

Review

Review and Prospects of Key Technologies for Integrated Systems in Hydrogen Production from Offshore Superconducting Wind Power

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Abstract: Hydrogen production from renewable energy sources is a crucial pathway to achieving the carbon peak target and realizing the vision of carbon neutrality. The hydrogen production from offshore superconducting wind power (HPOSWP) integrated systems, as an innovative technology in the renewable energy hydrogen production field, holds significant market potential and promising development prospects. This integrated technology, based on research into high-temperature superconducting generator (HTSG) characteristics and electrolytic water hydrogen production (EWHP) technology, converts offshore wind energy (OWE) into hydrogen energy locally through electrolysis, with hydrogen storage being shipped and controlled liquid hydrogen (LH₂) circulation ensuring a stable low-temperature environment for the HTSGs' refrigeration system. However, due to the significant instability and intermittency of offshore wind power (OWP), this HPOSWP system can greatly affect the dynamic adaptability of the EWHP system, resulting in impure hydrogen production and compromising the safety of the LH₂ cooling system, and reduce the fitness of the integrated system for wind electricity–hydrogen heat multi-field coupling. This paper provides a comprehensive overview of the fundamental structure and characteristics of this integrated technology and further identifies the key challenges in its application, including the dynamic adaptability of electrolytic water hydrogen production technology, as well as the need for large-capacity, long-duration storage solutions. Additionally, this paper explores the future technological direction of this integrated system, highlighting the need to overcome the limitations of electrical energy adaptation within the system, improve product purity, and achieve large-scale applications.

Keywords: high-temperature superconductor (HTS) turbines; offshore wind power; electrolytic water hydrogen production; hydrogen storage



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1. Introduction

With the rapid development of renewable energy sources like wind power, issues such as excessive fossil fuel consumption and the greenhouse effect have been mitigated to some extent [1,2]. However, the advancement of wind power technology has led to a continuous increase in the capacity of individual generators. The increasing weight and volume of

wind generators have heightened the challenges of maritime transportation, hoisting, and maintenance [3]. Superconducting materials, with their zero resistance characteristics, have been investigated as replacements for conventional copper wires in field windings, significantly increasing the power density of motors and reducing the weight of wind turbines to 1/2–1/3 that of conventional wind turbines of the same capacity [4,5]. This innovative technology offers an ideal solution for the miniaturization and weight reduction of wind turbines [6]. Research indicates that HTSGs with outputs above 10 MW offer distinct advantages over traditional wind turbines in terms of size and mass. The 10 MW superconducting motor proposed by the Superconductivity Corporation of the U.S. has a diameter of 4.5 m~5 m and weighs about 180 t. The mass of a permanent magnet motor of the same power is about 300 t, with a diameter of more than 10 m [7]. However, the randomness, intermittency, and volatility of wind energy can cause voltage and frequency fluctuations when wind power is integrated into the power grid, resulting in poor power quality and significant wind curtailment [8,9]. To stabilize the grid and maintain power quality levels, various technical strategies have been proposed and investigated [10,11].

Hydrogen energy is widely recognized as a clean and promising energy source for the future [12–15]. WPHP systems can efficiently utilize wind power to produce hydrogen and can also be combined with fuel cell power generation to achieve “peak-cutting” and “valley-filling” to ensure grid stability and security [16–19]. Recently, Hunan University’s wind power generation team proposed an innovative HPOSWP integrated technology [20]. Considering that the critical current of superconducting tapes increases as the ambient temperature decreases, this technology takes advantage of the large-current characteristics of HTS tapes in liquid hydrogen environments, combining superconducting wind turbines with LH₂ preparation technology to design an off-grid offshore superconducting wind power water electrolysis hydrogen production system. Additionally, LH₂ circulation provides a stable low-temperature environment for the refrigeration system, significantly reducing the weight and volume of the devices and achieving efficient renewable energy conversion. Moreover, it enables the conversion of OWE into hydrogen locally through electrolysis, while green hydrogen preparation addresses the grid-connected transmission issues of deep-ocean wind farms.

However, the fluctuations and interruptions in OWE impact the start–stop operations of HTS generators. Frequent power fluctuations may shorten the system’s operating lifespan and reduce the purity of the hydrogen produced, thereby compromising the stability and security of the hydrogen storage or even the whole integrated system. This paper focuses on the key technologies within the HPOSWP integrated technology, analyzes the feasibility, and proposes effective solutions to the current challenges faced by the system. It also discusses the future directions of the HPOSWP technology. This research aims to promote the progress of HPOSWP technology, establish a common technology for large-scale offshore WPHP systems, and promote technological improvements in the global wind power industry. This article is organized as follows: In Section 2, we review the development of the integrated superconducting wind power hydrogen production technology and describe the basic structure and performance of the system. Section 3 describes the key technologies of the liquid hydrogen cooling system. Section 4 compares and discusses the adaptive key technologies of the integrated system. We provide a future outlook in Section 5 and conclude the paper in Section 6.

2. Integrated System for Hydrogen Production from Offshore Superconducting Wind Power

In the development of renewable energy-based power systems, hydrogen production powered by offshore wind turbines is a major innovation of energy technology. In 2004, the

U.S. launched the Wind2H2 project, a demonstration initiative that used wind and photovoltaics to produce and store hydrogen via a generator array connected to an electrolysis stack. This project successfully addressed the key challenge of coupling renewable energy with EWHP, sparking global interest in renewable energy-driven hydrogen production technology. National strategies for the WPHP technology are shown in Figure 1a. In 2011, Canada developed a wind-hydrogen diesel demonstration project, and in 2012, Germany launched the RH2WKA wind-hydrogen combined heat and power demonstration project. In 2019, the Netherlands successfully implemented the PosHYdon project, the world's first OWP hydrogen production pilot, which validated the feasibility of offshore WPHP technology [21].

