg, Germany	This software is used only for simulation and cannot be used for an optimisation program.	[114]
ARES	University of Cardiff, UK	This system precisely simulates PV–wind–battery systems.	[115]
RAPSIM	University of Murdoch, Australia.	This is simulation software and is used to select hybrid PV–wind–diesel–battery systems.	[116]
SOMES	Utrecht University, The Netherlands.	This software can simulate the performance of renewable energy systems.	[117]
SOLSIM	Fachhochschule Konstanz, Germany	This model was developed for photovoltaic panels, wind turbines, diesel generators, and batteries.	[118]

6. Scope of Hydrogen to Meet the Net-Zero Emission Target

Hydrogen fuel production from hybrid renewable energy can meet the COP-26 Paris summit target by 2050, in using the technologies that produce net-zero greenhouse gas emissions. However, a limited number of studies on hybrid renewable energy systems consisting of solar and wind for producing hydrogen precisely predict the scope of utilising this energy. There is virtually no stand-alone hybrid system yet available for hydrogen production in remote locations. A fuel cell, an electrolyser, and other devices provide an opportunity to produce hydrogen energy and convert it to electrical energy as required. Hydrogen as electrolyser output during times of higher power production is stored in a tank and then utilised by the fuel cell during periods of low output from wind turbines and PV panels. However, the hydrogen storage system requires novel techniques to increase system resilience while minimising storage and transportation concerns.

An efficient energy storage system helps to overcome the intermittent nature of renewable energy systems; however, there are a very limited number of studies available on integrating hybrid renewable energy sources for hydrogen production. The deciding variable also includes the system's component size. The study identified useful applications to determine the ideal size for each component of hybrid renewable energy integrated with hydrogen production, which is a significant advancement over previous work. A very limited amount of information is available on the simulation and optimisation of green hydrogen production. Furthermore, no study has been conducted on a regenerative solar–wind–hydrogen, grid-independent hybrid system to ensure zero emission.

7. Concluding Remarks

The study concluded that green hydrogen has substantial potential as future fuel to meet the energy demand and net-zero emission target. The solar–wind hybrid power system would ensure the necessary power for producing hydrogen as an energy carrier without causing environmental hazards. Using these abundantly available renewable energy resources can reduce the dependency on fossil fuels and providing zero-emission energy would reduce carbon density and toxicity, benefiting the environment. The study also investigated the state-of-the-art applications of green hydrogen based on their technological readiness and practicality. This category includes renewable hydrogen energy storage and production technologies and stationary applications such as fuel cell power generators. Further investigation of the remote locations is recommended for hydrogen production from green energy sources.

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