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Review

Revolution in Renewables: Integration of Green Hydrogen for a Sustainable Future

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Abstract: In recent years, global efforts towards a future with sustainable energy have intensified the development of renewable energy sources (RESs) such as offshore wind, solar photovoltaics (PVs), hydro, and geothermal. Concurrently, green hydrogen, produced via water electrolysis using these RESs, has been recognized as a promising solution to decarbonizing traditionally hard-to-abate sectors. Furthermore, hydrogen storage provides a long-duration energy storage approach to managing the intermittency of RESs, which ensures a reliable and stable electricity supply and supports electric grid operations with ancillary services like frequency and voltage regulation. Despite significant progress, the hydrogen economy remains nascent, with ongoing developments and persistent uncertainties in economic, technological, and regulatory aspects. This paper provides a comprehensive review of the green hydrogen value chain, encompassing production, transportation logistics, storage methodologies, and end-use applications, while identifying key research gaps. Particular emphasis is placed on the integration of green hydrogen into both grid-connected and islanded systems, with a focus on operational strategies to enhance grid resilience and efficiency over both the long and short terms. Moreover, this paper draws on global case studies from pioneering green hydrogen projects to inform strategies that can accelerate the adoption and large-scale deployment of green hydrogen technologies across diverse sectors and geographies.

Keywords: electrolysis; green hydrogen; grid-forming control; hydrogen storage; offshore wind; renewable energy source; solar photovoltaic

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1. Introduction

The pressing challenges of global warming, air pollution resulting from fossil fuels, and the depletion of these non-renewable energy sources are driving a global shift towards adopting renewable energy sources (RESs), such as solar photovoltaics (PVs), hydro, geothermal, and wind. The Paris Agreement of 2016, which aims to keep global temperature rises well below 2 °C and ideally at 1.5 °C, represents a pivotal international effort in this shift [1]. It calls for a 45% reduction in emissions by 2030 and achieving net zero by 2050. Since then, there has been substantial growth in RESs. In 2023, global renewable capacity additions surged by nearly 50% compared to the previous year, reaching about 510 GW and marking the fastest growth in two decades [2]. Remarkably, the European Union (EU), the United States of America (USA), and Brazil recorded unprecedented increases. China's investment in solar and wind is part of its strategy to peak emissions before 2030 and reach carbon neutrality by 2060 [3]. In the USA, initiatives aimed at a net-zero electric grid by 2035 led to the approval of over 11 GW of wind, solar, and geothermal projects on public lands [4] and a bold goal to deploy 30 GW of offshore wind by 2030 [5]. The EU, under the revised Renewable Energy Directive [6], raised its 2030 renewable energy target to at least 42.5%. In 2023 alone, the EU added 56 GW of solar energy capacity, a 40% increase from the previous year. Germany contributed notably to this growth with 14.1 GW. The EU also saw an increase in its wind energy capacity, notably in Northern Europe. In India, the renewable capacity hit 180.79 GW by 2023, with a goal of 500 GW by 2030, including 30 GW from offshore wind [7].

Despite these energy transformation advances, the challenge remains significant due to the intermittent nature and geographical dependencies of RESs. This intermittency necessitates robust storage solutions to ensure energy reliability, dispatchability, and grid stability [8]. Albeit crucial, battery energy storage systems (BESSs) are limited in capacity and scalability and may lead to the curtailment of renewable electricity when production exceeds the storage and transmission capabilities of the electric grid. Furthermore, the geopolitical tensions exemplified by the Russia–Ukraine War highlight the critical importance of energy security. In this context, hydrogen, especially green hydrogen produced through the electrolysis of water using domestic renewable electricity, emerges as a promising alternative. With a higher heating value (HHV) of 141.8 kJ/g and a lower heating value (LHV) of 120 kJ/g [9], hydrogen is not only energy-dense but also versatile enough to serve various sectors, including power generation, aviation, and transportation [10]. Furthermore, hydrogen extends its utility beyond fuels to being a vital chemical feedstock in various industrial processes [11].

Hydrogen can be produced through several methods, both traditional and innovative. Traditional fossil fuel-based thermal processes include steam reforming (SR) [12], partial oxidation (POX) [13], and auto-thermal reforming (ATR) [14], which primarily produce what is known as gray hydrogen. In addition, coal gasification produces brown hydrogen, another carbon-intensive form [15]. Although prevalent, these methods contribute significantly to carbon emissions and pose environmental challenges. To mitigate emissions, blue hydrogen utilizes carbon capture and storage (CCS) technologies alongside traditional methods, which enhances the environmental profile of hydrogen production. While both green hydrogen and blue hydrogen are considered forms of clean hydrogen, green hydrogen, produced through water electrolysis, along with biomass-based methods such as gasification, POX, SR, and dark fermentation, offers more sustainable pathways [16]. Advanced techniques like solar thermal and thermochemical water splitting [17], alongside photoelectrochemical methods [18], also provide renewable alternatives to green hydrogen production. However, electrolysis distinguishes itself by directly harnessing intermittent RESs, which offer enhanced operational flexibility and produce high-purity hydrogen in a scalable and efficient manner. These advantages position water electrolysis as a key technology for integrating RESs into the electric grid, leading toward a sustainable energy future by providing a viable long-term solution to the storage and flexible dispatch of RESs. Nevertheless, water electrolysis faces challenges due to its high energy consumption and associated costs. Its efficiency is still relatively low, and large-scale deployment can strain water resources and require significant infrastructure investment. Furthermore, the intermittent nature of RESs used for electrolysis can pose challenges for continuous hydrogen production. Additionally, electrolyzer durability and maintenance requirements contribute to operational costs. To overcome these challenges, more innovative technological and engineering solutions are needed, such as advanced electrolysis technologies, improved water management systems, and novel hydrogen production methods.

In the current evolving energy landscape, the decreasing costs of renewable energy production significantly boost the viability of green hydrogen, making it an increasingly economical option for power generation in many regions. This cost reduction enhances the potential for RES-rich countries to produce green hydrogen competitively, supporting domestic industries and fostering export opportunities. National strategies play a key role in promoting this shift. For instance, the USA has unveiled its National Clean Hydrogen Strategy and Roadmap [19], aiming to achieve an annual production of 10 million metric tons (MMT) of clean hydrogen by 2030, 20 MMT by 2040, and 50 MMT by 2050. Additionally, it has set an ambitious "1 1 1" price goal to cut clean hydrogen costs by 80% to USD 1 per kilogram within a decade. China and India have also set ambitious production targets for clean hydrogen [20,21]. Similarly, Germany aims to build a 5 GW green hydrogen capacity by 2030, with plans to double this by 2040 [22], while Japan aims to ramp up its annual hydrogen and ammonia production to 3 MMT by 2030 and further increase it to 12 MMT by 2040 and 20 MMT by 2050 [23].

Both government initiatives and private sector investments are driving the expansion of green hydrogen, establishing it as a sustainable alternative to fossil fuels. However, the transition to a green hydrogen economy faces multiple challenges, including economic, technological, regulatory, and grid integration obstacles. The major cost disparities between green hydrogen and conventional fossil fuels are mainly due to the immature technologies in hydrogen generation and storage, as well as the high long-haul transport costs. Limited infrastructure and regulatory uncertainties further increase its operating expenses (OpEx) and complicate market development, while the need for transparent pricing and contractual standards remains unmet. Technological advancements in hydrogen production and storage are crucial for improving energy efficiency and scalability. Uncertainties also remain regarding the techno-economics of hydrogen facilities, the adoption rate of hydrogen technology, and its social acceptance. Despite these challenges, the strategic importance of green hydrogen in future energy systems continues to be recognized. To help effectively integrate this versatile energy carrier into the electric grid, coordination strategies must be developed to address the intermittency of RESs and the fluctuations in load demands [24]. Both effective long-term and short-term strategies are essential for successful green hydrogen development. Long-term planning and operational strategies ensure sustainability and scalability, while short-term control and power management strategies are crucial for day-to-day operations. These strategies are vital for the seamless operation of RESs, electrolyzers, and fuel cells [25], ensuring efficient hydrogen conversion and the safe integration of production with purification and storage systems [26]. The purpose of this paper is to provide a comprehensive review of the green hydrogen value chain, including production, transportation, storage, and applications. It also focuses on the integration of green hydrogen into electric grids and operational strategies for enhancing resilience and efficiency. Additionally, it draws on global case studies to inform strategies for accelerating the adoption of green hydrogen technologies.

