Research Progress and Prospects of Hydrogen Production via Water Electrolysis

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Abstract: Each of the four water electrolysis technologies has its own advantages and limitations. Alkaline water electrolysis is mature and suitable for large-scale, stable industrial applications. Proton exchange membrane electrolysis is well-suited for integration with renewable energy sources due to its fast response, though it remains relatively expensive. Solid oxide electrolysis offers high efficiency and can utilize high-temperature heat sources, but improvements in material and system stability are needed. Anion exchange membrane electrolysis offers cost advantages and strong development potential but still requires breakthroughs in materials and system design. In the future, selecting the most appropriate electrolysis technology based on specific application scenarios will be crucial for advancing the sustainable development of the hydrogen energy industry.

1. Introduction

With the growing global demand for clean energy, hydrogen is increasingly recognized as a key pillar in achieving energy structure transformation and carbon neutrality goals, due to its high efficiency and zero carbon emissions. Hydrogen not only has a high energy density and produces only water upon combustion, but also shows broad application prospects in transportation, industrial production, and energy storage. Among various hydrogen production technologies, water electrolysis stands out as a critical pathway for producing green hydrogen because it can directly utilize renewable electricity to split water into hydrogen and oxygen, thereby avoiding carbon emissions associated with fossil fuel-based hydrogen production. Especially with the rapid development of renewable energy sources like wind and solar power, the potential of water electrolysis is becoming increasingly prominent. However, current electrolysis technologies still face challenges such as high costs, suboptimal efficiency, and reliance on imported key materials. Therefore, in-depth research into the mechanisms, system classifications, catalyst development, related patented technologies, electrolyzer systems and control strategies, as well as the current challenges and future directions, is crucial for the continued growth of the hydrogen energy industry. This paper aims to systematically review and analyze these aspects to provide valuable insights and references for researchers and industry stakeholders.

2. Basic Mechanisms of Water Electrolysis for Hydrogen Production

2.1 Basic Reaction Equations and Mechanisms in Water Electrolysis

Water electrolysis is a process that decomposes water into hydrogen and oxygen, mainly involving the oxygen evolution reaction (OER) at the anode and the hydrogen evolution reaction (HER) at the cathode. During OER, water molecules lose electrons at the anode to generate oxygen; during HER, water molecules gain electrons at the cathode to produce hydrogen. These two reactions together constitute the electrolysis of water[1].

OER involves a multi-electron transfer process and is kinetically slow, making it the rate-limiting step of the entire reaction. In acidic media, the OER pathway includes the formation of adsorbed hydroxyl (OH*) on the catalyst surface, which is then converted into adsorbed oxygen (O*),

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hydroperoxyl (OOH*), and finally releases molecular oxygen (O_2). In alkaline media, the mechanism is similar but starts with hydroxide ions (OH^-) and proceeds through analogous intermediates [2-4].

HER is relatively faster than OER but still requires efficient catalysts to reduce the overpotential. In acidic conditions, the HER mechanism involves the Volmer step (proton reduction forming adsorbed hydrogen), Heyrovsky step (adsorbed hydrogen reacts with a proton to produce H_2), and Tafel step (two adsorbed hydrogen atoms combine to form hydrogen gas). In alkaline media, where protons are scarce, water molecules serve as the hydrogen source instead[3, 5]. The sluggish kinetics in alkaline HER are attributed to the additional energy required for water dissociation[6]. Figure 1 is a schematic illustration of water electrolysis and the hydrogen evolution reaction (HER) mechanisms.