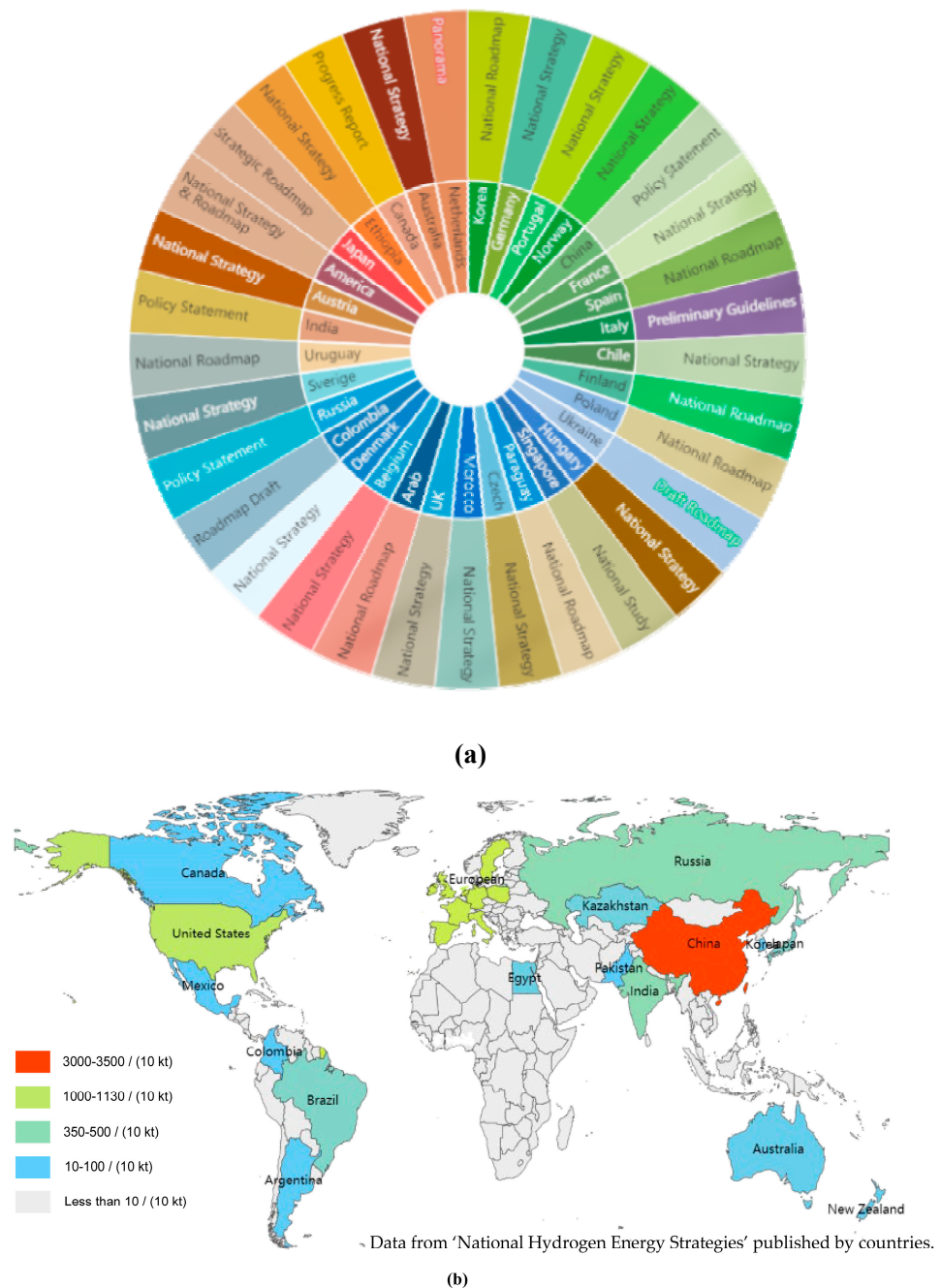


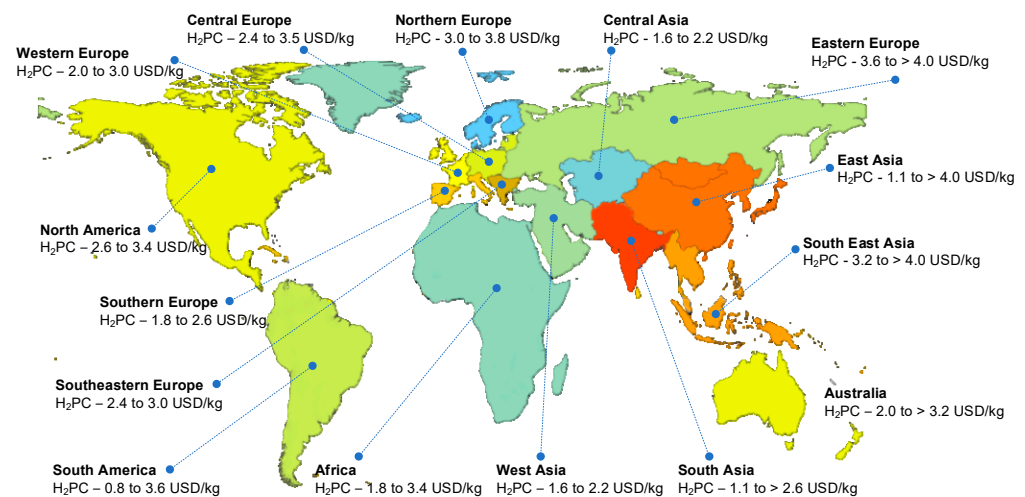
Figure 1. (a) Hydrogen production strategies in various countries; (b) global average annual hydrogen production.

As shown in Table 1, China's research into WPHP technology was initiated relatively late, with the first demonstration project of hydrogen production from wind power in Zhangbei carried out in 2014 and the Guyuan WPHP project officially launched in 2015 [20]. This project includes a 200 MW wind farm, a 10 MW EWHP system, and a comprehensive hydrogen utilization system. Hydrogen production is used in industrial production to reduce the consumption of coal, natural gas, and other energy sources. In 2020, the Yushu WPHP demonstration project was launched, featuring a wind turbine capacity of 400 MW and a hydrogen production capacity of 10 MW. This project is the largest of its kind in the world, filling the gap in the megawatt-scale coupled wind–hydrogen storage demonstration projects in China and positioning itself as a world-leading demonstration project [22]. Figure 1b shows the annual average global hydrogen production, where China's hydrogen production ranks first place in the world.

Table 1. Summary of demonstration projects of wind power hydrogen production around the world.

Year	Name	Wind Turbine Capacity (kW)	Hydrogen Production Power (kW)	Country
2011	Ramea	690	162	Canada
2011	Enertrag	6000	500	Germany
2012	Rh2-WKA	140,000	1000	Germany
2012	Yorkshire	225	30	England
2015	Guyuan	200,000	4000	China
2016	Hydrogen Office Building	750	30.5	U.K.
2017	Fufu County	750	30	U.K.
2019	PosHYdon	400,000	1250	Netherlands
2020	Yushu	400,000	10,000	China
2023	Sealhyfe	10,000	10,000	France

With the continuous development of hydrogen production technology, many scholars around the world have recently analyzed and reviewed the economics and feasibility of technologies for HP from wind power from various perspectives and the cost of hydrogen production in different regions, as shown in Figure 2. In 2000, Dutton summarized the practical challenges and technological bottlenecks in developing WPHP systems and emphasized the impact of wind power fluctuations on the operation of electrolysis cells [23]. In 2003, Kassem evaluated the economics and feasibility of WPHP technology, highlighting its potential as a low-cost source of electricity [24]. In 2005, Sherif studied hydrogen production technology and concluded that wind power could improve the competitiveness of hydrogen production [25]. In 2010, Bartels conducted an economic analysis of WPHP and confirmed its feasibility [26]. In 2014, Bhandari performed a life cycle assessment of a WPHP system and demonstrated the technological advances [27]. In 2015, Sarrias studied the coupled operation of electrolysis cells and wind turbines and compared the performance characteristics of four different electrolysis cells for WPHP technology [28]. In 2017, Ning investigated the adaptability of traditional WPHP equipment under wide power fluctuations and proposed adjustments to the process parameters to improve performance [29]. In 2021, Huang proposed a cooperative control strategy to protect the grid connection from disturbances to the system reliability and power quality [30]. In 2024, Zainal comprehensively evaluated the major hydrogen production methods based on cost, environmental impact, and technological maturity and confirmed the increased efficiency, cost competitiveness, and scalability of hydrogen production technologies [31].



Data from 'National Hydrogen Energy Strategies' published by countries.

Figure 2. Cost of hydrogen production in different regions.

The traditional WPHP technology uses the flexibility of EWHP systems to improve the wind power grid connection [30,32]. During periods of low power demand, this system focuses on hydrogen production and hydrogen storage technologies; during peak demand periods, stored hydrogen is used to supplement the wind power output [33]. However, as OWP development advances into the deep sea, the costs of submarine cables and offshore equipment construction and operation continue to rise. Additionally, power transmission losses remain a challenge. For high-voltage alternating current (HVAC) [34] and high-voltage direct current (HVDC) [35], transmission losses range between 1 and 5% and 2 and 4%, respectively, depending on the wind farm capacity and distance from the shore [11,36]. Moreover, the volatility and unpredictability of wind energy complicate the regulation and scheduling of the wind power output. As the total amount of wind power connected to the grid increases, issues such as harmonics, voltage fluctuations, and flicker become more prevalent during grid connection. This also severely impacts the stability of the generating units and significantly limits the development of wind power technology. To solve these problems, WPHP systems often incorporate static reactive power compensation equipment and employ flexible coordinated grid-connected technology to achieve stable control of the grid frequency and voltage [37]. In addition, active filtering equipment and compensation devices are used to mitigate voltage fluctuations and flicker [38]. However, these measures still fall short of fully resolving the problem of power quality degradation.

