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Technical trajectories and cost effectiveness of offshore wind driven green hydrogen production

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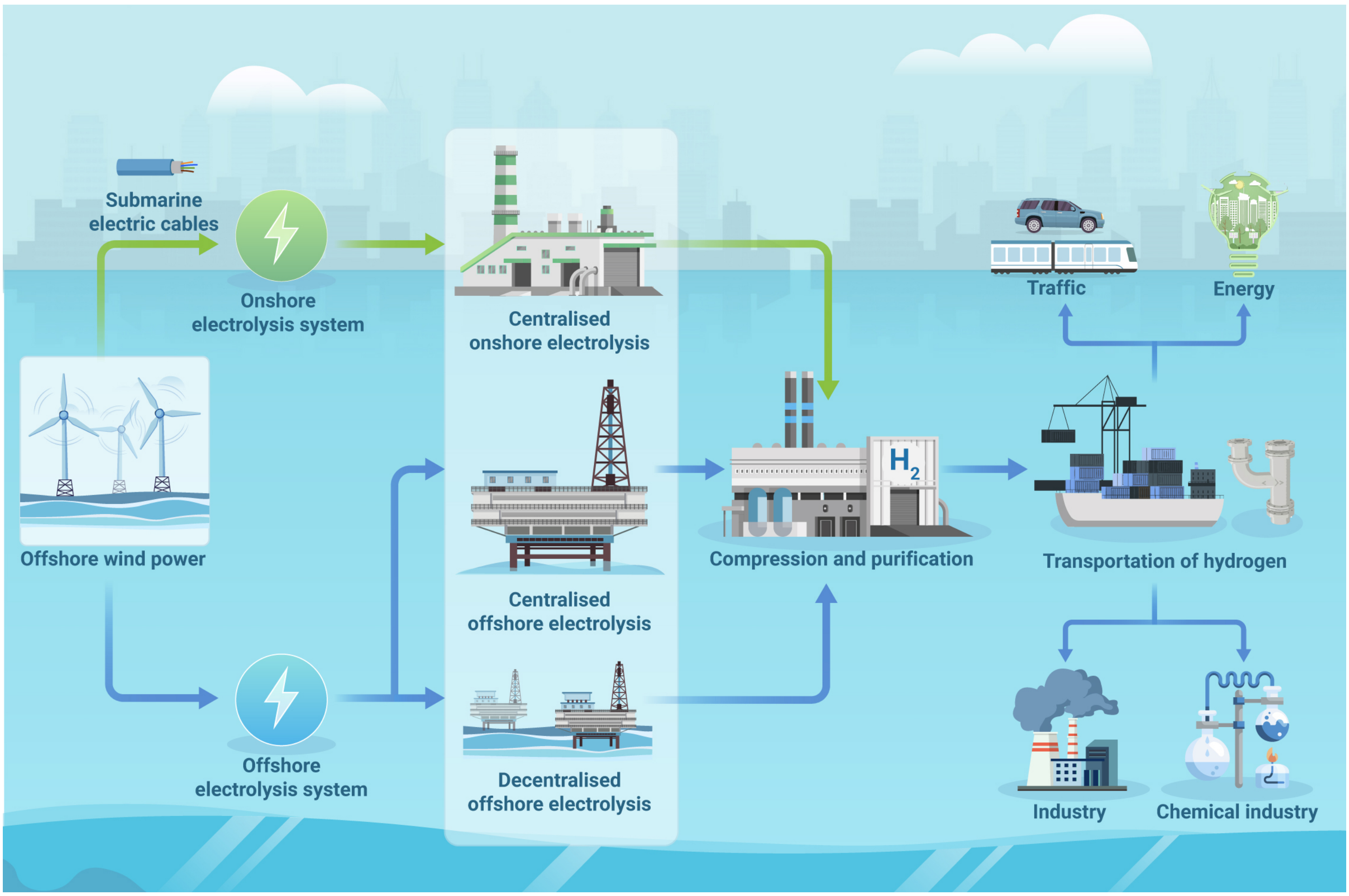
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Offshore wind-powered hydrogen production via AWE, PEMWE, and SOEC offers a key pathway for deep decarbonization.
- Spatial analysis reveals significant potential in Zhejiang, Guangdong, and Bohai Sea regions, with levelized costs projected to fall to \$1.5/kg by 2030.
- This near-zero emission technology produces hydrogen with a carbon footprint of only 0.4~0.8 kg CO_2 eq/kg H_2, critically supporting dual carbon goals.

