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The Development Status and Prospects of Direct Seawater Electrolysis for Hydrogen Production

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Abstract. The in-situ direct electrolysis of seawater for hydrogen production without desalination is a promising green hydrogen production method. Its core lies in achieving efficient blocking of seawater ions and efficient supply of pure water through the phase transition migration mechanism. This paper systematically reviews the principal evolution, key material optimization, and system integration progress of this technology, and focuses on analyzing the impact of waterproof breathable membranes, self-hydrating electrolytes, and efficient catalysts on the system performance. The research shows that this technology has achieved coupling operation with offshore wind power and has demonstrated good stability and adaptability in real marine environments. Although there are still challenges in catalyst cost and system scale-up, through the improvement of standard systems, the establishment of industrial chains, and the innovation of application models, this technology is expected to achieve commercial application within the next decade. In addition, continued cross-disciplinary collaboration is expected to further accelerate the technological refinement and practical deployment of seawater electrolysis systems.

Keywords: Hydrogen production without desalination of seawater, Principle of phase change migration, Optimization of core materials, Coupling with offshore wind power, Technical and economic feasibility

1. Introduction

Since 2007, global resource consumption has consistently exceeded the ecological carrying capacity of the Earth. Under the current development model, the resource demands far exceed the regeneration speed of the natural system. Facing the dual challenges of resource scarcity and environmental pressure, promoting green, low-carbon, and sustainable energy transformation has become an inevitable choice. Offshore wind power hydrogen production technology, as a clean energy solution, not only helps reduce reliance on fossil energy but also improves energy utilization efficiency, and is one of the important paths to achieve sustainable development [1].

The ocean covers 70% of the Earth's surface and is the largest hydrogen reserve on the planet. Skipping the energy-intensive and land-consuming seawater desalination process and directly converting seawater efficiently and economically into hydrogen has long been regarded as an unachievable technical path. It was not until June 2023 that the world's first pilot test of the offshore direct electrolysis hydrogen production technology without desalination of seawater, led by China's

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Dongfang Electric Group and the team of Academician Xie Heping, was successful. This vision was thus realized [2,3]. This technology achieves the goal of directly producing high-purity hydrogen from seawater through a revolutionary physical-mechanical method of separating seawater ions.

The in-situ direct electrolysis technology for hydrogen production from undistilled seawater has entered the large-scale engineering demonstration stage since September 2025, aiming at future industrial application. In the future, further in-depth research can be conducted on the aspects of industrialization and the construction of the ecological chain. This paper systematically studies the current development status and future trends of the in-situ direct electrolysis technology for hydrogen production from undistilled seawater, focusing on the seawater direct electrolysis technology based on the principle of phase change migration, analyzing the key factors such as core material optimization and system integration that affect the technical efficiency, aiming to clarify the path for this technology to move from the laboratory to engineering application, and providing theoretical basis and development suggestions to promote its commercialization process.

2. Principle and characteristics of the in-situ direct electrolysis of seawater for hydrogen production technology

2.1. Principle

The core principle of the in-situ direct electrolysis of seawater for hydrogen production technology is based on the "phase transition migration" mechanism. This technology constructs a hydrophobic porous polytetrafluoroethylene (PTFE) waterproof breathable membrane as the gas interface between seawater and self-wetting electrolyte (SDE, such as KOH solution). It utilizes the pressure difference of water vapor on both sides to drive water molecules to migrate spontaneously [4]. As shown in Figure 1, the specific process is as follows: Water molecules on the seawater side undergo vaporization at the interface and form water vapor, which diffuses through the micron-sized gas path within the membrane to the side of the self-wetting electrolyte (SDE, such as KOH solution), and then are absorbed by the electrolyte and re-liquefied. This "liquid-gas-liquid" phase transition migration process achieves the in-situ purification of seawater, providing pure water raw materials for the electrolysis reaction. Since liquid seawater and impurity ions (such as Cl^-, SO_4^{2-}, Mg^{2+}, etc.) cannot penetrate this hydrophobic gas interface, the system achieves an almost 100% ion barrier efficiency.