The remainder of this paper is organized as follows: Section 2 outlines the technological foundations for developing a green hydrogen economy. Section 3 explores the evolving market dynamics and highlights several ongoing or operational clean hydrogen pilot projects. The long-term and short-term operational strategies for green hydrogen systems are reviewed in Section 4 and Section 5, respectively. Finally, Section 6 concludes the paper with recommendations and potential future research directions.

2. Green Hydrogen Foundations

2.1. Green Hydrogen Value Chain

The green hydrogen value chain represents a transformative solution for creating sustainable energy systems, which encompasses several major stages: production, storage, transport, and end uses of hydrogen. Together, these stages form a critical pathway for the development and adoption of this clean energy carrier, enabling the transition to a low-carbon economy. Each stage plays a crucial role in the development and adoption of this clean energy carrier. The effective integration of these stages is essential for achieving a reliable, efficient, and cost-effective green hydrogen value chain. As the value chain continues to evolve, it is expected to unlock new opportunities for economic growth, job creation, and environmental sustainability. Furthermore, the successful deployment of green hydrogen can help mitigate climate change, improve air quality, and enhance energy security. Diagrams illustrating the value chain are presented below in Figure 1, with variations due to different placements of electrolyzers. The technologies related to each stage will be elaborated in the following subsections, which provide a comprehensive understanding of the current state of the art.

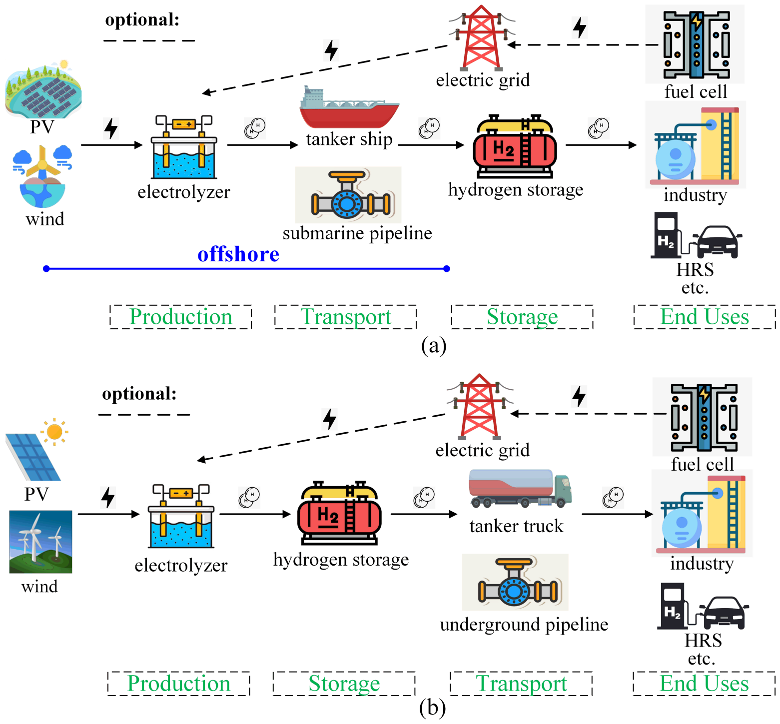

Figure 1. Structural illustrations of the typical green hydrogen value chain highlighting key stages and electrolyzer locations (the purification stage is not shown as it is optional). (**a**) When electrolyzers are offshore; (**b**) when electrolyzers are onshore.

2.1.1. Production through Electrolysis

Water electrolysis utilizes an external DC voltage to split water molecules into hydrogen and oxygen gases through electrochemical reactions at porous conductive electrodes [27]. Oxygen is produced at the anode (oxygen evolution reaction, OER) and hydrogen at the cathode (hydrogen evolution reaction, HER), facilitated by ion migration in an electrolyte containing diluted acids, bases, or salts. Electrolyzers often consist of multiple cells configured into a stack. The theoretical terminal voltage (reversible voltage, v_{rev}) of a cell is derived from the Gibbs free energy change (ΔG) and is represented by the Nernst equation:

$$v_{rev} = \frac{\Delta G}{n \times F} = \frac{\Delta H - T \times \Delta S}{n \times F}, \tag{1}$$

where ΔH is the enthalpy change (J/mol), T is the temperature (K), ΔS is the entropy change (J/(mol·K)), n is the number of electrons transferred per molecule of water (two in this case), and F is the Faraday constant (96,485 C/mol). Under standard conditions (25 °C, 1 atm), the theoretical reversible voltage is 1.23 V. Equation (1) shows that as the temperature increases, the reversible voltage decreases. In addition, when pressure is accounted for, (1) is modified as

$$v_{rev} = \frac{\Delta H - T \times \Delta S}{n \times F} - \frac{R \times T}{n \times F} \ln\left(\frac{p_{H_2} \times \sqrt{p_{O_2}}}{p_{H_2O}}\right), \tag{2}$$

where R is the universal gas constant (8.3145 J/(mol · K)) and p_{H_2}, p_{O_2}, and p_{H_2O} are the partial pressures (atm) of hydrogen, oxygen, and water vapor, respectively. The thermoneutral voltage (v_{tn}), where water electrolysis switches from endothermic to exothermic conditions, is 1.48 V [28]. Operational voltages often exceed v_{tn} due to activation, ohmic, and concentration overpotentials [29], which can be mitigated through advanced materials and cell design optimizations [30,31].

The production rates (mol/s) of hydrogen and oxygen molecules during water electrolysis, $\dot{n}_{\mathrm{H}_2}$ and $\dot{n}_{\mathrm{O}_2}$, are directly proportional to the current density j and Faradaic efficiency η_F, computed as follows:

$$\dot{n}_{H_2} = \frac{j \times A \times \eta_F}{n \times F}, \tag{3}$$

$$\dot{n}_{O_2} = \frac{j \times A \times \eta_F}{2 \times n \times F}, \tag{4}$$

where A is the electrode's active surface area. η_F accounts for the fact that not all of the electric current contributes to the desired reactions due to overpotentials and other losses.

Alkaline water electrolysis (AEL) is a mature and cost-effective technology suited for large-scale hydrogen production [32]. It provides a long service life and high reliability [33]. Nonetheless, AEL suffers from high internal resistance that diminishes efficiency [34] and operates more efficiently between 40% and 100% of its rated load, challenging its adaptation to variable RES power outputs [33]. Additionally, pressure differentials in AEL can cause gas diffusion issues [35], which affect gas purity. Furthermore, the bulky design makes the system less portable. Maintaining a balanced electrolyte concentration is critical for its optimal performance.

Acidic aqueous solutions enable the use of proton exchange membrane (PEM)-based electrolysis, characterized by high voltage efficiency and high gas purity [36]. PEMs, made from materials such as solid polysulfonated and perfluorosulfonic acid membranes, facilitate proton transport in hydrated form. PEMs have several advantages, including lower gas permeability, high proton conductivity, and the ability to withstand high-pressure differentials. Their thin structure reduces their dimensions, working voltages, and energy losses. Moreover, water serves as both a reactant and a coolant, which eliminates the need for a separate cooling system. PEM water electrolysis also features high current density, fast response, small footprint, and lower operation temperatures [37]. Different catalysts are employed for OER and HER, with noble metals like iridium and ruthenium dioxide enhancing catalytic performance but raising costs [38,39]. The need for high-purity water and the challenges associated with membrane degradation also drive up OpEx in PEM systems. In addition, these systems are susceptible to corrosion.

Solid oxide electrolyzer cells (SOECs) use yttria-stabilized zirconia to conduct oxygen ions at high temperatures, which enables efficient energy conversion [40]. SOECs can utilize steam or impure water; this flexibility is advantageous for decarbonization. Some SOEC systems can even operate in a bidirectional reversible mode, acting as a fuel cell when necessary. However, challenges include high capital expenditures (CapExs), performance degradation over time, and accelerated stack degradation at high temperatures and current densities [41,42]. Protective coatings on metal-supported SOECs can greatly improve performance and durability [43]. Ongoing research efforts aim to optimize electrode microstructures, develop more stable materials [40], and implement cell-conditioning protocols [44].