Our proposed HPOSWP integrated system utilizes HTS materials to replace traditional copper coils in wind turbines as field windings [4]. This substitution reduces the weight and volume of the HTSGs, effectively improving the power density and increasing the efficiency of wind energy utilization. The WPHP technology consumes OWE in situ [39], which eliminates the need for extensive power infrastructure and reduces transmission losses [40,41]. Figure 3 shows the structure of the integrated system, which consists of four subsystems: the HTS wind power system, the EWHP system, the LH₂ cooling system, and the LH₂ storage system. The hydrogen production system is positioned on a highly integrated floating platform, and it converts OWE into chemical energy through electrolysis for storage. The wind power system facilitates the coupling and conversion of multiple energy sources via the electricity convergence system and the hydrogen production system. Simultaneously, hydrogen energy plays a crucial role in system operation through the LH₂ cooling system, which provides the necessary low-temperature environment for the offshore superconducting wind power system. This process enables the conversion of electricity into chemical energy, thereby improving the overall economics of the sys-

tem's operation. As shown in Figure 4, the subsystems interact with and regulate one another thanks to the conversion and storage equipment within the system, ensuring graded utilization.

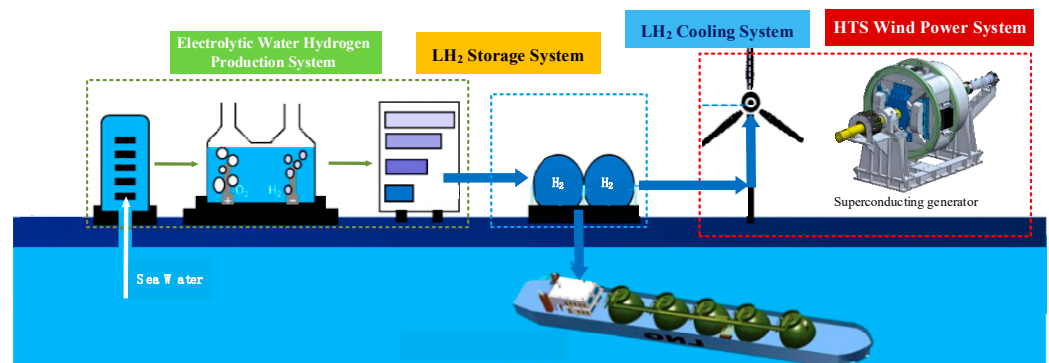


Figure 3. Integrated system structure of offshore HTSGs and hydrogen production.

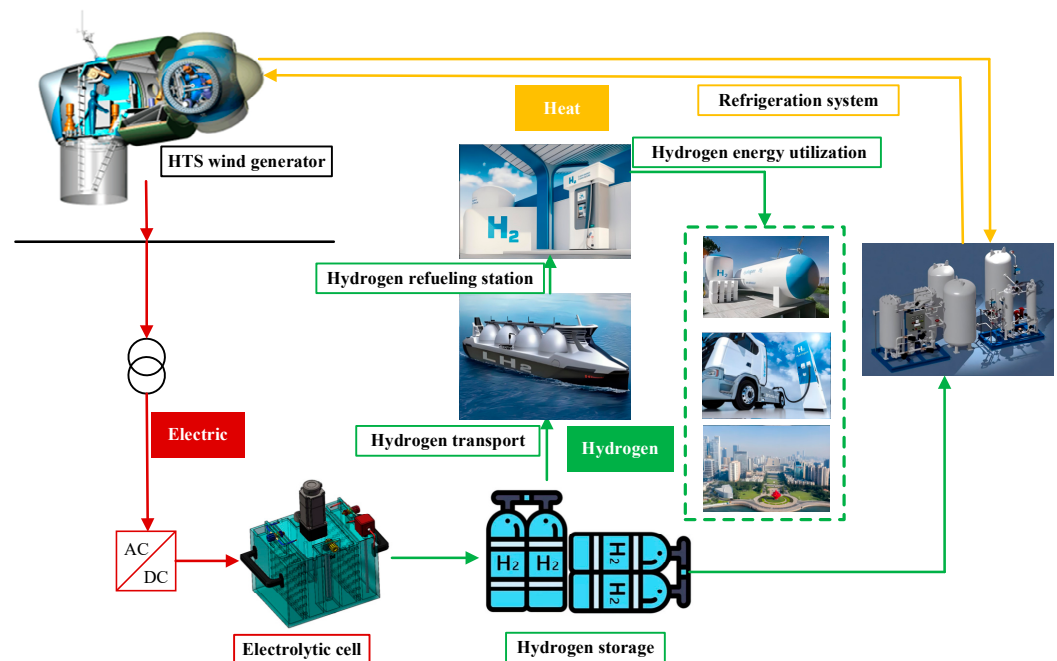


Figure 4. Integrated system logic diagram of offshore HTSGs and hydrogen production.

The HPOSWP system determines the speed of hydrogen processing by assessing wind energy levels and coordinates control based on wind power quality and hydrogen storage system operation. However, fluctuations in the wind power output can significantly affect the product purity of the hydrogen production system [42]. At low power levels, the hydrogen production system may cause contamination of the hydrogen storage system, and LH₂ with less than the required purity can cause immeasurable losses to the recirculating cooling system, leading to unstable operation of the refrigeration system and, in severe cases, to the collapse of the integrated system.

In addition to the challenges mentioned above, frequent fluctuations in wind energy can cause generators to start and stop repeatedly. The EWHP system, due to its complex multi-parameter control, responds slowly, with response times ranging from seconds to minutes. This slow response makes it challenging to quickly adjust to fluctuating wind energy output, leading to prolonged unsteady operation of the hydrogen production system [43–45].

In summary, to solve the adaptation of the integrated system to the wide power fluctuations of offshore wind energy, it is necessary to study the key technical challenges. These include optimizing the structure of the circulating cooling system, fine-tuning hydrogen storage parameters for reliability, improving the electrolyzer's design, adjusting the process parameters to increase the hydrogen purity, and implementing a dynamic coordination strategy based on system performance. These measures are essential for ensuring the stability and safety of the integrated system.

3. Key Technologies of LH₂ Circulating Cooling Systems

As the stator of HTSGs is exposed to an AC magnetic field, superconducting tapes are typically used in the field windings of the rotor, reducing AC losses in the coils. The armature windings of HTSGs are traditionally wound with copper wires, and conventional cooling methods are mostly used for the stator, such as water cooling and forced air cooling technologies [46]. The rotor's cryogenic system includes a refrigeration system, a transfer coupler, and a cooling circuit, as shown in Figure 5. This system is used for rotors with HTS coils. During HTSGs' operation, the refrigeration medium is introduced into the cooling circuit in the rotor through the transfer coupler when it absorbs the heat in the low-temperature environment and maintains the superconducting state of the coils. Since the cooling method for HTSGs is determined in the design stage, selecting the appropriate refrigeration medium and ensuring efficient provision of cooling power are key factors for the stable operation of the HTSGs.

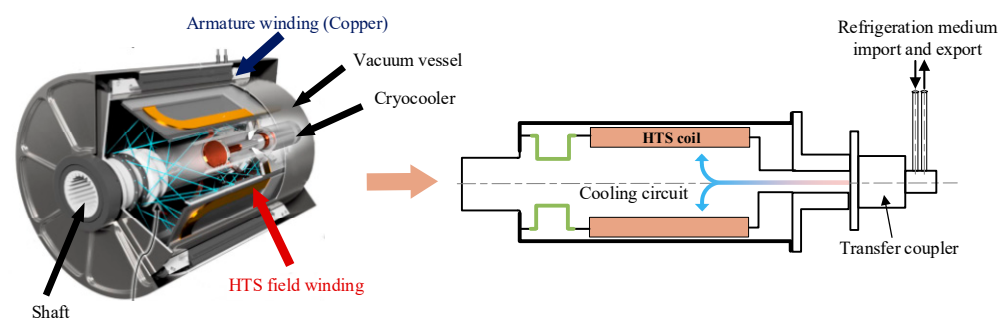


Figure 5. Schematic diagram of HTSGs and cryogenic system.