Technical trajectories and cost effectiveness of offshore wind driven green hydrogen production

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Hydrogen production from offshore wind power is a key pathway for deep decarbonization, converting abundant wind energy into green hydrogen to support energy system transformation. This report systematically analyzes its technical pathways, resource potential, spatial distribution, and economic and environmental benefits, reviews the applicability of mainstream water electrolysis technologies, including alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and solid oxide electrolysis (SOEC) in marine environments. The study also compares three system configurations, i.e., offshore centralized, offshore distributed, and onshore centralized hydrogen production. Spatial analysis reveals significant regional agglomeration, with Zhejiang and Guangdong exhibiting the highest marine resource potential, while Liaoning and Hebei around the Bohai Sea showing strategic advantages due to their proximity to load centers and established infrastructure. Economically, strategic policy interventions could reduce electrolyzer costs by 40% in the near term and up to 80% over the longer term, according to IRENA. The IEA projects that the levelized cost of hydrogen from offshore wind could fall to approximately \$1.5/kg by 2030 in favorable regions, achieving cost-competitiveness with blue hydrogen. Environmentally, the life-cycle carbon footprint of offshore wind-based hydrogen is only 0.4–0.8 kg CO_2 eq/kg H_2, significantly lower than the 9.3–11.9 kg CO_2 eq/kg H_2 of grey hydrogen. By prioritizing resource-rich coastal provinces with strong industrial bases, this approach offers a near-zero emission solution, providing a critical technical pathway toward achieving dual carbon goals.

INTRODUCTION

Global warming and climate change are primarily driven by the continued reliance on fossil fuels to meet growing global energy demands, resulting in substantial increases in carbon dioxide emissions. As a versatile energy carrier, hydrogen holds significant promise as a clean alternative to fossil fuels across multiple sectors, including industrial applications, transportation, and energy storage systems. Consequently, hydrogen energy has become a cornerstone of global energy transition strategies, offering a pathway toward decarbonization and sustainable development.[1] Among various hydrogen production methods, hydrogen production from offshore wind power has become an essential solution to ensure stable and reliable hydrogen supply due to its rich wind energy resources, high power generation hours and large-scale development.

Existing hydrogen production is primarily categorized into three pathways, i.e., grey, blue, and green hydrogen, each presenting distinct economic and environmental trade-offs. Grey hydrogen, predominantly produced via steam methane reforming (SMR) of natural gas without carbon capture measures, remains the most widely adopted production method due to its competitiveness cost. However, its significant carbon emissions (10.13kgCO_2/kgH_2) face growing regulatory challenges under increasingly stringent climate policies and carbon pricing mechanisms.[2] Blue hydrogen, which integrates carbon capture and storage (CCS) with SMR, can reduce emissions by 43~76% while leveraging existing natural gas infrastructure.[2] Nevertheless, its economic feasibility heavily depends on CCS system efficiency, natural gas price stability, and policy support for carbon mitigation technologies. In contrast, green hydrogen, produced through water electrolysis powered exclusively by renewable energy, offers near-zero carbon emissions and represents the most sustainable pathway. However, its widespread adoption is currently constrained by high energy requirements, substantial capital costs for electrolyzers, and underdeveloped infrastructure for large-scale deployment. According to authoritative analyses by the International Energy Agency,[3] the fossil fuel based hydrogen still dominates global production, accounting for 98~99% of total output. Grey hydrogen constitutes 75~80% of this share, primarily from SMR and coal gasification, while low-carbon hydrogen (blue and green combined) represents less than 1%. Notably, green hydrogen contributes a mere 0.04% of global production, with most projects remaining in demonstration or early commercial phases.

By converting offshore wind energy into green hydrogen, this approach effectively alleviates wind power curtailment, enhances the utilization efficiency of wind resources, enables the decarbonization of hydrogen energy value chains, and broadens the supply channels for hydrogen.[4] This model is regarded as a key pathway for future green hydrogen production and a direction for the sustainable development of the offshore wind industry with broad application prospects. Developing seawater electrolysis technologies compatible with renewable energy sources, aiming for low-cost, energy-efficient, and long lifespan hydrogen production from seawater, represents an practical approach to advancing a forward-looking and innovative green hydrogen economy that supports carbon peaking and carbon neutrality goals. The innovation and contribution of this study may exist in the following points: (i) the technological trajectories of offshore wind power hydrogen production are mapped, (ii) the geographic layout constraints of hydrogen production powered by offshore wind plants are sorted out, and (iii) the cost-benefit comparisons of offshore wind powered hydrogen production are compared. With the ongoing implementation of the dual carbon strategy, the integrated development of offshore wind power and hydrogen production will play an increasingly vital role in enhancing the efficient use of renewable energy, accelerating the transformation of the energy structure, and providing critical momentum for achieving green and low-carbon development.