Anion exchange membrane (AEM) electrolysis is another promising technology that combines features of AEL and PEM. AEM electrolysis uses economical non-noble metal catalysts and less expensive membranes [45]. It also has the potential to offer comparable performance to established technologies but remains in the developmental stage [46]. Challenges include cost-effectiveness, material stability, and the need for high-purity water [47].

In summary, each electrolysis method has its own advantages and disadvantages. A detailed comparison of their typical technical specifications is provided in Table 1. Direct seawater electrolysis also holds promise for sustainable hydrogen production. However, it faces challenges such as detrimental chlorine chemistry, sluggish kinetics, impurities, and electrode corrosion, all of which can reduce its efficiency and stability [48,49]. Efforts have been made to develop corrosion-resistant electrocatalysts and more stable electrolyzer configurations [50]. Moreover, the performance of electrolyzers is significantly impacted by the balance of plants (BoP), which includes auxiliary systems for cooling, safety, and hydrogen handling.

Table 1. Comparison of different electrolysis technologies.

	AEL	PEM	SOEC	AEM
Technological readiness	Mature	Commercialized	Demonstration	Prototype
OER	$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$	$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$	$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
HER	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Efficiency (%)	50–78	50–83	70–90	40–70
Current density (A/cm^2)	0.2–0.8	1–4	0.2–1	0.2–2
Productivity index (kg H_2/kWh)	0.8–1.2	1.2–1.8	1.8–2.5	0.8–1.5
Voltage ranges (V)	1.4–3.0	1.4–2.5	1.0–1.5	1.4–2.0
Response time at stand-by	seconds	milliseconds	minutes	seconds
Operating temperature (°C)	60–90	50–80	700–1000	40–60
Cell pressure (bar)	$\leq$30	$\leq$100	1–25	$\leq$35
Hydrogen purity (%)	99.5–99.9998	99.9–99.9999	99.9–99.999	99.9–99.9999
Stack lifetime (hour)	60,000–100,000	20,000–80,000	$<$20,000	$>$30,000
Cost (U.S.$/kW)	500–1400	1100–1800	2800–5600	N/A

2.1.2. Purification

Hydrogen purification can play an important role in the green hydrogen value chain, although its necessity varies depending on the intended application and the quality of hydrogen produced. While water electrolysis typically yields high-purity hydrogen, further purification may be required to meet specific purity standards for safe and effective use in various applications. For example, controlling oxygen levels is vital for safety reasons [51].

One commonly employed method is pressure swing adsorption (PSA) [52]. In this physical technique, a hydrogen gas mixture is passed through adsorption beds filled with materials like activated carbon, zeolites, or metal–organic frameworks (MOFs). These adsorbents selectively capture impurities such as water vapor, oxygen, and electrolytes while allowing hydrogen to pass through. By alternating between high and low pressures, the adsorbents are regenerated, which helps in yielding high-purity hydrogen. Another method is cryogenic distillation, which cools the gas mixture to extremely low temperatures, causing impurities with higher boiling points than hydrogen, such as water vapor and oxygen, to condense and separate. While effective, this process is energy-intensive and costly. However, it produces hydrogen that is readily liquefiable, which is advantageous for large industrial plants [53]. Membrane separation [54] is another physical method that employs selective membranes, such as palladium-based membranes or carbon molecular sieve membranes, allowing hydrogen to pass while blocking impurities. This method separates gases based on their differences in permeability and has the potential to be more environmentally friendly and economically viable than other technologies, although it is still developing. Catalytic purification [55] is a chemical method, which entails passing the hydrogen gas mixture over a catalyst bed, typically containing noble metals such as platinum or palladium. The catalyst selectively oxidizes impurities, converting them into easily removable compounds while leaving the hydrogen unaffected.

2.1.3. Storage

The pressure–temperature (P-T) phase diagram of hydrogen, as shown in Figure 2, delineates the stability regions of solid, liquid, and gaseous hydrogen under various pressure and temperature conditions. At low temperatures and high pressures, hydrogen is solid and can be divided into sub-phases such as orthorhombic, parahydrogen, and orthohydrogen [56]. With increasing temperature or decreasing pressure, hydrogen transitions to a narrow liquid state and then a gas. The triple point, where solid, liquid, and gas phases coexist in equilibrium, is at approximately 13.8 K and 7.04 kPa. The boiling point is 20.28 K at atmospheric pressure, and the critical point is at 33 K and 1.3 MPa. Given hydrogen's high gravimetric (120 MJ/kg) and low volumetric (0.01079 MJ/L) energy densities [57], increasing storage density is crucial. Storage methods include compressed gas, liquid, cryo-compression, physical and chemical adsorption, chemical carriers, and underground storage in depleted gas reservoirs and saline aquifers [58–60].

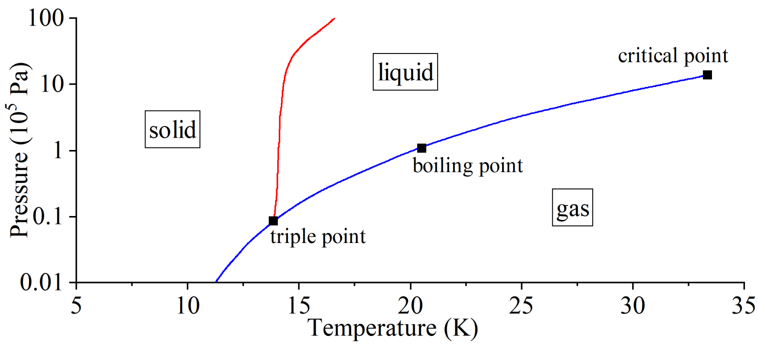

Figure 2. P-T phase diagram of hydrogen [61].

Key factors to consider when selecting storage methods include storage period, scale, mobility, safety, temperature, pressure, physical state, volumetric and gravimetric densities, costs, available technology, and resources [62]. Compressed gas storage is the most common and mature hydrogen storage method. Hydrogen is compressed to 350–700 bar and stored in high-pressure steel or composite fiber tanks. This method is simple, reliable, and suitable for various applications, including fuel cell vehicles (FCVs) and stationary storage, but has drawbacks such as low storage density and material embrittlement [63]. Liquid hydrogen storage involves cooling hydrogen gas below its boiling point and storing it in insulated cryogenic tanks. This method offers higher storage density than compressed gas and is ideal for large-scale, long-distance transportation and aerospace applications. However, liquefaction consumes up to 30–40% of the hydrogen's energy content to maintain low temperatures [64]. Cryo-compressed hydrogen storage combines the benefits of compressed gas and liquid storage by cooling hydrogen to around –200 °C and compressing it to 200–350 bar [65]. This method achieves higher storage densities than compressed gas storage while operating at higher temperatures than liquid hydrogen storage, reducing energy use and boil-off losses. Adsorption-based storage exploits the adhesion of hydrogen molecules to high-surface-area solid materials, such as MOFs, activated carbon, or carbon nanotubes. Adsorption efficiency has been improved with nanostructured materials like graphene [66] and copper-functionalized carbons [67]. However, further research is needed to improve the storage capacity, kinetics, and cost-effectiveness. Chemical hydrogen storage uses the reversible bonding of hydrogen to a carrier, which can be liquid organic (LOHCs, e.g., methylcyclohexane) [68] or solid-state (e.g., metal hydrides like magnesium hydride) [69]. These methods offer high storage densities, safety, and ease of handling but often require high temperatures or expensive catalysts for hydrogen release and may have a limited cycle life. Inorganic nonmetal hydrides such as ammonia and boron nitrogen hydrides are formed from specific reactants and hydrogen and decomposed when needed [65]. However, this process is inefficient and uneconomical due to strong chemical bonding. In addition, ammonia is highly caustic and toxic. Underground hydrogen storage utilizes geological formations, such as depleted natural gas reservoirs or saline aquifers, to store vast quantities of hydrogen. This method is particularly suitable for long-term, seasonal storage and can help balance supply and demand in a future hydrogen economy [70].