The driving force of this technology stems from the pressure difference of water vapor between seawater and the self-humidifying electrolyte. When the water migration rate reaches equilibrium with the electrolysis consumption rate, the system establishes a new thermodynamic equilibrium, achieving continuous and stable water migration and hydrogen production. The micro-scale gas path design significantly shortens the water vapor migration path, increases the water migration rate, and completely blocks impurities such as chloride ions, sulfate ions, and magnesium ions in seawater, fundamentally avoiding electrode corrosion and side reactions [5,6].

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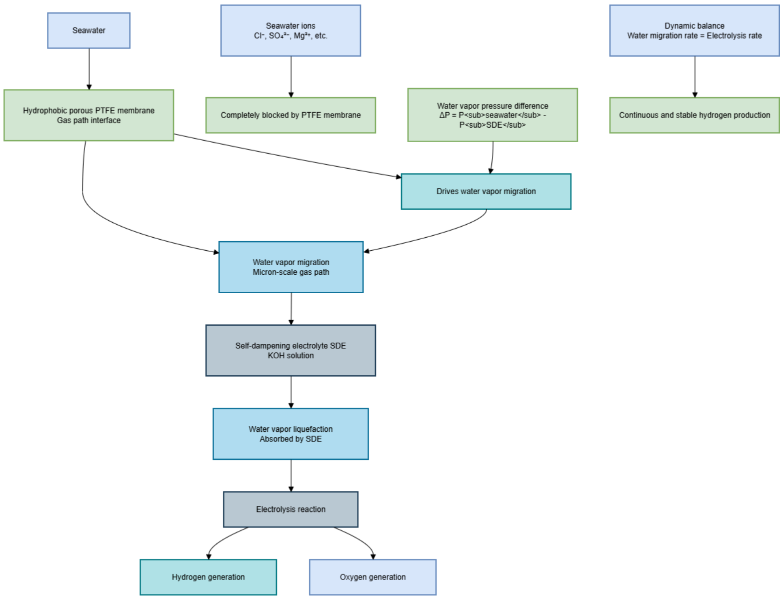

Figure 1. Principle flowchart of in-situ direct electrolysis for producing hydrogen from undiluted seawater (photo/picture credit: original)

2.2. Features

The most notable feature of this technology lies in its inherent safety. The core phase change migration mechanism completely blocks soluble impurities such as chloride ions and magnesium ions in seawater at the physical level, providing a highly pure electrolytic environment for electrochemical reactions. This characteristic fundamentally avoids the common problems in traditional seawater electrolysis, such as electrode corrosion, catalyst deactivation, and chlorine evolution side reactions, thereby significantly enhancing the long-term operational stability of the system and the service life of key components.

At the system architecture level, this technology demonstrates a high degree of integration and simplicity. It eliminates the indispensable and energy-intensive pre-treatment unit (such as reverse osmosis desalination equipment) and the complex subsequent purification system in the traditional seawater hydrogen production process. This integrated design not only reduces the initial equipment investment and system complexity but also enhances the overall operational reliability and simplifies the maintenance process. Moreover, by skipping the high-energy-consuming seawater desalination step, the total hydrogen production energy consumption of the system can be significantly reduced, giving it inherent advantages in efficiently coupling with fluctuating renewable energy sources (such as offshore wind power).

It is particularly noteworthy that this technology has successfully achieved direct coupling operation with offshore wind power under actual sea conditions. Its system possesses dynamic self-regulation capabilities, which can intelligently adjust the hydrogen production rate in response to fluctuations in wind energy input, demonstrating excellent adaptability to intermittent renewable energy sources. This inherent compatibility has laid a solid technical foundation for the construction of a new model of integrated offshore clean energy supply, "power generation - hydrogen production", representing a highly promising path for marine hydrogen energy development.

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3. Key factors affecting efficiency

3.1. Optimization of core materials

In the development process of in-situ direct hydrogen production technology using undiluted seawater, the optimization of core materials is not only the foundation for enhancing efficiency but also the fundamental driving force for advancing the technology from theory to practice. This optimization process involves the precise coordination and collaborative innovation of multiple key components. Each breakthrough in this process may lead to a qualitative leap in system performance.