Common cooling media for HTSGs include neon, helium, nitrogen, oxygen, and hydrogen. Neon and helium, being rare gases, are expensive, which significantly impacts the economic feasibility of HTSGs [47]. With advances in HTS materials, the operating temperature range of HTSGs has expanded to 66~77 K. The boiling point of nitrogen is 77.15 K, and it has the advantages of having chemical stability and being non-toxic and non-explosive, making it an ideal cooling medium for low-temperature applications [48,49]. However, as the critical current of HTS materials increases rapidly with lower cooling temperatures, even exceeding kA values, researchers are continually exploring new cooling media to achieve a more compact HTSG design and reduce cooling costs. Hydrogen has emerged as a promising option due to its excellent physical properties, including a low boiling temperature, high specific heat, low viscosity, and excellent thermal conductivity [50]. Studies have found that HTS coils cooled with LH₂ carry currents higher than those cooled with liquid nitrogen while also achieving higher cooling system efficiency [51]. The researcher Shirai Y used conventional correlation methods to predict natural convective heat transfer in saturated LH₂ and provided valuable data on heat transfer in forced flows of LH₂ [52]. Given the flammability and explosiveness of hydrogen, and the challenges posed by hydrogen embrittlement, the design and manufacturing of LH₂ cooling systems must prioritize proven safety and security [53].

Moreover, as an HTSG operates under load, the armature winding temperature can reach up to 350 K, which is significantly higher than the HTS field winding operating temperature of 20 K. This temperature difference results in radiant heat losses between the field winding and the external environment. Additionally, conduction heat leakage occurs due to current leads and supporting components within the cryogenic container, further contributing to the thermal load [54]. Due to insufficient condensation, the refrigerant temperature in the cryogenic system will increase, making it difficult to maintain the stable operation of the superconductor. Conversely, if the cooling capacity exceeds the total heat load of the cryogenic system, excessive condensation may occur, leading to improper operation of the entire cryogenic system [55]. Therefore, a stable source of hydrogen is essential for scaling the application of the innovative integrated system. Depending on the required HPOSWP system capacity and storage duration in different scenarios, hydrogen storage employs three methods: high-pressure gaseous hydrogen storage (HGHS), LH₂ storage, and solid-state hydrogen storage (SSHS) technologies [56].

HGHS technology compresses hydrogen to pressures of up to 70 MPa and stores it in steel or composite gas cylinders [57]. These storage tanks can be constructed from materials such as steel, aluminum, and carbon fiber-reinforced plastic composites and take forms such as HGHS cylinders, composite hydrogen tanks, and glass containers. This storage method is straightforward, technically feasible, and cost-effective, making it the most mature hydrogen storage technology in widespread use today. However, it has a low volumetric energy density (only 25 g/L, significantly below the U.S. Department of Energy's target of 70 g/L), as shown in Figure 6. Additionally, HGHS has limited storage capacity, the metal cylinders are heavy, and there is a risk of hydrogen embrittlement. For implementation in HPOSWP systems, not only do we need to consider safety issues, but we also need to add a hydrogen liquefaction device to circulate LH₂. However, this addition complicates the system, increases its volume, and reduces its energy utilization efficiency.

LH₂ storage technology is suitable for large-capacity hydrogen storage, achieving a volumetric storage density of up to 70.9 g/L at 20 K [58]. This technology can be directly applied to the refrigeration needs of HPOSWP integrated systems without the need for conversion, simplifying the system structure and reducing the equipment complexity. However, it is critical for storage containers to have advanced thermal insulation, anti-freezing, and other safety features due to the hydrogen embrittlement phenomenon. Special containers with insulation systems are required to minimize the energy exchange between LH₂ and the environment [57]. The high energy consumption involved in the liquefaction process and the complexity of the insulation system design limit the further development of this method, making it more suitable for short-term HPOSWP system hydrogen storage.

SSHS technology offers a high volumetric hydrogen storage density, enhanced security, high efficiency, and the potential for integrated production and storage [59]. However, it remains in the material research and development stage in laboratories. As research progresses, SSHS is expected to become the primary method of HPOSWP system hydrogen storage in the future.

In addition, hydrogen storage in submarine salt caverns and offshore abandoned oil and gas fields represents an emerging area within hydrogen storage technology [58]. Submarine salt caverns offer advantages such as a large storage volume, low cost, effective sealing, and rapid extraction and injection, making them ideal for hydrogen energy. However, this approach will be affected by submarine geological formations, the technical maturity is not sufficient to support comprehensive application, and the related technology needs to be continuously improved [60]. Offshore abandoned oil and gas fields provide a large storage capacity, durability, and high security for hydrogen storage. However, the presence of residual gases such as CH₄, H₂, and CO₂ can affect the hydrogen quality and

subsequent utilization [58]. While offshore abandoned oil and gas fields offer economic advantages, the technology is still in development and requires further refinement.

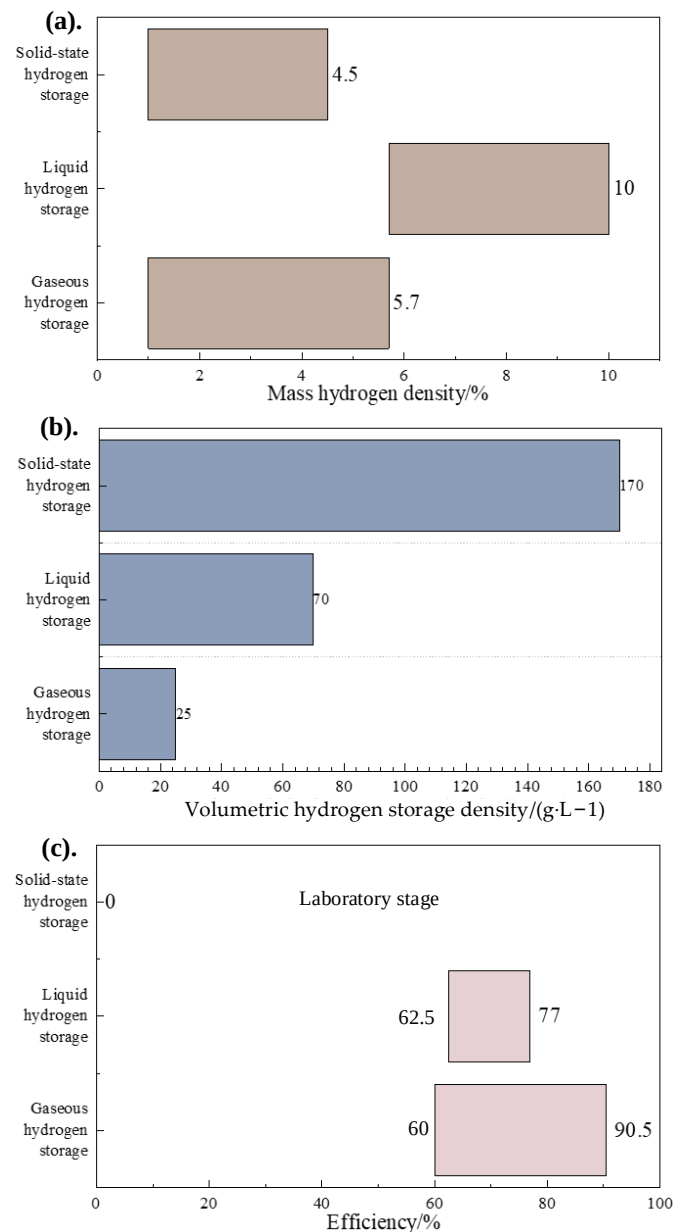


Figure 6. Comparison of different hydrogen energy storage technologies.

4. Key Technologies in Dynamic Adaptation of Integrated Systems

The output of HPOSWP integrated technology is intermittent and random, necessitating a strong dynamic adjustment capability in the EWHP system. The complex multi-parameter control of the EWHP system results in slow dynamic response times, failing to meet the rapid regulation requirements of superconducting wind power technology under wide power fluctuations in offshore wind energy. To solve the adaptation challenges of the HPOSWP system regarding the wide power fluctuations in offshore wind energy, optimizing and upgrading the EWHP device are essential for ensuring the stability and safety of the integrated system. EWHP technology is mainly divided into three methods: alkaline water electrolysis (AWE), proton exchange membranes (PEMs), and solid oxide electrolysis cells (SOECs) [61,62]. The schematic diagrams of the different hydrogen pro-

duction technologies are shown in Figure 7, and the relevant parameters are summarized in Table 2.