Nevertheless, it requires careful site selection, monitoring, and infrastructure development for safety and integrity in hydrogen storage.

2.1.4. Transport

The transport of hydrogen is closely related to how it is stored. The choice of transportation method depends on the scale of production, distance to end-users, existing infrastructure, and specific end-use requirements. Green hydrogen can be transported as compressed hydrogen or liquid hydrogen or via green ammonia, methanol, LOHCs, and other hydrogen carriers [71]. Compressed hydrogen gas is primarily transported by road in tube trailers or multi-element gas containers (MEGCs). Repurposing natural gas pipelines for hydrogen blending or pure hydrogen can often be more economical than building new hydrogen pipelines. However, material compatibility due to different properties between hydrogen and natural gas is a major concern [72]. Pipeline diameter affects transport efficiency due to pressure drop. Larger diameters require less compression but are more expensive, while smaller diameters necessitate additional compressors due to increased pressure drop [73]. Liquid hydrogen, with its higher storage density, is efficient to transport in cryogenic liquid tankers by road, rail, or sea. However, the liquefaction process is energy-intensive and requires specialized equipment to minimize boil-off losses. Hydrogen carriers, such as green ammonia, methanol, and LOHCs, can leverage existing liquid transport infrastructure efficiently and cost-effectively [74,75]. Green ammonia and methanol are synthesized from green hydrogen with nitrogen and captured carbon dioxide, respectively. While methanol releases carbon dioxide upon reformation, affecting its overall carbon footprint, LOHCs, which are stable under ambient conditions, store hydrogen through chemical absorption and release it via a dehydrogenation process requiring heat [76]. Green ammonia and methanol can be directly used at their destinations, but LOHCs require a closed-loop system for rehydrogenation, which is energy-intensive and has potential toxicity challenges. Moreover, the relative immaturity of LOHC technology currently limits its immediate large-scale application [77].

Distance is another crucial criterion for transport selection. A report [78] by the International Renewable Energy Agency (IRENA) compares ammonia, liquid hydrogen, LOHCs, and pipelines, and identifies ammonia by ship and hydrogen pipelines as the most cost-effective options. Another report [79] published by the Joint Research Center (JRC) further considers methanol as a hydrogen carrier and compressed hydrogen by ship. JRC suggests compressed hydrogen pipelines for distances under 6500 km, liquid hydrogen shipping for 6500–10,000 km, and LOHCs for over 10,000 km. Compressed hydrogen transport via ship is an option for distances up to 3000 km when pipelines are not feasible. These evaluations help guide the selection of appropriate hydrogen transport technologies over varying distances, though practical implementation at scale remains to be fully developed.

2.1.5. End Uses

Hydrogen serves as a versatile energy carrier and promotes the decarbonization of challenging sectors. Figure 3 shows hydrogen consumption by sector in 2020 globally [80] and in the USA [81]. It is evident that the industry sector represents the primary consumer of hydrogen, where hydrogen is essential in oil refining, ammonia and methanol production, and steel manufacturing [82]. In oil refining, hydrogen is used to remove sulfur and upgrade heavy oils. Notably, ammonia production, which uses the Haber–Bosch process to combine atmospheric nitrogen with hydrogen [83], dominates global hydrogen consumption. During methanol production, hydrogen is combined with carbon monoxide. Furthermore, in the steel industry, hydrogen acts as a reducing agent in the direct reduction of iron (DRI) processes [84], providing a cleaner alternative to traditional coal-based methods.

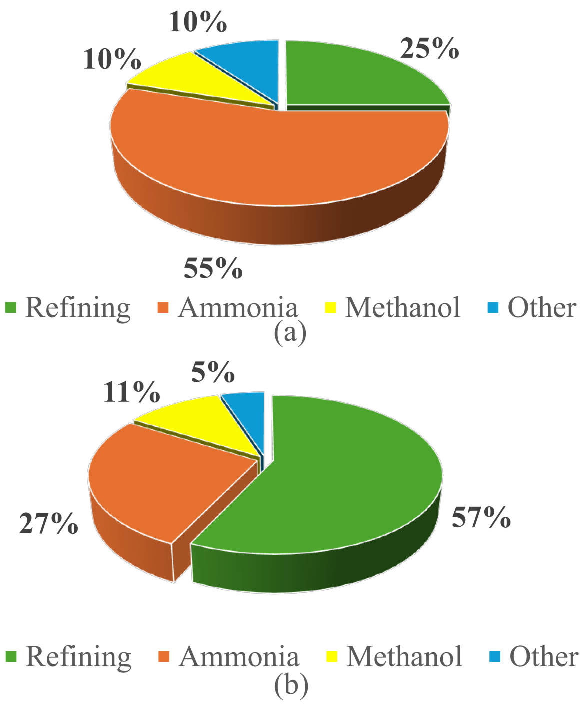

Figure 3. Hydrogen consumption by end use in 2020. (**a**) Hydrogen consumption in the world. (**b**) Hydrogen consumption in the USA.

Other sectors, such as transportation, building, and electricity generation, are emerging as new end users of hydrogen. In transportation, hydrogen FCVs, which convert hydrogen into electricity, producing only water as a byproduct, are gaining traction as a sustainable alternative to conventional fossil-fuel-powered vehicles [85]. Compared to battery electric vehicles (BEVs), FCVs offer longer driving ranges and shorter refueling times, making them suitable for long-haul buses and heavy-duty trucks. Additionally, hydrogen is being adopted for larger transport forms such as trains, ships, and airplanes. These applications demonstrate hydrogen's adaptability and potential for diverse transportation applications [86]. Driven by the global buildout of hydrogen refueling stations (HRSs), the demand for it in transportation is expected to surpass industrial use by 2050 [87]. In the building sector, hydrogen technologies can provide combined heat and power (CHP) systems to enhance overall energy efficiency [88] and are being explored for blending into natural gas networks to reduce the carbon footprint of heating systems [89]. For electricity generation, both hydrogen-fueled turbines and fuel cells provide flexible and dispatchable power. Turbines achieve thermodynamic efficiencies of 30–40% in simple cycles and potentially over 60% in combined cycles [90]. Furthermore, existing natural gas turbines could be retrofitted to run on hydrogen, leveraging established infrastructure for a smoother transition to cleaner energy technologies. Fuel cells, though generally more costly, can reach electrical efficiencies of 40–60% and even higher in cogeneration scenarios [91]. However, managing nitrogen oxide (NO_x) emissions during high-temperature combustion is critical to meeting environmental standards without compromising performance [92]. Innovative applications, such as integrating green hydrogen production with bitcoin mining [93], are also explored. Such integration could boost renewable energy deployment and mitigate climate change by reinvesting the economic gains from green hydrogen and bitcoin mining into further renewable energy projects.

2.2. RESs for Green Hydrogen Production

RESs are vital for supplying the electricity required to power electrolyzers for green hydrogen production. This subsection reviews two major types of RESs suitable for this purpose: wind and solar PV systems.

Wind turbines convert the kinetic energy of wind into mechanical power using rotor blades. They generally operate in maximum power point tracking (MPPT) mode to maximize energy extraction. For grid support purposes, turbines can also operate in a deloading mode [94]. Specifically, offshore wind farms are favored for their higher-capacity factors due to stronger and more consistent wind resources. Offshore wind farms typically utilize larger turbines in marine environments, which achieve economies of scale while minimizing impacts on ocean dynamics [95]. However, wake effects can decrease the efficiency of downstream turbines by 20% to 45% [96], which may be mitigated through optimized farm layout [97], wake steering via yaw control [98], and high-fidelity computational fluid dynamics (CFD) simulations [99].