Firstly, the innovative design of the waterproof breathable layer constitutes the core breakthrough point of this technology [7]. This micron-scale interface, located between seawater and electrolyte, directly determines the efficiency limit of the entire system. The latest research indicates that an ideal waterproof breathable layer must simultaneously meet multiple demanding requirements. Its pore size distribution must be controlled at the sub-micron level, ensuring efficient passage of water vapor while completely blocking various ions. The hydrophobicity of the material needs to have persistent and stable chemical properties, without performance degradation even under long-term immersion and high salinity conditions. The mechanical strength must be sufficient to withstand the continuous fluctuations and pressure changes in the real marine environment. The optimized interface material not only does not fail due to wave impact but can utilize this dynamic disturbance to prevent concentration polarization at the interface and enhance local convection to improve mass transfer efficiency. This ingenious "transforming disadvantages into advantages" design concept reflects the high integration of materials science and fluid mechanics.

In terms of the innovation of electrolyte systems, researchers are making breakthroughs along two parallel paths. Although the traditional liquid electrolyte system is relatively mature, its concentration regulation requires extremely precise balancing skills - too high a concentration will increase the vapor pressure difference, thereby accelerating water migration but reducing the ionic conductivity; too low a concentration will have the opposite effect. This balanced relationship requires the system to have intelligent dynamic adjustment capabilities. And the more revolutionary breakthrough comes from the development of new gel electrolytes [8]. This multifunctional material, prepared through the freeze-ion regulation technology, successfully achieves the perfect unity of high ionic conductivity and excellent mechanical properties. It is worth noting that this gel electrolyte not only has excellent indicators, but also its preparation process has good scalability, capable of being made into large-sized components and suitable for high current density scenarios, paving the way for future industrial applications. More importantly, the solid-phase characteristics of the gel electrolyte fundamentally avoid the risk of electrolyte leakage, which is of immeasurable value for equipment operating in sensitive marine environments for a long time.

Although the optimization of catalysts is relatively less important in this technology, it remains an indispensable part for enhancing overall efficiency. Under the protection of the phase transition migration mechanism, the catalyst does indeed escape the corrosion and poisoning threats faced in traditional seawater electrolysis, but its intrinsic activity still directly affects the energy conversion efficiency of the system. Current research focuses on developing new catalysts with high activity and good stability [4,9]. For instance, the Mo-Ni_3S_2/NF composite catalyst that performs well in alkaline environments achieves this by precisely regulating its electronic structure, effectively reducing the overpotential of the hydrogen evolution reaction while maintaining structural stability during long-term operation. It is worth noting that the optimization of catalysts must be designed in conjunction with other components of the system, including chemical compatibility with the

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electrolyte and response characteristics under dynamic conditions. This requires researchers to approach the problem from a systems perspective rather than pursuing the performance limits of a single component in isolation.

3.2. System integration and engineering

If the optimization of core materials provides the possibility for efficient operation, then the level of system integration and engineering determines whether this potential can be transformed into reality in the complex and variable real marine environment. This process not only tests the technical capabilities of engineers but also reflects a profound understanding of the characteristics of the marine environment and the flexible application of systematic thinking.

The inherent dynamic self-regulating and balancing mechanism within the system is the core wisdom for maintaining efficient and stable operation. This ingenious physical mechanism enables the system to autonomously respond to various operational fluctuations, demonstrating adaptive characteristics similar to those of living organisms. When the electrolysis rate suddenly increases due to fluctuations in external energy supply, the electrolyte concentration will rise accordingly. This change not only does not cause system imbalance but instead naturally increases the vapor pressure difference at the interface, thereby automatically accelerating the water migration process and providing sufficient raw material supply for the enhanced electrolysis reaction. Conversely, when the electrolysis rate decreases, the system will automatically slow down the water migration speed to avoid ineffective consumption of water and energy. This inherent adaptability not only significantly reduces the complexity of the control system but is also a natural advantage for direct coupling with fluctuating renewable energy sources. In-depth study of the dynamic characteristics and boundary conditions of this mechanism, as well as optimization of its response speed and stability, becomes the key path to improving the overall efficiency of the system.