(a). Alkaline Water Electrolysis

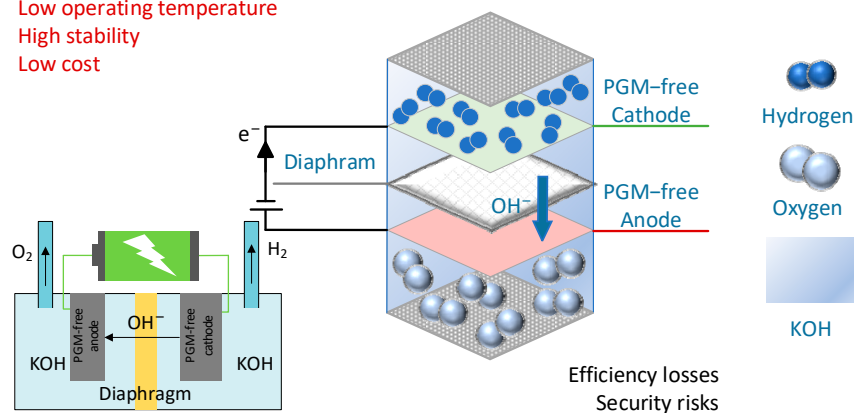
Current density: limited to 0.45 A/cm^2

Operating temperature: $70\text{--}90^\circ\text{C}$

Low operating temperature

High stability

Low cost



(b). Proton Exchange Membrane

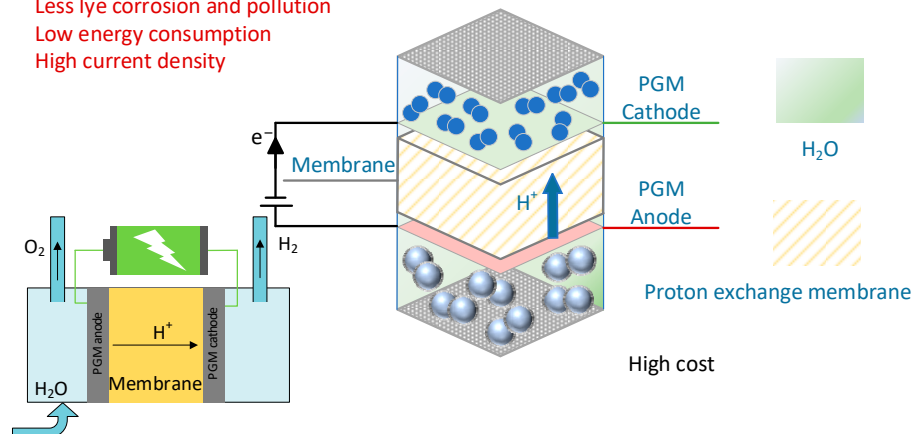
Current density: potentially up to 10 A/cm^2

Operating temperature: $50\text{--}80^\circ\text{C}$

Less lye corrosion and pollution

Low energy consumption

High current density



(c). Solid Oxide Electrolysis Cell

Current density: just 0.3 A/cm^2

Operating temperature: $700\text{--}1000^\circ\text{C}$

High energy conversion efficiency

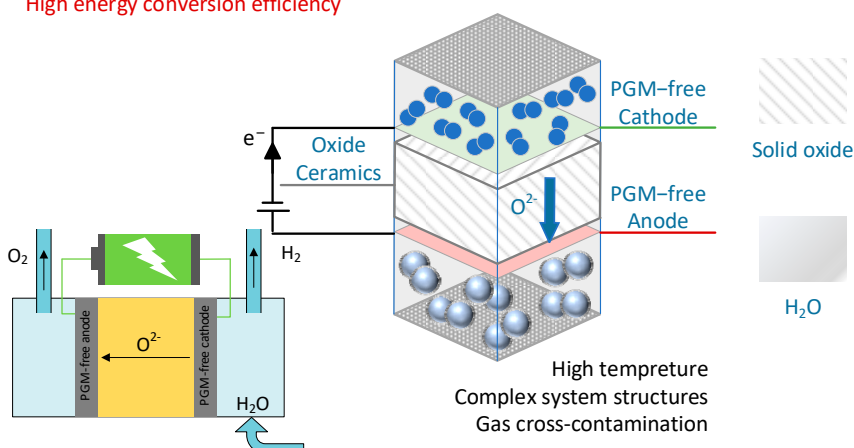


Figure 7. Schematic diagrams of (a) AWE electrolytic hydrogen production, (b) PEM electrolytic hydrogen production, and (c) SOEC electrolytic hydrogen production.

Table 2. Comparison of technologies for hydrogen production from water electrolysis.

Parameter	AWE	PEMs	SOECs
Electrolyte/separator	KOH	Proton exchange membrane	Solid oxide
Operating temperature/°C	70–90	50–80	700–1000
Work stress/MPa	0.1–3.0	<7.0	0.1
Current density/(A·cm ^{−2})	0.2–0.4	1–10	1–2
Efficiency/%	60–80	70–90	85–100
Load range	15–100	0–150	0–120
Cold start time	min	s	-
Energy consumption/(kWh/Nm ³)	4.5–5.5	3.5–5	2.6–3.6
Cell life/h	60,000	50,000–80,000	<20,000
System lifetime/a	20–30	10–20	-
Investment cost/(RMB·kW ^{−1})	6000–8000	10,000–12,000	-
Technology readiness level	8–9	8–9	5–6
Industrialization level	Maturation	Commercial cultivation	Laboratory stage

AWE technology offers advantages such as a low operating temperature, high stability, and low cost, making it the most mature technology for water electrolysis, with significant potential for large-scale renewable energy applications [63,64]. However, it faces challenges in rapid startup and variable load adaptation. Ideally, the electrolysis cells should tolerate power fluctuations ranging from 0% to 100% of their rated operating power. However, existing commercial AWE cells have a minimum operating power limit of 25% to 50% of their rated capacity. When the power falls below this threshold, the cells must be shut down, requiring 30–60 min to restart [65]. This limitation hampers quick adjustments in hydrogen production and reduces the efficiency of hydrogen production from wind power, making it less compatible with renewable energy sources.

In contrast, PEM technology electrolysis cells have a shorter dynamic response time and offer flexible operation under various conditions. These features make them well suited for coupling with offshore superconducting wind power to form an HPOSWP system, which helps stabilize the volatility of the renewable energy power [66]. However, PEM technology has not yet achieved significant breakthroughs. It is currently constrained by its limited capacity (50–250 kW) and high costs, making it more suitable for small-scale superconducting wind–hydrogen coupled power generation systems [67]. It is anticipated that, in the coming years, PEM systems will become more cost-effective and widely adopted through reductions in the platinum content in the electrodes, the development of lower-cost materials, and further research into proton exchange membrane materials and catalysts [68,69].

Compared to AWE and PEM technologies, SOEC systems operate at high temperatures and have a relatively long response time, making them more appropriate for waste heat recovery in various industrial processes rather than for large-scale HPOSWP systems, which have intermittent and fluctuating characteristics. However, challenges such as complex system structures, faster performance decay, and gas cross-contamination due to high-temperature operation persist, and SOEC technology is currently in its early demonstration phase [70,71].

Recently, a novel approach to in situ direct EWHP has been proposed [72]. This method addresses the challenges posed by the volatility induced by multi-field coupling and complex marine conditions during direct hydrogen production from seawater, enabling large-scale and stable hydrogen production. To further validate the feasibility of phase change migration seawater hydrogen technology in real-world conditions, Liu designed and developed a 1.2 Nm³/h offshore renewable energy floating platform [73]. This platform

was successfully integrated with OWP and operated continuously and stably for 10 days, achieving a seawater impurity ion blocking rate exceeding 99.99%, with the hydrogen production reaching a purity of 99.9%~99.99%. This innovation effectively addresses the persistent issue of corrosion in seawater hydrogen production.