MATERIALS AND METHODS

Offshore wind power hydrogen production technology pathways

The technical routes of hydrogen production from offshore wind power are mainly divided into three categories, i.e., distributed electrolytic hydrogen production from offshore wind power, centralized electrolytic hydrogen production from offshore wind power and onshore electrolytic hydrogen production from offshore wind power.[5] As shown in Figure 1.The first two routes are based on wind energy captured by offshore wind farms, where hydrogen is produced by electrolyzing water offshore and transported back to land by dedicated pipelines or ships.

Centralized hydrogen production from offshore wind power refers to the centralized transmission of electricity generated by wind turbines to offshore substations. After voltage transformation, direct current power is transmitted to the offshore electrolysis device for hydrogen production through cables. This technology route has the significant advantage of large-scale development, is suitable for unified operation and maintenance management, and is usually deployed in deep sea areas with more stable and abundant wind energy resources. However, the problems of transportation cost and pipeline maintenance caused by long-distance transportation still need to be solved.

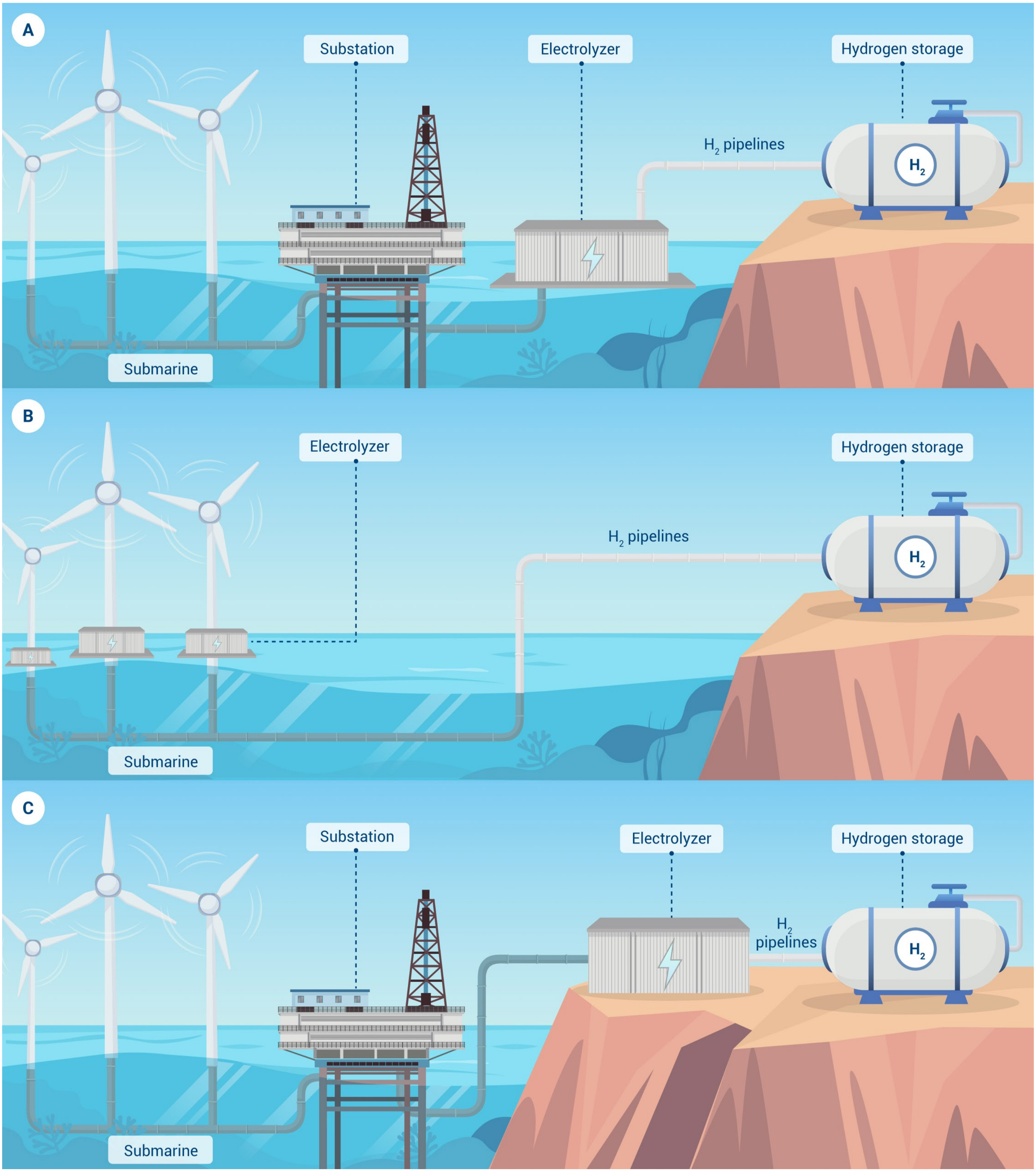

Figure 1. Three technical routes for hydrogen production from offshore wind power generation (A) Distributed electrolysis hydrogen production from offshore wind power; (B) Centralized hydrogen production from offshore wind power ; (C) Onshore electrolysis hydrogen production from offshore wind power.

The offshore wind power distributed electrolysis hydrogen production adopts the modular combination mode of one-to-one correspondence between wind turbines and electrolyzers, and the power generated by the wind turbines is directly supplied to the supporting hydrogen production equipment. This mode shows strong system independence, with the single unit fault not affecting the normal operation of other equipment. Meanwhile, due to the local utilization of power, the power loss in the process of cable transmission is effectively reduced. However, its development also faces many challenges, including the limited space of wind turbine platforms and the impact of offshore wind power output fluctuation on the life of electrolyzers. Offshore wind power onshore electrolysis hydrogen production is to transport the offshore wind power passing through the offshore substation back to the electrolyzer on the shore through the sea cable, and the hydrogen is produced by electrolysis of water on the shore. This method is suitable for offshore wind farm with convenient maintenance and mature technology, but the high loss caused by power transportation will limit its development.