Anti-vibration design and the intelligent coupling of renewable energy represent the highest challenge in the engineering stage. The real marine environment is a complex system full of uncertainties, with various factors such as wind, waves, and tides acting together, posing a severe test for any marine engineering equipment. A successful engineering solution must simultaneously address the dual challenges of mechanical stability and chemical stability. At the mechanical level, innovative structural design is required to ensure that the equipment maintains structural integrity and operational stability under conditions of 3-8 levels of strong wind and 0.3-0.9 meters of waves, which involves the comprehensive application of multidisciplinary knowledge such as fluid dynamics analysis, material fatigue testing, and vibration control. At the chemical level, it is necessary to ensure the integrity and functionality of the phase transition interface even under continuous mechanical vibration, preventing performance degradation due to material microcracks or interface deformation. The most advanced floating hydrogen production platforms currently on the market have delivered satisfactory results in the face of these challenges through the combination of modular design, intelligent weighting systems, and adaptive anchoring technologies.

The establishment of an intelligent monitoring and predictive maintenance system is a crucial guarantee for ensuring long-term operational efficiency. Unlike traditional chemical equipment, offshore hydrogen production facilities face unique maintenance challenges - the erosion of electronic equipment by high salinity and humidity environments, the impact of biological adhesion on material performance, and data transmission delays in remote monitoring, all of which require innovative solutions. Modern engineering practices have achieved a transformation from passive maintenance to proactive maintenance through measures such as deploying multi-sensor networks, constructing digital twin models, and applying machine learning algorithms to predict equipment

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degradation trends. This intelligent operation and maintenance system not only can promptly detect and handle abnormal conditions, but also continuously optimizes operating parameters through data accumulation and analysis, ensuring that the system always operates at the optimal efficiency range.

Ultimately, the true value of this technology lies in its seamless integration capability with the renewable energy ecosystem [10]. The hydrogen production system must establish a deep dialogue with fluctuating power sources such as offshore wind power and offshore photovoltaic power, being able to understand the fluctuation patterns of energy supply, predict power generation trends, intelligently adjust the hydrogen production load, and activate the self-protection mechanism in extreme weather conditions. This highly intelligent coupling requires breaking through traditional engineering thinking and treating the hydrogen production device as an active node in the future marine energy internet, rather than a passive energy consumer. Only when the breakthroughs at the material level are integrated with the engineering wisdom at the system integration level can this technology truly achieve the transformation from laboratory potential to industrial efficiency, and ultimately build a stable, efficient, and sustainable "power generation - hydrogen production - storage and transportation" integrated marine energy system.

4. Application

The in-situ direct electrolysis of seawater for hydrogen production technology, which has no intention of diluting seawater, represents a significant breakthrough in the energy sector and is demonstrating broad application prospects. In June 2023, China Dongfang Electric Group and the team led by Academician Xie Heping achieved the first successful offshore pilot test of this technology worldwide, marking a crucial turning point for this innovative technology from the laboratory to engineering application. This technology adopts a unique physical-mechanical driving method and successfully achieves the effective isolation of seawater ions, opening up a new path for directly utilizing seawater for hydrogen production [2].

In terms of engineering practice, in 2024, Xie Heping's team further deepened their cooperation with Dongfang Electric, successfully achieving a significant breakthrough where the offshore wind power direct drive seawater hydrogen production system operated continuously and stably for 10 days. This system demonstrated outstanding performance in the real marine environment, with the impurity ion blocking rate of seawater reaching over 99.99%. The purity of the produced hydrogen remained stable between 99.9% and 99.99%, verifying the feasibility of integrating the technology with renewable energy systems.

At the material science level, the team of Yan Ya from the Shanghai Institute of Silicate Science of the Chinese Academy of Sciences published a new catalyst research result in the journal Science in 2025, successfully solving the problem of dissolution and corrosion of the key metal hydroxide active sites during alkaline water oxidation [4]. This breakthrough provides an important material foundation for improving system durability and efficiency, and removes key obstacles for industrialization promotion. This research is consistent with other advanced catalyst design ideas, jointly promoting the progress of material foundations [7,9].

From the perspective of industrialization development, this technology is undergoing a significant transformation from demonstration verification to commercial application. In the future, a complete technical standard system needs to be established to promote the large-scale production of core materials, and a complete industrial chain covering equipment manufacturing, system integration, and operation and maintenance should be established. At the same time, economic evaluation and full life cycle cost analysis will become important supports for promoting the commercialization of the technology.