The primary distinction in different offshore wind technologies lies in their supporting structures: fixed-bottom structures and floating platforms [100]. Fixed-bottom structures, such as monopiles and gravity-based foundations, are suitable for shallower waters (up to 40 m deep), whereas floating structures, such as spar-buoys and semi-submersibles, allow deployment in deeper waters [101]. To harness offshore wind for green hydrogen production, three major configurations are employed [102]. Centralized onshore electrolysis utilizes a floating offshore substation to capture electrical power from wind farms and transmit it through power export cables such as high-voltage alternating current (HVAC), high-voltage direct current (HVDC), and low-frequency alternating current (LFAC) or fractional-frequency alternating current (FFAC) systems [103,104]. This configuration supports flexibility, enabling direct electricity supply to the grid or hydrogen production for energy storage or direct industry use. However, it incurs significantly higher transmission costs, up to eight times more than hydrogen pipelines [105], and experiences higher energy losses in cables (3.5% per 1000 km for HVDC and 6.7% per 1000 km for HVAC), compared to less than 1% for hydrogen pipelines over the same distance [106]. Centralized offshore electrolysis employs large-scale electrolyzers on offshore platforms, using desalinated seawater and transmitting hydrogen via dedicated pipelines. This setup is cost-effective and energy-efficient, enhancing electrolysis capacity and production scalability. However, it poses risks to marine life from desalination byproducts. Decentralized offshore electrolysis generates hydrogen at each wind turbine, where electrolyzers and desalination units are integrated directly. Such a modularized configuration simplifies management during failure events. Semi-submersible platforms are particularly suitable for this approach, although it faces challenges in scalability and increased OpEx [107].

Solar PV systems convert sunlight directly into electricity through semiconducting materials and are widely used from residential to industrial scales. Solar PV systems are also traditionally controlled in MPPT mode for maximum energy harvesting [108]. However, with the increasing penetration of solar PVs, flexible active power control is implemented to ensure their smooth and smart integration into the electric grid [109]. New developments in solar technology include offshore PV installations [110], which could be integrated with hydrogen production systems, similar to offshore wind systems.

3. Evolving Market Dynamics

While the market for green hydrogen is still in its nascent stage, there is already a growing worldwide interest. However, the presence of market uncertainties could deter private investments due to a critical dilemma. The need for economies of scale to achieve economic viability is evident, yet uncertainty surrounding green hydrogen's adoption may hinder investment in its production and transport infrastructure. Moreover, the limited availability and higher costs of green hydrogen, compared to carbon-intensive alternatives, are likely to deter potential users. In addition, social acceptance is also needed to support visions for the hydrogen economy [111]. It is vital for governments to factor in socio-environmental impacts and public perception in order to enact policies that enhance viability for stakeholders, promote price transparency, and standardize contracts.

According to HyResource [112], 55 major countries and regions have initiated hydrogen strategies or guidelines aiming for significant progress by 2030 and 2050, with the upcoming decade considered pivotal for establishing a hydrogen economy. In 2022, global hydrogen use was 95 MMT, and the International Energy Agency (IEA) predicts a surge to over 150 MMT by 2030 in a net-zero scenario [113]. Although the global installed electrolysis capacity reached 1.1 GW in 2023 [114], only 4% of total hydrogen production was green [115], which indicates a substantial supply–demand gap. Currently, the cost of green hydrogen, at approximately USD 6.4/kg, is two to three times higher than that of gray or blue hydrogen [116], largely due to high renewable electricity costs, which make up 80% of the production expenses [117]. However, these costs are expected to decline as renewable technologies advance. In addition, improving electrolyzer efficiency and reducing catalyst costs are also key to affordability. Moreover, demand for critical raw materials like rare earths is substantial across various electrolysis technologies. Technology diversification can protect against disruption in critical material supply. The existing gaps in hydrogen transport and storage infrastructure, coupled with the challenges of scaling up production, necessitate significant public investment and the formation of industrial clusters to reduce costs and foster infrastructure development. Pilot projects and streamlined permitting processes are also essential to increase market development and attract private investment. Currently, several clean hydrogen pilot projects are either under development or in early operation, with some of them detailed in Table 2. These projects serve as real-world testbeds for new technologies and methodologies in green hydrogen production, storage, and transportation. By successfully demonstrating the feasibility and efficiency of advanced electrolysis technologies, improved water management systems, and novel hydrogen production methods, these projects help validate technological innovations. By analyzing the challenges encountered in these initial projects, future initiatives can better plan for infrastructure needs, reducing both costs and implementation time. Moreover, they can inform policy and regulatory decisions with critical operational data. Looking beyond 2030, the expansion of the green hydrogen market is expected to drive down costs and enhance market liquidity through technological advancements and economies of scale, which ultimately reduce reliance on public subsidies.

Targeted sectors, main goals, and transition strategies vary significantly across countries, shaped by each country's energy structure, demand forecasts, and resources [118]. The development of domestic markets is crucial, but international trade will be key to addressing mismatches between hydrogen supply and demand. While pure hydrogen is typically sourced domestically or from nearby regions, hydrogen derivatives, which are easier to transport over long distances, are suitable for global trade. The global landscape for green hydrogen production and trade is evolving, with countries like South Korea, Japan, and Germany, which face high demands but have limited renewable energy potential, planning to import substantial amounts of green hydrogen to meet their energy needs [119]. These countries are identified as major importers due to their ambitious national hydrogen strategies and goals to decarbonize their energy systems. Conversely, countries rich in RESs like Australia and North African nations are emerging as potential green hydrogen exporters [120]. In regions such as Chile, where freshwater is scarce, using seawater or wastewater for electrolysis presents a sustainable solution [121]. As the domestic hydrogen market ramps up, China is poised to become a leading importer, while India's slower uptake indicates it may not meet its hydrogen needs domestically, according to Deloitte's predictions [122]. Conversely, the USA, endowed with substantial resources and industrial capabilities, is likely to meet most of its demand by 2030. After 2030, the USA will transition to an exporter, aligning with its national strategy [19]. The structure of the hydrogen market in turn profoundly affects international energy policies and global trade dynamics. Centralized markets focus on mass-market solutions and cost efficiencies at a global scale, but decentralized markets prioritize flexibility, local needs, and the resilience of supply chains. Furthermore, a centralized model could lead to new trade routes and alliances, similar to the traditional oil economy, while a decentralized model promotes a more multi-polar and resilient energy landscape. In a centralized scenario, countries strategically located between major hydrogen exporters and importers could become key distributors, leveraging their geographic advantages to facilitate trade. However, the specific roles of distributors will evolve depending on how the market develops and matures.

Table 2. Overview of various clean hydrogen pilot projects.

Project Name	Capacity	Status	Country	Brief Description
NortH2 Project [123]	10 GW	Developing	Netherlands	Consortium with Shell, aims to produce 1 MMT of hydrogen annually using offshore wind.
H2Mare Project [124]	Not specified	Developing	Germany	32 partners, adding electrolyzers to wind turbines for green hydrogen, operational by 2025.
AquaVentus [125]	10 GW	Developing	Germany	Generates hydrogen using offshore wind for a European network, completion by 2035.
Murchison Renewable Hydrogen Project [126]	5 GW	Developing	Australia	Uses wind and solar for hydrogen, targets 2 MMT of ammonia by 2028.
Western Green Energy Hub (WGEH) [127]	50 GW	Developing	Australia	Integrates wind and solar for 3.5 MMT of hydrogen and 20 MMT of ammonia annually.
Beijing Jingneng Inner Mongolia [128]	5 GW	Operational	China	Utilizes wind and solar for 0.4–0.5 MMT hydrogen yearly.
NEOM Green Hydrogen Plant [129]	4 GW	Developing	Saudi Arabia	Combines solar and wind for daily production of 600 MMT hydrogen, operational by 2026.
Appalachian Hydrogen Hub (ARCH2) [130]	Not specified	Developing	USA	Uses natural gas for clean hydrogen, includes infrastructure for CO_2 storage.
Mid-Atlantic Hydrogen Hub (MACH2) [130]	Not specified	Developing	USA	Focuses on renewable hydrogen for decarbonization, reducing 1 MMT carbon per year.
California Hydrogen Hub (ARCHES) [130]	Not specified	Developing	USA	Produces hydrogen from renewables and biomass, reducing 2 MMT carbon annually.
Gulf Coast Hydrogen Hub (HyVelocity) [130]	Not specified	Developing	USA	Uses gas with carbon capture for hydrogen, aims to cut 7 MMT carbon yearly.
St. Gabriel Green Hydrogen Plant [131]	Not specified	Operational	USA	Plug Power and Olin Corp project, initially producing 15 MMT of hydrogen daily.
Calistoga Resiliency Center [132]	293 MWh	Developing	USA	The largest utility-scale green hydrogen energy storage project in the USA, designed to provide long-duration storage.