Seawater based hydrogen production currently follows two principal approaches, i.e., indirect electrolysis using purified seawater and direct seawater electrolysis. The primary technical challenge in direct seawater electrolysis arises from the complex ionic composition of seawater. During seawater electrolysis, parallel to the primary water-splitting reaction, impurity-induced side reactions may occur under high current densities. Notably, chloride ions are oxidized at the anode, generating toxic chlorine gas, which subsequently reacts with hydroxide ions to form corrosive hypochlorite species. Concurrently, dissolved impurities including sulfate, magnesium, and calcium ions can adversely affect hydrogen evolution efficiency through multiple interference mechanisms.[6] While contemporary industrial electrolysis predominantly employs ultrapure water, seawater electrolysis powered by renewable electricity presents a promising sustainable alternative, leveraging seawater's global abundance and potential economic viability.[7] The indirect approach, involving prior desalination, essentially constitutes conventional freshwater electrolysis and represents the most technologically mature seawater-derived hydrogen production method. The underlying electrochemical mechanism comprises two half-reactions, i.e., Cathodic hydrogen evolution reaction (HER) and Anodic oxygen evolution reaction (OER). Currently, three predominant water electrolysis technologies exist for hydrogen production, including alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis (SOEC). Generally, the complete offshore wind-to-hydrogen value chain encompasses four key operational stages, i.e., offshore wind power generation, seawater pretreatment, electrolytic hydrogen production, and hydrogen storage/transportation, with comparative analysis of the three aforementioned electrolysis technologies.

Alkaline water electrolysis (AWE) is the most mature and commercially established electrolysis technology up to date, with industrial applications dating back to the early 20th century. This technology offers energy conversion efficiencies of 50~68% and has undergone significant improvements in electrode performance and current density through decades of development.[8] The system configuration consists of electrode pairs (anode and cathode) separated by a porous diaphragm in an alkaline electrolyte solution, typically 20~30% potassium hydroxide (KOH) due to its optimal ionic conductivity and stability. During operation, water molecules undergo reduction at the cathode to produce hydrogen gas at near-ambient temperatures, while hydroxyl ions (OH-) migrate through the diaphragm to the anode where oxygen evolution occurs. AWE offers distinct advantages including non-reliance on precious metal catalysts, favorable economic viability, and extended operational lifetime, making it particularly suitable for large-scale hydrogen production under steady-load conditions. However, technical limitations persist, including relatively low current density, sluggish dynamic response, potential gas crossover through diaphragms, and electrolyte corrosion issues, all of which constrain its compatibility with intermittent renewable power sources and dynamic operating regimes.