Therefore, research on large-scale, efficient EWHP systems capable of handling wide power fluctuations and realizing efficient conversion of electrical energy is essential for the widespread application of integrated systems. This research involves analyzing the impact of wind power fluctuations on hydrogen production quality, efficiency, and cell life while continuously upgrading materials and developing efficient hydrogen production technologies under fluctuating power supply conditions.

5. Future Directions

5.1. HTS Wind Turbine Technology

Frequent fluctuations in wind power can cause HTS turbines to start and stop repeatedly, negatively impacting hydrogen production efficiency, reducing the hydrogen yield, and causing unnecessary losses in the system. To improve energy utilization, it is necessary to minimize the cooling capacity required for liquid hydrogen. However, the system's heat load includes not only the AC losses of the HTS turbine during operation but also heat conducted from the external environment to the cryogenic region. If this heat applied to the field windings is not dissipated in time, the continuous accumulation of heat will result in localized magnet quenching, compromising insulation between the windings and damaging the field windings. Currently, vacuum dynamic sealing technology is used to eliminate convective heat transfer between the HTS windings and external environment, while cold-conducting structures channel the cold to the surface of the HTS coils to improve the cooling speed, thereby reducing the system's cooling power. However, due to the temperature difference between the cooling work mass entering and exiting the cryogenic rotary joint, heat exchange occurs at the joint, resulting in an increase in the temperature of the cooling work mass flowing into the cryostat and reducing the cooling efficiency of the system. Therefore, upgrading the material of the cryogenic rotary joint and optimizing the cold conduction system are critical to achieving rapid heat dissipation and maintaining the stable operation of HPOSWP integrated systems.

5.2. LH₂ Circulating Cooling Technology

Considering the challenges posed by the explosive nature of hydrogen and hydrogen embrittlement, as well as the risk of thermal and cooling imbalances leading to system inefficiencies, the safety and reliability of LH₂ recirculation cooling systems must be thoroughly validated. Therefore, a stable source of hydrogen, as well as the selection of an appropriate type of hydrogen, is crucial for scaling up the application of HPOSWP integrated systems. HGHS systems are technologically mature and low-cost, but they require the addition of a hydrogen liquefaction unit to enable refrigeration. This addition not only complicates the system but also increases the risk of hydrogen embrittlement, thereby reducing the overall safety of the integrated system. As hydrogen production technology advances and industrial scales expand, LH₂ storage technology, suitable for large-scale applications, is gaining attention. This technology can be directly applied to the refrigeration needs of integrated systems without the need for conversion, simplifying the system structure and reducing the equipment complexity. However, storage containers must feature advanced thermal insulation, freeze protection, and other safety features to minimize the energy exchange between LH₂ and the environment. Key development areas for this technology include reducing energy consumption during hydrogen liquefaction, improving the thermal insulation of storage containers, and extending the service life of the technology.

Research into SSHS materials is crucial for future advancements, focusing on breakthroughs in the catalytic properties of electrode materials, integration of electrochemical reactors, and optimization of the system design.

5.3. Electrolytic Water Hydrogen Production Technology

The complex multi-parameter control of EWHP systems results in slow dynamic response characteristics, with response times ranging from seconds to minutes, which cannot be adjusted quickly enough to accommodate the wide power fluctuations in wind energy output. This leads to long-term unstable operation of EWHP systems, making them insufficient in quickly adjusting to the wide power fluctuations in offshore wind energy output. This prolonged instability in the EWHP system operation not only shortens the equipment lifespan but also leads to hydrogen purity degradation, which compromises the safety of the LH₂ cooling system. To solve the challenge of adapting HPOSWP systems to significant offshore wind power fluctuations, technology advancements need to focus on optimizing and upgrading EWHP devices and establishing a solid technical foundation for widespread adoption. PEM technology offers higher efficiency, more flexible operation modes, and a more compact equipment structure. PEM technology offers several advantages, including low operating voltage and energy consumption, high current density (typically 2~3 A/cm², potentially up to 10 A/cm²), compact structure, high hydrogen purity (up to 99.9999%), and simple control [67]. The Siemens Silyzer 300 system offers dynamic load adjustment from 0% to 100%, with a response rate of up to 10% of the rated power per second. Companies such as Proton in the U.S. and Cummins in Canada have developed MW-class systems, and 100 kW-class systems have been commercialized [74]. However, the use of Pt alloys as electrode materials significantly raises manufacturing costs. Therefore, reducing the reliance on precious metals in electrode catalysts, developing low-cost materials, and further researching proton exchange membrane materials have become key development priorities for hydrogen production technology.

6. Conclusions

With continuous advancements in the preparation process, superconducting materials have achieved higher critical current densities and superior mechanical and electromagnetic properties, offering significant practical potential in power transmission and high-field magnet applications. The hydrogen production from offshore superconducting wind power integrated systems, as an important link in the new superconducting technology, not only advances HTS materials in the wind power sector but also opens broader markets in aerospace, naval propulsion, rail transportation, national defense, and military applications. This paper briefly summarizes the development trend of WPHP technology, describes the basic structure and key technologies of the integrated system, and points out existing challenges. In response to the dynamic adaptability of the system under wide power fluctuations within a multi-field coupling framework, the system's circulating cooling technology is thoroughly evaluated. By analyzing and comparing different refrigeration media, LH₂ hydrogen storage technology is identified as a future development trend based on current limitations in hydrogen storage methods. For hydrogen production under wide power fluctuation conditions, PEM technology is highlighted as the most suitable option for the integrated system, after evaluating the performance of EWHP technologies. In response to the development challenges of the integrated system, future development directions have been proposed to target the safe operation of the LH₂ refrigeration system, focusing on system configuration optimization and stable operation. This paper provides valuable insights and references for the future development and demonstration applications

of this integrated technology of offshore superconducting wind power generation for hydrogen production.

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References

1. Muttaqi, K.; Islam, M.; Sutanto, D. Future power distribution grids: Integration of renewable energy, energy storage, electric vehicles, superconductor, and magnetic bus. *IEEE Trans. Appl. Supercond.* **2019**, *29*, 1–5. [\[CrossRef\]](#)
2. Ahmed, N.; Muhammad, S.; Tao, H.; Cao, S.; Ji, R.; Jiang, M.; Yao, L. Integration of energy storage system and renewable energy sources based on artificial intelligence: An overview. *J. Energy Storage* **2021**, *40*, 102811.
3. Apostolaki-Iosifidou, E.; McCormack, R.; Kempton, W.; McCoy, P.; Ozkan, D. Transmission design and analysis for large-scale offshore wind energy development. *IEEE Power Energy Technol. Syst. J.* **2019**, *6*, 22–31. [\[CrossRef\]](#)
4. Nam, G.; Sung, H.; Kim, C.; Park, M.; Yu, I. Design and characteristic analysis of a 1 MW superconducting motor for ship propulsions. *IEEE Trans. Appl. Supercond.* **2019**, *29*, 5203305. [\[CrossRef\]](#)
5. Jing, L.; Wang, T.; Tang, W.; Liu, W.; Qu, R. Characteristic analysis of the magnetic variable speed diesel–electric hybrid motor with auxiliary teeth for ship propulsion. *IEEE/ASME Trans. Mech.* **2023**, *29*, 668–678. [\[CrossRef\]](#)
6. Chow, C.; Ainslie, M.; Chau, T. High temperature superconducting rotating electrical machines: An overview. *Energy Rep.* **2023**, *9*, 1124–1156. [\[CrossRef\]](#)
7. Snitchler, G.; Gamble, B.; King, C.; Winn, P. 10 MW class superconductor wind turbine generators. *IEEE Trans. Appl. Supercond.* **2011**, *21*, 1089–1092. [\[CrossRef\]](#)
8. Varela, C.; Mostafa, M.; Zondervan, E. Modeling alkaline water electrolysis for power-to-x applications: A scheduling approach. *Int. J. Hydrogen Energy* **2021**, *14*, 9303–9313. [\[CrossRef\]](#)
9. Zhang, C.; Wang, J.; Ren, Z.; Yu, Z.; Wang, P. Wind-powered 250 kW electrolyzer for dynamic hydrogen production: A pilot study. *Int. J. Hydrogen Energy* **2021**, *46*, 34550–34564. [\[CrossRef\]](#)
10. Ferdinand, R.; Melzer, P.; Monti, A. Power quality issues at the grid connection point of HVDC connected offshore wind farms and their influence on the production. In Proceedings of the 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, 21–25 October 2018; pp. 1–6.
11. Yang, B.; Liu, B.; Zhou, H.; Wang, J.; Yao, W.; Wu, S. A critical survey of technologies of large offshore wind farm integration: Summary, advances, and perspectives. *Prot. Control. Mod. Power Syst.* **2022**, *7*, 17. [\[CrossRef\]](#)
12. Mohammadi, A.; Mehrpooya, M. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. *Energy* **2018**, *158*, 632–655. [\[CrossRef\]](#)
13. Widera, B. Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. *Therm. Sci. Eng. Prog.* **2020**, *16*, 100460. [\[CrossRef\]](#)
14. Nguyen, T.; Abdin, Z.; Holm, T.; Merida, W. Grid-connected hydrogen production via large-scale water electrolysis. *Energy Convers. Manag.* **2019**, *200*, 112108. [\[CrossRef\]](#)
15. Abdin, Z.; Zafaranloo, A.; Rafiee, A.; Merida, W.; Lipinski, W.; Khalilpour, K. Hydrogen as an energy vector. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109620. [\[CrossRef\]](#)