4. Long-Term Operational Strategies

Long-term operational strategies are crucial for green hydrogen integration to effectively allocate resources, comply with environmental and safety regulations, and meet sustainability goals amid evolving technologies and market dynamics. Green hydrogen production systems are primarily categorized into islanded and grid-connected configurations. An islanded system, also known as standalone or off-grid, operates independently from the external electric grid and utilizes RESs to produce hydrogen via water electrolysis. These systems are suitable for remote locations where grid connections are impractical or economically unfeasible. On the other hand, grid-connected systems enhance scalability and flexibility. They can utilize grid electricity when renewable outputs are insufficient and either feed excess renewable electricity back into the grid or convert stored hydrogen into electricity to provide critical support to the grid when needed.

Choosing between islanded or grid-connected systems during the system planning stage depends on multiple factors, such as the availability and variability of RESs, cost implications, technical challenges, environmental impacts, and regulatory and market conditions. Islanded systems rely heavily on local RESs and may face limitations due to peak demand constraints [133]. Conversely, grid-connected systems provide broader access to RESs, which can reduce costs such as the levelized cost of electricity (LCOE), LCOH, and carbon abatement cost (CAC) or increase the net present value (NPV) of the investment, as evidenced in various simulation-based studies [134–136]. Grid-connected systems also benefit from economies of scale and a more consistent energy supply, which can further lower costs. However, they must manage the variability of renewable electricity and integrate effectively with the gas network, a challenge compounded by price disparities between gas and electricity. A multi-variant comparative analysis [137] underscores the significance of regulatory and environmental factors in selecting system configurations. Market dynamics and stakeholder priorities are also critical, as they influence decisions based on hydrogen production costs and carbon emissions [138].

4.1. Long-Term Operational Strategies for Grid-Connected Hydrogen Systems

Long-term operational strategies for green hydrogen systems generally employ techno-economic studies, formulated as mathematical optimization problems with different objective functions. For grid-connected systems, cost minimization is a primary optimization objective. Reference [139] proposes a multi-stage stochastic programming model to optimize sequential planning and minimize NPV, ensuring robustness against system uncertainties. A bi-level multi-objective capacity optimization model for hydrogen-based multi-microgrid systems [140] aims to minimize the total annual cost (TAC), reduce annual carbon emissions, and enhance self-sufficiency. Furthermore, Ref. [141] projects significant cost reductions and efficiency improvements by 2030 and 2050 in the UK through scenario and sensitivity analyses, seeking to minimize the LCOH as offshore wind and electrolyzer technologies advance. Additionally, Ref. [142] aims to minimize electricity costs based on NPV, capital recovery factors, and total electricity demand. Meanwhile, Ref. [143] employs a multi-objective genetic algorithm to optimize the cost of electricity and operational efficiency. The planning model for an integrated electricity–hydrogen energy system [144] uses stochastic and robust optimization to manage generation-load uncertainties, which aims to minimize annual investment and OpEx. It also incorporates an N-1 contingency criterion for reliability.

Some studies also prioritize profit maximization in their strategic long-term operations. For instance, Ref. [145] focuses on maximizing annual profits through optimal sizing and the flexible operation of power-to-hydrogen (P2H) systems while enhancing wind power utilization and facilitating energy market arbitrage. Another study [146] utilizes mixed-integer linear programming (MILP) to maximize annual economic benefits. It concludes that hydrogen energy storage offers limited cost-effectiveness for single applications, such as bulk hydrogen sales or electricity regeneration using fuel cells. Instead, integrating grid services significantly increases its value, which could account for up to 76% of total benefits in the assessed case studies. Additionally, Ref. [147] develops optimal control strategies for a system that integrates an offshore wind farm with hydrogen storage. This system maximizes operational revenues, operates under power purchase agreements (PPAs), and interacts with electricity markets through a Markov decision process, which emphasizes the importance of hydrogen offtake agreements in supporting the energy transition. Finally, Ref. [148] uses mixed-integer nonlinear programming (MINLP) to optimize the size and operation of HRSs. This multi-scale approach seeks to maximize revenues through hydrogen sales and market participation, including energy arbitrage and frequency containment reserve (FCR) provision.

Reliability of energy supply is crucial for grid-connected green hydrogen systems, particularly when hydrogen is blended with natural gas. A reliability evaluation model for integrated electricity–gas systems (IEGSs) [149] utilizes a sequential Monte Carlo simulation to assess reliability and accounts for the temporal characteristics of RESs. Similarly, Ref. [150] examines the impacts of distributed hydrogen injections on system reliability, introducing new reliability indices and a multi-state model to evaluate gas adequacy and interchangeability under uncertainties. This research also develops a contingency management scheme to minimize load curtailments and gas interchangeability deviations during component failures. Beyond these model-based strategies, data-driven approaches are gaining traction. For instance, a study on a hydrogen/ammonia-based energy hub [151] employs a modified double deep Q-network (Double-DQN) for optimal scheduling, highlighting the profitability of the biomass-to-gas-to-power (B2X2P) pathway and the operational flexibility of the power-to-gas-to-power (P2X2P) pathway.

However, most existing research relies on centralized optimization, which may overlook the intricate interactions, sector coupling, and competitive relationships among stakeholders in grid-connected green hydrogen systems. Such optimization may struggle to balance the varied interests of all entities involved while maintaining information privacy. In contrast, distributed optimization proves more effective in coordinating multiple stakeholders. Paper [152] presents a data-driven, multi-objective, distributionally robust optimization model for a hydrogen-involved total renewable energy combined cooling, heating, and power (H-RE-CCHP) system. This model aims to minimize costs and carbon emissions while ensuring system resilience under source-load uncertainties.

Long-term operational strategies must manage numerous uncertainties. To effectively utilize hydrogen as a seasonal energy storage solution, it is essential to incorporate seasonal projections that reflect the inherent uncertainty in seasonal arbitrage and fluctuating RESs, which impact both hydrogen production and demand [153]. Uncertainties also arise from the technical characteristics and parameters of future system components. Traditional optimization methods such as heuristic, stochastic, and robust optimizations have limitations. Heuristic methods may yield sub-optimal solutions and lack generalizability, while stochastic optimization requires detailed knowledge of probability distributions and can be computationally intensive. Robust optimization often leads to conservative and costly outcomes and struggles with scalability issues. The effectiveness of these methods is highly constrained by the accuracy of uncertainty modeling and the underlying assumptions [154]. Advancements in data-driven optimization techniques, such as distributionally robust optimization and reinforcement learning, could leverage real-world data to better model uncertainties and adapt to changing conditions, thus reducing dependency on pre-defined uncertainty models. However, the success of these methods heavily relies on the quality and quantity of the available data. For example, RES datasets may not account for curtailed energy due to grid constraints, and forecast data often require validation [155]. Simplifications in studies, such as ignoring wake effects in offshore wind farms, can reduce optimization accuracy. Furthermore, essential planning data, such as freshwater supply, often lack completeness or granularity, which could be improved through data augmentation or interpolation, and by using proxy data such as rainfall patterns and reservoir levels. Moreover, commonly used economic metrics like LCOE, LCOH, CAC, and NPV may not fully capture the broader economic and environmental impacts, which can misrepresent the true costs and benefits of projects. NPV calculations, which are particularly sensitive to discount rates, might underestimate long-term risks and uncertainties. Additionally, few studies consider learning rates regarding technology costs and device deterioration factors in techno-economic studies, which could lead to inaccuracies in long-term optimization results.