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With the continuous breakthroughs in related technologies and the continuous improvement of the industrial ecosystem, the in-situ direct electrolysis of undiluted seawater for hydrogen production technology is expected to play a significant role in marine energy development, off-island energy supply, and maritime transportation, providing new technical paths and development opportunities for the global green energy transition.

5. Future outlook

The future outlook is presented from the perspectives of industrialization and the construction of the ecological chain. For instance: economic aspects and standard establishment, creating a brand-new industrial chain, and envisioning forward-looking applications.

5.1. Economic optimization and standard system construction

The focus of future research will be on enhancing the economic efficiency of the technology. Through the large-scale production and cost control of core materials (such as waterproof breathable layers and gel electrolytes), as well as the optimization of system integration processes, it is expected to significantly reduce the unit hydrogen production cost. At the same time, establishing technical standards and safety regulations throughout the entire value chain is of utmost importance. This includes formulating performance testing standards for hydrogen production equipment using seawater electrolysis, safety operation norms for offshore platforms, and quality standards for hydrogen gas, laying the foundation for the standardized promotion and market access of the technology.

5.2. Building the "Marine Green Hydrogen" value chain

The maturity of this technology will give rise to a brand-new "Marine Green Hydrogen" value chain. The upstream will focus on the research and development and manufacturing of key materials (such as the phase-change migration interface materials developed by Xie Heping's team and the highly stable catalysts developed by Yan Ya's team) and specialized equipment. The middle part will cover the design, construction, offshore installation, and intelligent operation and maintenance services of modular hydrogen production platforms. The downstream will promote the large-scale application of hydrogen in shipping fuels, green chemical industries, remote island power supply, etc., and drive the development of related infrastructure such as high-pressure hydrogen storage, low-temperature liquid hydrogen transportation, pipeline hydrogen transportation, or carrier (such as ammonia, methanol) storage and transportation.

5.3. Forward-looking application scenarios

Beyond the current coupling model of offshore wind power, more innovative application paradigms may emerge in the future. For instance, the "Navigator" series of mobile hydrogen production platforms can be developed to enable them to move with the optimal wind resource areas for mobile production, maximizing energy output. Further, a large-scale offshore integrated energy platform that integrates "power generation - hydrogen production - carbon dioxide capture - synthesis of green fuels" can be envisioned. This platform can directly convert green hydrogen and captured CO_2 into transportable green methanol or other synthetic fuels at sea, ultimately building a complete and closed-loop marine zero-carbon energy system.

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Through the coordinated advancement of technology, industry, and application, the in-situ direct electrolysis of seawater for hydrogen production technology is expected to move from the demonstration stage to large-scale commercial application within the next decade, becoming an important force supporting the global energy transition towards a low-carbon model [3].

6. Conclusion

The technology of direct electrolysis of seawater without any desalination process is an important component of the future green energy system and is closely related to energy transition and carbon neutrality.

This study reveals that the non-dehydration seawater electrolysis technology based on the "phase transition migration" principle, through its unique physical-mechanical isolation mechanism, can achieve an ion-blocking efficiency of over 99.99%. When combined with the offshore wind power system, it forms a complete energy recycling chain. This innovative combination not only enables efficient energy production while protecting the marine environment, but also effectively solves the problems of storage and transmission of renewable energy by directly converting wind power into hydrogen energy. Since the electricity generated by wind power is immediately used for electrolyzing seawater to produce hydrogen, there is no need for additional space to store electricity, nor is there a need to incur a large amount of cost to transmit electricity to other regions.

However, the high production costs and the low degree of production scale-up have limited the future development of offshore wind hydrogen production technology. This is specifically manifested in the fact that the costs of core materials, such as waterproof breathable layers and gel electrolytes, remain high, the large-scale production process is not yet mature, and the verification of offshore engineeringization and system integration technologies still needs to be further conducted.

In the future, efforts should be made to address the technical bottlenecks in the development of low-cost catalysts, and at the same time, policy support should be provided to promote industrialization and large-scale development. It is suggested to advance in three dimensions: key material innovation, standard system establishment, and the construction of the entire industrial chain, to promote the commercial application of this technology. This research provides theoretical support and practical references for the coordinated development of offshore wind power and hydrogen energy industries, and is of great significance for promoting the construction of clean energy systems in coastal areas of our country.

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