16. Alawad, S.; Mansour, R.; Al-Sulaiman, F.; Rehman, S. Renewable energy systems for water desalination applications: A comprehensive review. *Energy Convers. Manag.* **2023**, *286*, 117035. [\[CrossRef\]](#)
17. Takach, M.; Mirza, S.; Dorothee, P.; Michael, K.; Frank, S.; Karsten, M. Review of hydrogen production techniques from water using renewable energy sources and its storage in salt caverns. *Energies* **2022**, *15*, 1415. [\[CrossRef\]](#)
18. Apostolou, D.; Peter, E. The past, present and potential of hydrogen as a multifunctional storage application for wind Power. *Renew. Sustain. Energy Rev.* **2019**, *112*, 917–929. [\[CrossRef\]](#)
19. d’Amore-Domenech, R.; Leo, T.; Pollet, B. Bulk power transmission at sea: Life cycle cost comparison of electricity and hydrogen as energy vectors. *Appl. Energy* **2021**, *288*, 116625. [\[CrossRef\]](#)
20. Shen, L.; Zhai, Y.; Wu, X.; Huang, S.; Huang, S. Progress and Development Trend of Integrated Research on Hydrogen Production from Offshore Superconducting Wind Power. *Trans. China Electrotech. Soc.* **2024**, *1*, 1–22. (In Chinese)
21. Kong, L. *Optimal Configuration and Coordinated Control Strategy of Wind Solar Hydrogen Integrated Energy System*; North China Electric Power University: Beijing, China, 2017; Volume 1.
22. Li, Y.; Feng, J.; Lu, Y. Key technologies and prospects of large-capacity offshore wind power flexible DC transmission. *High Volt. Technol.* **2022**, *48*, 3384–3393.
23. Dutton, A.; Bleijs, J.; Dienhart, H.; Falchetta, M.; Hug, W.; Prischich, D.; Ruddell, A. Experience in the design, sizing, economics, and implementation of autonomous wind-powered hydrogen production systems. *Int. J. Hydrogen Energy* **2000**, *25*, 705–722. [\[CrossRef\]](#)
24. Kassem, N. Offshore wind farms for hydrogen production subject to uncertainties. *Int. Jt. Power Gener.* **2003**, 36924, 857–864.
25. Sherif, S.; Barbir, F.; Veziroglu, T. Wind energy and the hydrogen economy-review of the technology. *Sol. Energy* **2005**, *78*, 647–660. [\[CrossRef\]](#)
26. Bartels, J.; Pate, M.; Olson, N. An economic survey of hydrogen production from conventional and alternative energy sources. *Int. J. Hydrogen Energy* **2010**, *35*, 8371–8384. [\[CrossRef\]](#)
27. Bhandari, R.; Trudewind, C.; Zapp, P. Life cycle assessment of hydrogen production via electrolysis—A review. *J. Clean Prod.* **2014**, *85*, 151–163. [\[CrossRef\]](#)
28. Sarrias-Mena, R.; Fernández-Ramírez, L.; García-Vázquez, C.; Jurado, F. Electrolyzer models for hydrogen production from wind energy systems. *Int. J. Hydrogen Energy* **2015**, *40*, 2927–2938. [\[CrossRef\]](#)
29. Ning, N. Study on adaptability of wide power fluctuation in water electrolysis hydrogen production plant. *Ship Sci. Technol.* **2017**, *39*, 133–136.
30. Huang, C.; Zong, Y.; You, S.; Traeholt, C.; Zheng, Z.; Xie, Q. Cooperative control of wind-hydrogen-SMES hybrid systems for fault-ride-through improvement and power smoothing. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 1–7. [\[CrossRef\]](#)
31. Zainal, B.; Ker, P.; Mohamed, H.; Ong, H.; Fattah, I.; Rahman, S.; Nghiem, L.; Mahlia, T. Recent advancement and assessment of green hydrogen production technologies. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113941. [\[CrossRef\]](#)
32. Hou, P.; Enevoldsen, P.; Eichman, J.; Hu, W.; Jacobson, M.; Chen, Z. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark. *J. Power Sources* **2017**, *359*, 186–197. [\[CrossRef\]](#)
33. Bernal-Aguistin, J.; Dufo-López, R. Hourly energy management for grid-connected wind–hydrogen systems. *Int. J. Hydrogen Energy* **2008**, *33*, 6401–6413. [\[CrossRef\]](#)
34. Ackermann, T. Transmission systems for offshore wind farms. In *Wind Power in Power Systems*; Permissions Department, John Wiley & Sons Ltd.: Chichester, UK, 2005; pp. 479–503.
35. Liu, H.; Chen, Z. Contribution of VSC-HVDC to frequency regulation of power systems with offshore wind generation. *IEEE Trans. Energy Convers.* **2015**, *30*, 918–926. [\[CrossRef\]](#)
36. Negra, N.; Todorovic, J.; Ackermann, T. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. *Electr. Pow. Syst. Res.* **2006**, *76*, 916–927. [\[CrossRef\]](#)
37. Fang, R.; Liang, Y. Control strategy of electrolyzer in a wind-hydrogen system considering the constraints of switching times. *Int. J. Hydrogen Energy* **2019**, *44*, 25104–25111. [\[CrossRef\]](#)
38. Dinh, V.; Leahy, P.; McKeogh, E.; Murphy, J.; Cummins, V. Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. *Int. J. Hydrogen Energy* **2021**, *46*, 24620–24631. [\[CrossRef\]](#)
39. Hosseini, S.; Wahid, M. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renew. Sustain. Energy Rev.* **2016**, *57*, 850–866. [\[CrossRef\]](#)
40. Hassan, Q.; Ammar, M.; Saadoon, A.; Ahmed, A.; Jasim, A.; Sameen, A.; Hayder, M.; Ali, K.; Szymon, W.; Marek, J. Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation. *Int. J. Hydrogen Energy* **2023**, *48*, 17383–17408. [\[CrossRef\]](#)
41. Dixon, C.; Reynolds, S.; Rodley, D. Micro/small wind turbine power control for electrolysis applications. *Renew. Energy* **2016**, *87*, 182–192. [\[CrossRef\]](#)
42. Dobó, Z.; Palotás, Á. Impact of the voltage fluctuation of the power supply on the efficiency of alkaline water electrolysis. *Int. J. Hydrogen Energy* **2016**, *41*, 11849–11856. [\[CrossRef\]](#)