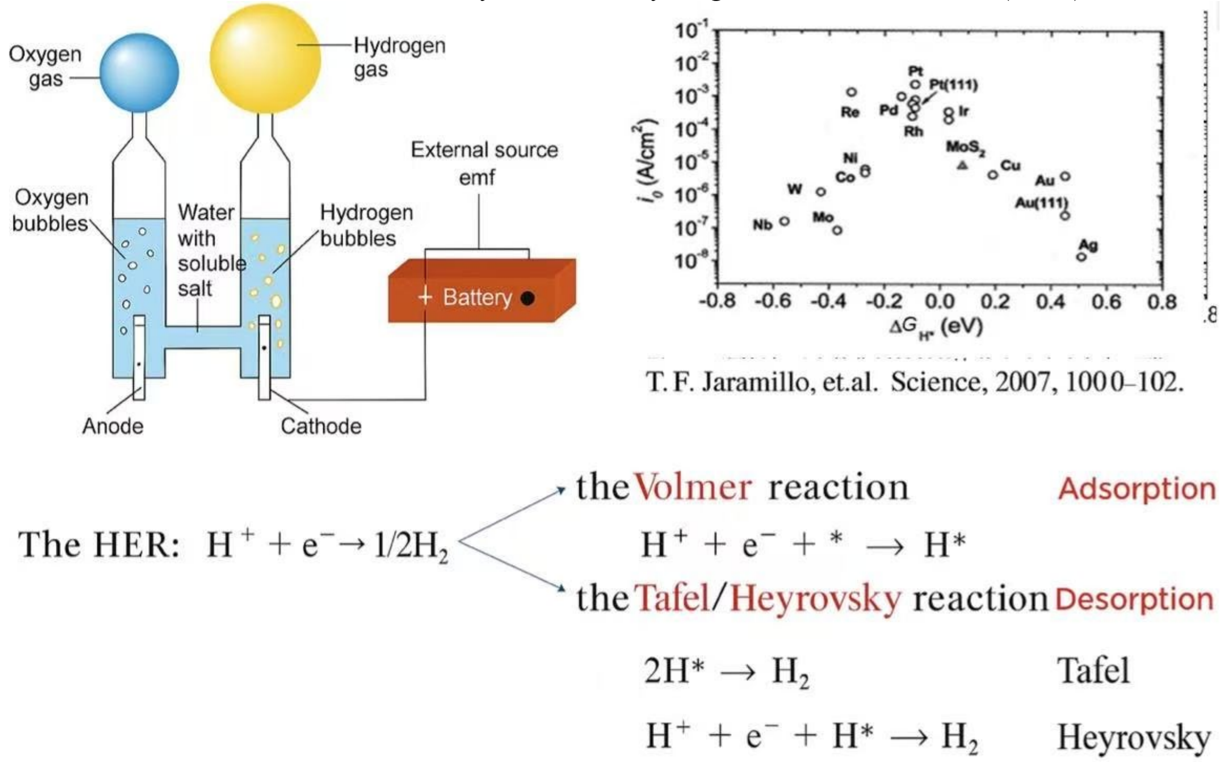

Figure 1: Schematic Illustration of Water Electrolysis and the Hydrogen Evolution Reaction (HER) Mechanisms.

Overall, the efficiency of water electrolysis is primarily limited by the kinetics of OER and HER, and the development of high-performance electrocatalysts is essential for achieving efficient and stable hydrogen production [1, 2, 7].

2.2 Main Types of Water Electrolysis

Water electrolysis technologies are mainly categorized into four types based on the electrolyte and operating conditions. Each has distinct characteristics in terms of maturity, cost, efficiency, and application scenarios.

2.2.1 Alkaline Water Electrolysis (ALK)

ALK is the earliest industrialized hydrogen production method via electrolysis, characterized by high maturity, low equipment cost, and stable operation. It typically uses hydroxide solutions (e.g., 30% KOH or 26% NaOH) and membranes made of asbestos, PPS, or PSU/PSF [8], operating at 0–45 °C with current densities around 0.2–0.4 A/cm² and energy consumption of ~4.5–5.5 kWh/Nm³, yielding efficiencies between 60% and 82%[11]. Nickel-based catalysts (Ni, Fe, Co) offer good alkaline tolerance and long lifetimes (20–30 years)[9, 12]. However, ALK systems suffer from thick diaphragms and large ohmic resistance, resulting in slow dynamic response, long start-up times, and poor adaptability to fluctuating renewable energy sources[11]. Figure 2 shows the configuration of Alkaline water electrolyzer.