Proton exchange membrane water electrolysis (PEMWE) technology, developed since the 1960s, has achieved high system integration through continuous technological advancements, although it still faces challenges in key materials and core technologies that rely on supplies from developed countries. This technology utilizes the bipolar electrolyzer structure composed of anode and cathode electrodes with a perfluorosulfonic acid proton exchange membrane forming the membrane electrode assembly (MEA). During operation, water undergoes oxidation at the anode to produce oxygen, electrons and protons, with the protons migrating through the membrane to the cathode where they combine with electrons to form hydrogen. PEMWE offers distinct advantages including high current density, excellent gas purity, rapid start-stop capability, and wide load adjustment range, making it particularly suitable for coupling with intermittent renewable energy sources like wind and solar power.[9] The compact system design enables high-pressure hydrogen output with good integration flexibility. However, this technology requires high-purity water inputs and depends on precious metal catalysts such as iridium for the anode, resulting in higher manufacturing costs. Additionally, its long-term operational stability remains slightly inferior compared to alkaline water electrolysis systems.

Solid oxide electrolysis (SOE or SOEC) is a high-efficiency, high-temperature hydrogen production technology that employs solid oxide ceramics as the electrolyte to electrolyze water vapor into hydrogen at operating temperatures typically ranging from 500 to 850°C.[10] Unlike solid oxide fuel cells (SOFC), which generate electricity through electrochemical oxidation of hydrogen, SOEC performs the reverse process via water electrolysis. On the cathode side, water vapor is dissociated into hydrogen atoms and oxygen ions under the action of a catalyst. Electrons reduce the hydrogen atoms to form hydrogen gas, while oxygen ions (O^{2-}) migrate through the electrolyte layer characterized by high oxygen ion conductivity to the anode side, where they release electrons and form oxygen. Both electrodes adopt a porous structure to facilitate gas diffusion and enhance the activity of the three-phase boundary. The principal advantage of SOEC lies in its exceptionally high energy conversion efficiency, which can theoretically approach 100%, far surpassing that of low-temperature electrolysis technologies such as AWE and PEM.[8] By utilizing external heat sources, such as industrial waste heat, nuclear energy, or concentrated solar thermal energy, SOEC significantly reduces electrical energy consumption and enhances overall system efficiency. However, its high-temperature operation introduces considerable engineering challenges, including difficulties in system sealing, limited chemical and mechanical stability of electrode and electrolyte materials under high-temperature and high-humidity conditions, and increased complexity and cost due to the need for separation of the hydrogen-water vapor mixture produced at the cathode. Note that, SOEC remains at the experimental and pilot-demonstration stage, hindered by limited stack lifetime, thermal safety concerns, and system-integration complexity, which make near-term commercialization unlikely.

In offshore wind-to-hydrogen systems, the primary water electrolysis technologies, i.e., alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and solid oxide electrolysis cells (SOEC) demonstrate distinct development potentials and application values based on their respective technical characteristics. AWE, with its mature technology, cost-effectiveness and operational stability, remains preferable for fixed offshore wind farms and onshore centralized hydrogen production, maintaining short-term commercial advantages despite its limited dynamic response to fluctuating offshore power inputs. PEMWE's high current density, rapid start-stop capability and compact design make it particularly suitable for direct integration with offshore wind power, especially in floating platform applications and distributed hydrogen production systems, as evidenced by multiple international demonstration projects establishing it as the future core technology for offshore hydrogen production. SOEC exhibits long-term potential for deep-sea multi-energy complementary systems combining wind, solar thermal or industrial waste heat through its thermoelectric synergy advantages, potentially enabling efficient offshore energy islands or hydrogen hubs, though current material stability and system reliability challenges maintain it at the research and development phase. The technical parameters of the three mainstream water electrolysis hydrogen production are compared as shown in Table 1.

RESULTS

Hydrogen production potentials and geographical layout constraints

According to the International Renewable Energy Agency classification system, the hydrogen production potential of wind power can be divided into different levels, i.e., theoretical potential, technical potential, economic potential and market potential. China holds significant potential for offshore hydrogen production, with an estimated annual capacity of 292.1 Mt. In particular, the eastern coastal provinces are expected to contribute approximately 90 Mt annually, capitalizing on their geographical advantages.[15] This regional output is comparable to, or even exceeds, the projected total national hydrogen demand of countries by 2050.According to projections by the China Hydrogen Energy Alliance, China's hydrogen demand is expected to reach 37~42 Mt per year by 2030, with renewable hydrogen accounting for about 8%-15% of that.[16] China's total hydrogen demand is expected to reach 90~130 Mt a

Table 1. Comparison of technical parameters for three water electrolysis technologies