4.2. Long-Term Operational Strategies for Islanded Hydrogen Systems

In islanded hydrogen systems, the relationship among stakeholders is typically more straightforward due to the absence of direct involvement from electric utilities and grid operators. However, this simplicity raises concerns about system reliability. To this end, Ref. [156] utilizes harmony search (HS) algorithms to optimize solar and wind power generation combined with hydrogen storage. This approach aims to minimize total system costs while maintaining reliability, as measured by the Loss of Power Supply Probability (LPSP) reliability index. Likewise, Ref. [157] applies an improved particle swarm optimization algorithm to develop cost-effective and reliable solar-hydrogen energy systems for green buildings under technical and economic constraints. To enhance long-term reliability and resilience, a two-stage risk-constrained stochastic programming formulation is introduced in [158]. This approach utilizes a data-driven power-flow linearization technique and a dual cutting-plane-based decomposition algorithm, which proves to be scalable and effective in managing complex uncertainties in hydrogen-based off-grid microgrids. Further exploring integrated storage solutions, Ref. [159] uses a two-step MILP model to determine the most cost-effective configurations and operational profiles. This model integrates long-duration hydrogen storage with short-duration lithium-ion batteries to meet all power demands, which highlights the impact of component pricing on the overall costs of the energy-storage systems.

The potential for green hydrogen and ammonia production and export from Saudi Arabia is explored in [160]. Utilizing geographical data from three coastal locations, this study assesses the production costs and levelized costs of ammonia and hydrogen by 2030. It highlights that operational flexibility and energy buffers are crucial for meeting production constraints, with the northwest area of Saudi Arabia showing particular promise for superior green fuel production. The competitiveness of other areas depends on further reductions in renewable energy CapEx and improvements in electrolyzer efficiency. Moreover, Ref. [161] introduces a convex relaxation-based planning model for islanded hydrogen-based carbon-free microgrids. By using annual data to simulate long-term operation, it significantly reduces computational time and costs. Meanwhile, Ref. [162] conducts a techno-economic analysis in three island communities in Canada. This analysis focuses on using RESs for hydrogen and electricity production to meet the demands of stakeholders, including residential buildings and HRSs. The primary goal is to minimize the net present cost (NPC) of the systems, and it concludes that long-term projects tend to be more cost-effective than short-term ones due to higher salvage values. A techno-economic assessment of a hydrogen-based islanded microgrid on a remote island in Northeast Australia is detailed in [163]. This study aims to lower energy costs and carbon dioxide emissions. It evaluates cost-effective scenarios for green hydrogen production, transportation, and electricity generation while considering the limited land area and geographical conditions.

Data-driven methods are increasingly popular. For instance, Ref. [164] resolves stochastic optimization scheduling for an islanded hydrogen microgrid using deep reinforcement learning. It minimizes microgrid lifecycle costs while managing uncertainties and energy capacity degradation. Furthermore, the study leverages a bidirectional and long short-term memory convolutional neural network for wind power and load forecasting, which showcases potential improvements in operational efficiency and reliability of microgrid energy management.

Overall, the literature indicates that long-term operational strategies for islanded hydrogen systems encounter challenges similar to those faced by grid-connected systems. The potential benefits of green hydrogen in off-grid communities are limited by the volatile energy output of RESs and the lack of cost-effective energy storage alternatives. These challenges underscore the urgent need for technological advancements and cost reductions in energy storage to fully harness the benefits of green hydrogen in these settings.

5. Short-Term Operational Strategies

Short-term operational strategies address the immediate challenges of integrating green hydrogen into the current energy system. These strategies focus on managing the intermittent nature of RESs and optimizing day-to-day or real-time decisions regarding energy storage, conversion, and market transactions. Unlike long-term operational strategies that rely on static system models, short-term operational strategies utilize dynamic models. In this section, the short-term operational strategies for both grid-connected and islanded systems are reviewed, with each presenting unique challenges.

5.1. Short-Term Operational Strategies for Grid-Connected Hydrogen Systems

Various studies have developed optimized strategies for the day-to-day operation of grid-connected hydrogen systems. Reference [165] presents an improved deep deterministic policy gradient (DDPG) algorithm for the intra-day real-time scheduling of an integrated hydropower-photovoltaic-hydrogen (HPH) system. It seeks to optimize revenues while addressing uncertainties in inflow water, PV generation, and electric load demand. However, its centralized approach may encounter the challenge of dimensionality during online scheduling. To consider multi-stakeholder scenarios while preserving privacy, other research employs distributed optimization techniques. In [166], a bi-level strategic operation framework is proposed to integrate an integrated energy system (IES) with a hybrid charging station using a hierarchical Stackelberg game and DRO. This framework sets dynamic pricing and power, led by the IES, but neglects network constraints and the variability in market electricity prices and RESs, which may critically impact the accuracy of outcomes in practice. Reference [167] introduces a peer-to-peer trading framework that employs the alternating direction method of multipliers (ADMM) to minimize operational costs and enhance energy efficiency of multiple IESs. However, it oversimplifies hydrogen logistics and transportation dynamics. Similarly, Ref. [168] proposes a cooperative model using the Nash bargaining theory for energy trading between wind turbines and hydrogen fueling stations (HFSs). While this model addresses privacy concerns and uses scenario-based methods to accommodate uncertainties, it assumes a uniform scenario for power export from wind turbines and ignores electric network constraints. In terms of real-time control, Ref. [169] introduces a supervisory control system that utilizes Z-source converters to integrate various systems and balance power efficiently. Its innovative configuration allows for voltage adaptation and effective power control, validated through simulation and hardware-in-the-loop (HIL) tests.

Dynamic modeling has been widely adopted for optimizing short-term operational strategies. Nonetheless, most studies primarily focus on the dynamics in the electrical domain, while hydrogen systems are multi-domain systems. In [170], a comprehensive simulation of a 500 kW AEL system integrated into the electric grid is presented. This study focuses on harmonic analysis and robust control to manage voltage deviations and ensure grid stability. Importantly, this research highlights the necessity of incorporating electrochemical equations for accurate electrolyzer modeling, which is essential for designing effective control systems. Likewise, Ref. [171] introduces a dynamic model for a pressurized AEL using a multi-physics approach. This model integrates electrochemical, thermodynamic, heat transfer, and gas evolution processes to simulate the complete dynamical behavior of these systems when coupled with RESs. The model is validated with experimental data from a commercial AEL system, confirming its accuracy in predicting electrolyzer behavior.

However, many of the above studies generally overlook the crucial role of grid ancillary services such as frequency regulation and voltage control, which are essential for maintaining grid stability and resilience. In contrast, Ref. [172] introduces a dynamic model for PEM electrolyzers that explores their potential to provide fast frequency response (FFR) in RES-rich grids. It shows how the electrolyzers' pre-contingency operating point and converter overloading capabilities can significantly influence FFR provision and overall system frequency control. In [173], a unified dynamic model is proposed to assess the capabilities of electrolyzers in providing frequency control ancillary services (FCAS). The model integrates virtual synchronous machine (VSM) control within the electrolyzer's operation. However, it notes that operational constraints related to the hydrogen buffer's capacity and consumption rate may limit downward FCAS and risk electrolyzer shutdowns. Additionally, Ref. [174] introduces a marginal pricing mechanism to enhance grid resilience through frequency response services. It includes P2H systems in the frequency response market and addresses the challenge of integrating their highly nonlinear dynamic frequency behavior into economic dispatch models using a novel convexification approach. In [175], the article discusses the use of electrolyzers to manage grid congestion by utilizing excess local renewable electricity for hydrogen production. Congestion management strategies, including re-dispatch bidding and capacity-limiting contracts, are explored. However, the economic feasibility of using electrolysis for congestion management depends on local hydrogen demand and the availability of incentives, with scenarios near RESs and industrial hydrogen demand showing the highest potential. In addition, the ownership and operation of electrolyzers by grid operators present the highest potential impact on congestion but face great legal barriers, indicating the complex relationship between regulatory frameworks and the deployment of electrolysis for grid management. The importance of grid-forming control is emphasized in the literature as crucial to providing ancillary services in electrical power systems. It helps establish and maintain the voltage and frequency of the electric grid, as system inertia and damping decrease due to the replacement of traditional synchronous generators with power electronics converters [176,177]. Reference [178] explores PEM electrolyzers as grid-forming loads to actively participate in voltage and frequency regulation. The study details a control system that manages dynamic grid conditions and hydrogen production effectively, as validated through simulations and HIL tests. Other studies further consider fuel cells. Reference [179] proposes a model and control coordination scheme for a wind-to-hydrogen set. To enhance system stability and efficiency, the model integrates a grid-forming inverter-based wind turbine with an electrolyzer and a fuel cell. Moreover, the control scheme optimizes electricity production from variable-speed wind turbines and maintains the balance between supply and demand in the renewable energy system. Finally, Ref. [180] develops a hybrid system integrating hydrogen storage with a wind turbine to enhance grid-connected operating performances. This system focuses on maximizing wind energy utilization, suppressing output power fluctuation, and improving continuous operating stability. Case studies validate the system's effectiveness in terms of low-voltage ride-through (LVRT) capability and reactive power production.