43. Aguirre, O.; Carlos, O.; Oscar, C. Control strategies for alkaline water electrolyzers: A survey. *Int. J. Hydrogen Energy* **2024**, *86*, 1195–1213. [\[CrossRef\]](#)
44. Jang, D.; Cho, H.; Kang, S. Numerical modeling and analysis of the effect of pressure on the performance of an alkaline water electrolysis system. *Appl. Energy* **2021**, *287*, 116554. [\[CrossRef\]](#)
45. Zhang, C.; Xia, P.; Zhang, X. Multi-attribute decision-making method of pumped storage capacity planning considering wind power uncertainty. *J. Clean Prod.* **2024**, *449*, 141655. [\[CrossRef\]](#)
46. Lim, M.; Chai, S.; Yang, J.; Hong, J. Design and verification of 150-krpm PMSM based on experiment results of prototype. *IEEE Trans. Ind. Electron.* **2015**, *62*, 7827–7836. [\[CrossRef\]](#)
47. Pearson, R.; Costley, A.; Phaal, R.; Nuttail, W. Technology Roadmapping for mission-led agile hardware development: A case study of a commercial fusion energy start-up. *Technol. Forecast. Soc.* **2020**, *158*, 120064. [\[CrossRef\]](#)
48. Huang, X.; Zhou, C.; Zhang, K.; Wu, L.; Zhang, J.; Cao, W. Comparison of electromagnetic performance of SCPM wind power generators with different topologies. *IEEE Trans. Appl. Supercond.* **2019**, *29*, 1–5. [\[CrossRef\]](#)
49. Qiu, M.; Huo, H.; Xu, Z.; Xia, D.; Lin, L.; Zhang, G. Technical analysis on the application of HTS bulk in “permanent magnet” motor. *IEEE Trans. Appl. Supercond.* **2005**, *15*, 3172–3175. [\[CrossRef\]](#)
50. Stautner, W.; Xu, M.; Mine, S.; Amm, K. Hydrogen cooling options for MgB₂-based superconducting systems. *Am. Inst. Phys.* **2014**, *1573*, 82–90.
51. Hirabayashi, H.; Kimura, N.; Makida, Y.; Shintomi, T. Hydrogen cooled superferriic magnets for accelerators and beam lines. *IEEE Trans. Appl. Supercond.* **2004**, *14*, 329–332. [\[CrossRef\]](#)
52. Shirai, Y.; Tatsumoto, H.; Hata, K.; Shiotus, M.; Kobayashi, H.; Naruo, Y.; Inatani, Y. Preliminary study on heat transfer characteristics of liquid hydrogen for coolant of HTC superconductors. *Am. Inst. Phys.* **2010**, *1218*, 337–339.
53. Nam, G.; Sung, H.; Ha, D.; No, H.; Koo, T.; Ko, R.; Park, M. Design and analysis of cryogenic cooling system for electric propulsion system using liquid Hydrogen. *Energies* **2023**, *16*, 527. [\[CrossRef\]](#)
54. White, G.; Meeson, P. *Experimental Techniques in Low-Temperature Physics*; Oxford University Press: Oxford, UK, 2002.
55. Pienkos, J. *Cooling, Thermal Design, and Stability of a Superconducting Motor*; The Florida State University: Tallahassee, FL, USA, 2009.
56. Usman, M. Hydrogen storage methods: Review and current status. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112743. [\[CrossRef\]](#)
57. Abe, J.; Popoola, A.; Ajenifuja, E.; Popoola, O. Hydrogen energy, economy and storage: Review and recommendation. *Int. J. Hydrogen Energy* **2019**, *44*, 15072–15086. [\[CrossRef\]](#)
58. Andersson, J.; Grönkvist, S. Large-scale storage of Hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 11901–11919. [\[CrossRef\]](#)
59. Faye, O.; Szpunar, J.; Eduok, U. A critical review on the current technologies for the generation, storage, and transportation of Hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 13771–13802. [\[CrossRef\]](#)
60. Muhammed, N.; Haq, B.; Shehri, D.; Ai-Ahmed, A.; Rahman, M.; Zaman, E. A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. *Energy Rep.* **2022**, *8*, 461–499. [\[CrossRef\]](#)
61. Miao, B.; Giordano, L.; Chan, S. Long-distance renewable hydrogen transmission via cables and pipelines. *Int. J. Hydrogen Energy* **2021**, *46*, 18699–18718. [\[CrossRef\]](#)
62. Buttler, A.; Spliethoff, H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2440–2454. [\[CrossRef\]](#)
63. David, M.; Ocampo-Martínez, C.; Sánchez-Peña, R. Advances in alkaline water electrolyzers: A review. *J. Energy Storage* **2019**, *23*, 392–403. [\[CrossRef\]](#)
64. Schalenbach, M.; Zeradjanin, A.; Kasian, O.; Cherevko, S.; Mayrhofer, K. A perspective on low-temperature water electrolysis—challenges in alkaline and acidic technology. *Int. J. Electrochem. Sci.* **2018**, *13*, 1173–1226. [\[CrossRef\]](#)
65. Ulleberg, Ø.; Nakken, T.; Ete, A. The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools. *Int. J. Hydrogen Energy* **2010**, *35*, 1841–1852. [\[CrossRef\]](#)
66. Wirkert, F.; Roth, J.; Jagalski, S.; Neuhaus, P.; Rost, U.; Brodmann, M. A modular design approach for PEM electrolyser systems with homogeneous operation conditions and highly efficient heat management. *Int. J. Hydrogen Energy* **2020**, *45*, 1226–1235. [\[CrossRef\]](#)
67. Babar, P.; Pawar, B.; Lokhande, A.; Gang, M.; Jang, J.; Suryawanshi, M.; Pawar, S.; Kim, J. Annealing temperature dependent catalytic water oxidation activity of iron oxyhydroxide thin films. *J. Energy Chem.* **2017**, *26*, 757–761. [\[CrossRef\]](#)
68. Villagra, A.; Millet, P. An analysis of PEM water electrolysis cells operating at elevated current densities. *Int. J. Hydrogen Energy* **2019**, *44*, 9708–9717. [\[CrossRef\]](#)
69. Frensch, S.; Fouda-Onana, F.; Serre, G.; Thoby, D.; Araya, S.; Ker, S. Influence of the operation mode on PEM water electrolysis degradation. *Int. J. Hydrogen Energy* **2019**, *44*, 29889–29898. [\[CrossRef\]](#)
70. Kamlungsua, K.; Su, P.; Chan, S. Hydrogen Generation Using Solid Oxide Electrolysis Cells. *Fuel Cells* **2020**, *20*, 644–649. [\[CrossRef\]](#)

71. Sapountzi, F.; Gracia, J.; Weststrate, C.; Fredriksson, H.; Niemantsverdriet, J. Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Prog. Energy Combust.* **2017**, *58*, 1–35. [[CrossRef](#)]
72. Xie, H.; Zhao, Z.; Liu, T.; Wu, Y.; Lan, C.; Jiang, W.; Zhu, L.; Wang, Y.; Yang, D.; Shao, Z. A membrane-based seawater electrolyser for hydrogen generation. *Nature* **2022**, *612*, 673–678. [[CrossRef](#)] [[PubMed](#)]
73. Liu, T.; Zhao, Z.; Tang, W.; Chen, Y.; Lan, C.; Zhu, L.; Jiang, W.; Wu, Y.; Wang, Y.; Yang, Z.; et al. In-situ direct seawater electrolysis using floating platform in ocean with uncontrollable wave motion. *Nat. Commun.* **2024**, *15*, 5305. [[CrossRef](#)]
74. Cai, X.; Lin, R.; Xu, J.; Lu, Y. Construction and analysis of photovoltaic directly coupled conditions in PEM electrolyzer. *Int. J. Hydrogen Energy* **2022**, *47*, 6494–6507. [[CrossRef](#)]

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