Technology	AWE	PEMWE	SOEC
Current Density ($A\cdot cm^{-2}$)	0.2~0.8[11]	0.6~2.0[12]	0.3~1.0[11]
Operating Temperature (°C)	70~90[13]	50~80[13]	700~850[13]
Operating Pressure (bar)	2~10[12]	15~30[9]	<30[12]
Stack Lifetime (kh)	60[13]	50~80[13]	<20[13]
Efficiency (LHV, %)	50~68[13]	67~82[14]	75~85[13]
CAPEX (USD/kW)	500~1400[11]	1100~1800[11]	2800~5600[17]

year by 2060.[17]

In terms of spatial distribution, the hydrogen production potential of offshore wind power exhibits pronounced regional agglomeration, providing a solid basis for formulating differentiated regional development strategies. The regional resource endowment also leads to different development paths, i.e., renewable energy-rich regions prioritize green hydrogen production, whereas natural gas pipeline hub regions prioritize storage and transportation. It is particularly noteworthy that there are significant differences in the spatial distribution of economic potential and resource potential. At the provincial level, Zhejiang and Guangdong have the greatest potential, with annual production capacities projected to reach 10.8 million tons and 7.4 million tons, respectively.[18] Although wind resources in northern China are relatively limited, provinces such as Liaoning and Hebei rely on their proximity to energy consumption centers and sound infrastructure, which is expected to lead the way in achieving cost-competitive hydrogen supply by 2030.

In terms of industrial layout and regional synergy, hydrogen production in the resource area and hydrogen consumption in the load area have been established. The offshore wind power hydrogen production is highly consistent with the national macro strategy. China's five major offshore wind power bases, namely Shandong Peninsula, the Yangtze River Delta, Southern Fujian, eastern Guangdong, and the Gulf of Tonkin, provide a solid project carrier for large-scale hydrogen production. Meanwhile, the coastal economic circles such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Greater Bay area, with active hydrogen energy policies and strong industrial bases, naturally become the core markets for offshore hydrogen energy consumption and application. The Bohai Economic Rim provinces of Liaoning and Hebei and the southeastern coastal provinces of Fujian and Jiangsu also showed the alternative conditions for offshore wind power hydrogen. With the continuous improvement of wind power technology and electrolysis efficiency, the intensity of hydrogen production in key coastal areas is expected to increase significantly. Hydrogen production from offshore wind power is thus expected to become the core pillar of China's green hydrogen energy supply system by systematically promoting technology research and development, improving the policy system, and optimizing space layout, providing critical support for the transformation of the energy structure and the achievement of carbon peaking and carbon neutrality.

The alignment with provincial development plans further clarifies this path, which is highly consistent with their being the first to realize their economic potential. For example, Zhejiang and Guangdong with the greatest potential emphasize the creation of high-altitude manufacturing sites for hydrogen energy equipment and the large-scale deployment of fuel-cell vehicles through demonstration city clusters, i.e., core advantages in key fuel-cell materials and equipment will be formed and fuel-cell vehicles will be deployed on a large scale in demonstration city clusters by 2025. Fujian and Jiangsu, with resource endowments, are committed to building a Coastal hydrogen corridor and a leading area for Yangtze River Delta hydrogen development. The Bohai Rim region, including Liaoning and Hebei, with the advantage of being close to the market, the plan focuses on building a Hydrogen energy trading center in Northeast Asia, building an Industrial by-product hydrogen supply chain, and making breakthroughs in transportation and ports through Hydrogen import into ten thousand homes.

Cost-benefit comparisons of offshore wind powered hydrogen production

Green hydrogen represents a zero-carbon emission energy production method with substantial environmental advantages. In contrast to conventional fossil fuel based hydrogen production, e.g., steam methane reforming or coal gasification, green hydrogen demonstrates near-zero lifecycle carbon emissions. Specifically, offshore wind-powered hydrogen production utilizes exclusively renewable energy inputs during operation, eliminating direct process emissions. The limited lifecycle emissions associated with this pathway originate primarily from equipment manufacturing and transportation processes, yet remain significantly lower than those of gray hydrogen production methods. Table 2 summarizes the technical parameters, production costs, and carbon footprints of the hydrogen production pathways, providing a comparative framework for evaluating their suitability in offshore wind-to-hydrogen systems.