Apart from the above-mentioned challenges, grid-connected hybrid electrolyzer and fuel cell systems, including regenerative fuel cells, also suffer from sub-optimal round-trip efficiency, which only reaches about 51% [181]. This efficiency limitation poses a significant challenge to the economic viability of widespread hydrogen electrification. Moreover, the role of green hydrogen systems in providing black start capabilities, another critical ancillary service for grid stability, requires further exploration. The lack of detailed studies on black start capabilities indicates a critical gap in current research, which points to the necessity for more comprehensive investigations. These gaps in research underscore an urgent need for more comprehensive studies to enhance the efficiency and operational effectiveness of these systems in grid support roles.

5.2. Short-Term Operational Strategies for Islanded Hydrogen Systems

In islanded hydrogen systems, BESSs are essential for supporting the integration of hybrid electrolyzer and fuel cell systems. They help balance short-term fluctuations in energy supply and demand [182], thereby enhancing system flexibility and resilience. Maintaining a stable and reliable power supply is a primary goal of short-term operational strategies.

In [183], the authors present a bi-objective optimization model formulated as a MINLP problem, which is designed to ensure the resilient operation of microgrids that integrate P2H systems comprising electrolyzers, hydrogen storage systems, and fuel cells. In order to enhance the operational efficiency of the microgrid in the islanded mode, three resilience measures are considered: minimizing imported power, reducing power loss, and maximizing hydrogen levels in the tanks. Furthermore, the the Generalized Bender Decomposition technique is employed in conjunction with the Multi-Objective Goal Programming approach to effectively address the model's complexity and improve computational performance.

Previous research also emphasizes real-time control to maintain stable system frequency and voltage. For example, Ref. [184] develops a decentralized coordination control strategy for an islanded DC microgrid. This strategy integrates PVs, BESSs, AELs, and fuel cells, featuring an adaptive control strategy for electrolyzers to adjust energy conversion efficiency based on the DC bus voltage and a P-V droop control strategy for PVs. It also operates fuel cells in constant power mode as a backup power source. Another study [185] presents a load frequency control method utilizing a Cascade Double-Input Interval Type 2 Fuzzy Logic Controller (C-DIT2-FLC) optimized by an Improved Salp Swarm Algorithm (ISSA). The controller effectively balances demand and supply, as demonstrated by simulation studies using actual solar radiation and load demand data. However, the reliance on the ISSA for optimization may not always guarantee globally optimal solutions, due to the inherent limitations of heuristic optimization. In addition, Ref. [186] develops a data-driven model predictive control (MPC) strategy for hydrogen energy storage systems (HESSs), utilizing the Dynamic Mode Decomposition with control (DMDc) method. This strategy enhances frequency regulation by optimally coordinating with distributed generators and shows improvements over traditional proportional-integral (PI)-based control strategies in simulation case studies. However, its simplification, such as neglecting line congestion constraints, could limit its applicability and accuracy in real-world scenarios.

Further studies expand operational strategies across different time scales and in both grid-connected and islanded modes, thereby enhancing the adaptability and robustness of hydrogen systems under various operational conditions. For instance, Ref. [187] explores a hybrid wind–solar-energy storage system for hydrogen production. It addresses the challenges of system structure design and source-load-storage coordination control, utilizing the HOMER software for storage capacity planning and proposing decentralized coordinated control for the energy management system. Its effectiveness is verified through electromagnetic transient simulations and HIL experiments. Moreover, Ref. [188] develops a hierarchical MPC framework that optimizes both the long-term and short-term operations of microgrids. It integrates wind generation and hydrogen storage to track load demand, maximize market revenues, and balance power supply. Similarly, Ref. [189] presents a hierarchical MPC strategy that optimizes the operation of a multi-tank HESS within an islanded wind-solar microgrid. This setup enhances hydrogen storage capacity, which helps smooth the variability of RESs and ensure a reliable power supply. It aims to optimize economic and operational efficiency while extending the longevity of system components.

6. Conclusions and Outlook

6.1. Conclusions

This paper provides a comprehensive review of the value chain and associated technologies for green hydrogen, which showcases its versatility as a fuel, chemical feedstock, energy carrier, and storage medium. Additionally, this paper explores the evolving market dynamics and highlights several clean hydrogen pilot projects that are currently operational or underway. The analysis identifies key challenges that hinder the development of a mature green hydrogen economy and emphasizes the crucial role of hydrogen storage in addressing the intermittency of renewable energy sources (RESs) in both grid-connected and islanded systems. Furthermore, the discussion encompasses both long-term and short-term operational strategies for green hydrogen, providing a holistic perspective on its potential applications. The recommendations are summarized as follows.

To fully realize the potential of green hydrogen ecosystems, it is crucial to reduce the cost of production; expand midstream infrastructure, including storage and distribution; and increase hydrogen demand in specific sectors where no other cost-competitive or technically viable alternatives exist. Current major challenges include a lack of ubiquitous hydrogen distribution infrastructure, insufficient manufacturing at scale, and issues of cost, durability, reliability, and availability throughout the value chain. To overcome these challenges, supportive policies and regulations are necessary in the initial stages to incentivize investment in hydrogen infrastructure and address potential safety concerns, which can pave the way for a more resilient and sustainable energy grid.

The initial deployment of hydrogen should target hard-to-abate sectors that currently rely on conventional natural gas. Industries such as the ammonia production and petrochemical sectors, with established supply chains and economies of scale, offer immense potential. In addition, co-locating hydrogen supply and demand can reduce the need for new long-distance infrastructure, thereby lowering the costs associated with early market expansion until a stable, large-scale hydrogen demand emerges. The shared infrastructure, including access to raw materials, downstream supply chains, hydrogen transport, and electrical power transmission systems, coupled with a strong and well-trained labor pool, can enhance regional economic competitiveness. As regional hydrogen clusters begin to form, developers should prioritize community engagement to foster social acceptance of green hydrogen. Targeted regional outreach and networking could accelerate the development of a green hydrogen value chain. Over time, the global hydrogen economy is expected to thrive through international collaboration.

Electrolyzers, which consume a significant amount of electricity, are a major contributor to green hydrogen generation costs. To encourage large-scale electrolysis, it is essential to further reduce renewable electricity prices and improve electrolyzer efficiency. The efforts include reducing the CapEx of electrolyzers and the BoP, improving durability and reliability to lower maintenance fees, and leveraging production and investment tax credits to further decrease electricity costs. Given the uncertainties surrounding the green hydrogen economy, supportive policies are indeed crucial. Furthermore, conducting lab-scale tests and pilot project demonstrations can mitigate technological uncertainties and de-risk the industry. Such initiatives enable the practical assessment of technologies under real-world conditions, which accelerates innovation and increases investor confidence.

6.2. Outlook

The major focus of this paper is to explore the feasibility of the grid integration of hydrogen storage to improve the operational efficiency of hybrid energy systems for enhanced grid stability and resilience. Currently, the electrification of hydrogen remains costly due to its relatively low efficiency. However, as technologies for electrolyzers, fuel cells, and low-NO_x combustion technologies improve, they will allow the more efficient provision of grid ancillary services. In addition, given the complex, multi-physics, and multi-domain nature of hybrid hydrogen systems, developing advanced coordinated controls with interdisciplinary expertise will be crucial to enhancing the stability and operational efficiency of electrical systems integrated with hydrogen storage. Looking ahead, one of our future directions is to implement physics-informed deep learning to develop real-time coordinated control strategies. These control strategies will be refined using simulated data from real-time hardware-in-the-loop simulations.

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