Financial viability is assessed through the levelized cost of hydrogen (LCOH) framework, which incorporates capital expenditures (CAPEX), operating expenses (OPEX), and input costs.[19] The CAPEX component covers wind farm construction, electrolyzer systems, and supporting infrastructure, with electrolyzers representing the dominant cost factor. The technological advancements and economies of scale are driving substantial CAPEX reductions. According to IRENA analysis, strategic policy interventions including the scaling of manufacturing capacity, promotion of technological innovation, and development of competitive supply chains have the potential to reduce electrolyzer capital costs by 40% in the near term and by up to 80% over the longer term.[20] Recent industry data indicated that Chinese alkaline electrolyzer costs currently range between $480~720/kW, substantially lower than those in Western markets.[21] OPEX for electrolytic hydrogen production primarily comprise maintenance, consumables, labor, and electricity procurement, with electricity costs typically accounting for over 60% of total OPEX.[22] The continued decline in the cost of renewable electricity generation, particularly from wind and solar photovoltaic sources, directly contributes to reducing the levelized cost of hydrogen (LCOH).

The economic competitiveness of green hydrogen hinges on two critical levers, i.e., Electrolyzer cost reduction and renewable electricity price declines. Complementary policy instruments, including capital subsidies, production incentives, and carbon pricing mechanisms, further enhance viability through cost structure optimization and market scaling effects. The hydrogen production value chain encompasses multiple interdependent factors, including equipment costs, electricity prices, policy frameworks, and technological efficiency, which exhibit significant regional and temporal variations while facing future uncertainties. As outlined in the BNEF report,[25] the key assumptions for green hydrogen cost projections include renewable electricity prices ranging from $20~60/MWh depending on regional resource endowments, electrolyzer system capacities between 10~100MW and wind farm capacity factors of 35~50%. The synergistic implementation of these measures will be instrumental in achieving commercial-scale deployment of green hydrogen.

Offshore wind power demonstrates significant regional decarbonization potential through dual pathways of electricity generation and low-carbon fuel production. Projections indicated its deployment could mitigate 5~7 billion tons of CO_2 emissions from the global power sector within two decades, while concurrently improving air quality and strengthening energy security through reduced fossil fuel imports.[28] Although current hydrogen production costs remain elevated, the substantial environmental benefits combined with considerable cost reduction potential, achievable through technological innovation, economies of scale, and policy mechanisms, position offshore wind-to-hydrogen as a prospective cornerstone for cost-competitive green hydro-

Table 2. Comparisons with other hydrogen production technologies.

Hydrogen Type	Grey Hydrogen(SMR)	Blue Hydrogen(SMR+CCS)	Green Hydrogen
Hydrogen production technology	Produced via Steam Methane Reforming (SMR) of natural gas, without carbon capture	Based on SMR or Auto-Thermal Reforming (ATR) coupled with Carbon Capture, Utilization and Storage (CCUS) technologies	Produced via electrolysis of water using renewable electricity Key electrolyzer types include Alkaline (AWE), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis Cells (SOEC)
Technical Characteristics	Technologically mature and widely deployed; Low capital and operational expenditure; High greenhouse gas emissions	Leverages existing natural gas infrastructure; Offers substantial emission reductions; Residual emissions and methane leakage remain concerns	Near-zero lifecycle carbon emissions when powered by renewables; Enables flexible operation and sector coupling; Technology is rapidly advancing, though not yet cost-competitive at scale
Cost of hydrogen production	$1.50~$2.50/kg[23]	$1.50~$3.50/kg[24]	$3.74~$11.70/kg[25] depending on the price of electricity and the type of electrolyzer
Carbon Emissions	9.3~11.9[26] $kgCO_2eq/kgH_2$	1.5~6.2[3] $kgCO_2eq/kgH_2$ depending on carbon capture efficiency, methane leakage, and the source of natural gas	0.4~0.8[27] $kgCO_2eq/kgH_2$ Hydrogen production from offshore wind power

gen supply, crucial for global carbon neutrality objectives.

CONCLUSIONS

China's rapid expansion of offshore wind capacity and hydrogen energy infrastructure has established a basic foundation for offshore wind-to-hydrogen development. The 14th Five-Year Plan for Renewable Energy Development outlines five major offshore wind bases in the Shandong Peninsula, the Yangtze River Delta, Southern Fujian, Eastern Guangdong, and Beibu Gulf, with provincial-level capacity targets collectively approaching 200 GW. This ambitious initiative is expected to drive peak construction activity over the next 5~10 years. By the end of September 2025, China's cumulative offshore wind installations exceeded 44 GW, representing the world's largest annual capacity additions and providing critical infrastructure for industrial-scale offshore wind hydrogen production. Meanwhile, China's Medium- and Long-Term Plan for Hydrogen Energy Industry Development (2021-2035) establishes hydrogen as a strategic energy vector within the national energy infrastructure, emphasizing its fundamental role in facilitating low-carbon energy transitions.

As one of the key technologies for achieving global carbon neutrality, hydrogen production from offshore wind power offers significant emission reduction potential. In industrial applications, the steel industry worldwide is actively pursuing a transition from carbon-based metallurgy to hydrogen-based metallurgy. In addition, the application of green hydrogen in heavy-duty transportation sectors, such as trucking, shipping, and aviation, has the potential to reduce carbon emissions by approximately 1 billion tons annually, offering crucial support for the deep decarbonization of the transportation industry.[3] The application scope of hydrogen energy continues to expand beyond transportation into key industrial sectors including power generation, chemicals, steel manufacturing, and energy storage systems. Notably, offshore wind-based hydrogen production demonstrates significant market potential for integration with coastal industrial clusters, particularly for chemical synthesis, steel decarbonization, and renewable energy storage.

Hydrogen production technologies vary widely depending on application scenarios, particularly in coastal and offshore environments. Offshore hydrogen production primarily utilizes water electrolysis powered by renewable energy sources including wind and solar energy. By leveraging the abundant wind and solar resources available in nearshore areas and combining them with mature water electrolysis technologies, large-scale clean hydrogen production can be achieved. Furthermore, offshore blue hydrogen production is feasible through natural gas reforming coupled with carbon capture and storage (CCS), leveraging existing offshore natural gas infrastructure. Currently, offshore hydrogen production primarily relies on water electrolysis powered by offshore wind. Offshore wind resources are abundant and stable, making them well-suited for large-scale hydrogen generation. Electrolyzers powered directly by offshore wind farms can produce hydrogen, which is then transported to shore via pipelines or ships.[29] Additionally, the direct electrolysis of seawater represents a promising future direction for offshore hydrogen production. Although at the early stage, this technology has the potential to become a significant pathway for offshore hydrogen generation.

Direct seawater electrolysis for hydrogen production remains at the early stage, facing significant technical challenges. A key issue is ensuring that the electrolyzer's cathode and anode can withstand the harsh and complex chemical composition of seawater. Moreover, the highly variable marine climate increases equipment failure rates and leads to high maintenance costs. Considerable optimization is still required before large-scale deployment becomes feasible. Future research may focus on the design of electrocatalysts and the development of corrosion-resistant anode materials, along with highly efficient electrocatalysts capable of operating reliably in harsh seawater environments. Efforts should also aim to simultaneously enhance the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) while minimizing the competing chloride evolution reaction (ClER). Additionally, improvements in electrode and cell design are needed to reduce pH gradients between the anode and cathode under high current densities, thereby minimizing associated energy losses.

Currently, the cost of hydrogen production from offshore wind power is primarily influenced by the construction and operational costs of offshore wind farms, the capital expenditure and operating costs of electrolyzers, as well as the additional expenses associated with hydrogen compression, storage, and transportation. Government subsidies for green hydrogen and the implementation of carbon pricing mechanisms are expected to enhance the economic competitiveness of offshore wind hydrogen production. According to the International Energy Agency (IEA), the levelized cost of hydrogen produced from offshore wind could decline to approximately $1.5 per kilogram by 2030 in regions with the most favorable wind resources.[2] At this cost level, green hydrogen is expected to become cost-competitive with blue hydrogen—which is estimated to range between $1.5 and $3.0 per kilogram.[2] By 2050, further cost reductions could see green hydrogen fall below this range under optimistic technology development scenarios.[30] However, its large-scale commercialization remains contingent upon the establishment of economically competitive and environmentally sustainable production and utilization value chains.

In the context of the global response to climate change, hydrogen production from offshore wind power has emerged as an innovative energy solution with substantial potential and broad application prospects. The integration of offshore wind power with water electrolysis technology addresses the challenge of renewable energy curtailment and enables the decarbonization of the entire hydrogen energy value chain, contributing to the green transformation of the energy system. This report reviews the technological pathways, economic feasibility, and emission reduction benefits of offshore wind hydrogen production, and proposes key recommendations for its future development. With ongoing technological advances and proactive policy support, offshore wind hydrogen production is expected to become the most cost-effective approach to green hydrogen generation, providing critical momentum for achieving global green and low-carbon development. Through sustained innovation and supportive policy frameworks, offshore wind hydrogen production will play an increasingly vital role in the worldwide energy transition, advancing human society toward a sustainable future.

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AUTHOR CONTRIBUTIONS

M.H. and S.L. designed the research; X.L., L.C. and K.L. performed the investigation and validation; X.L., S.L. and M.H. prepared the original draft and conducted data curation; M.H., S.L. and C.A. reviewed and edited the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.