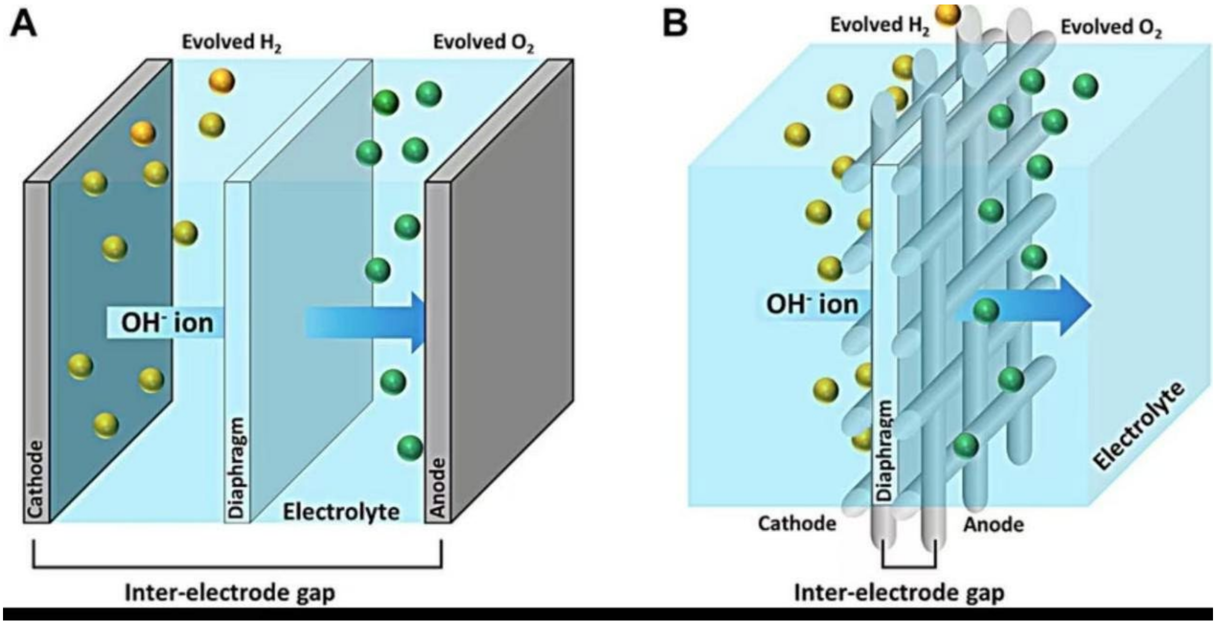

Figure 2: Configuration of Alkaline Water Electrolyzer: Conventional and Advanced Designs.

2.2.2 Proton Exchange Membrane Water Electrolysis (PEMWE)

PEMWE uses solid polymer electrolyte membranes (typically PFSA such as Nafion) and operates at 25–80 °C, enabling high current densities (up to 4 A/cm²), high hydrogen purity (> 99.99%), fast dynamic response, and compact system design[12]. However, it relies on expensive noble metal catalysts (Pt, Ir, Pt/C, IrO_2) and costly membrane materials, making the system expensive[11]. Current efficiencies range from 67% to 82%, with advanced systems reaching ≈82% (higher heating value basis) and potential efficiency projections up to ≈86%, approaching theoretical maxima near 94%[11]. The Membrane Electrode Assembly (MEA) structure in Proton Exchange Membrane (PEM) electrolyzers is shown in Figure 3.

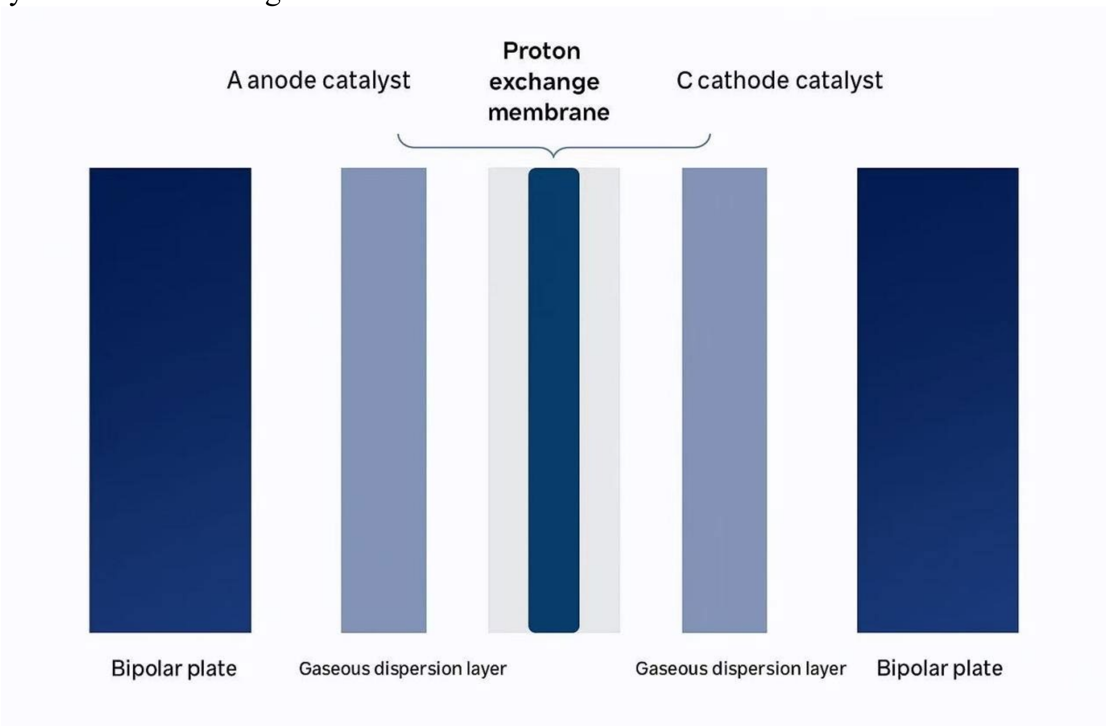

Figure 3: Membrane Electrode Assembly (MEA) Structure in Proton Exchange Membrane (PEM) Electrolyzers

2.2.3 Solid Oxide Electrolysis Cell (SOEC)

SOEC operates at high temperatures (700–900 °C) using ceramic electrolytes such as yttria-stabilized (YSZ) or scandia-stabilized zirconia (SCSZ), achieving efficiencies over 90%. It can leverage industrial waste heat or renewable heat sources to reduce electrical consumption[11]. High temperatures enhance reaction rates and catalyst activity, but stringent requirements on material thermal stability and system sealing, along with cumbersome start-up/shutdown procedures, have limited its deployment mainly to laboratory research stages[11].

2.2.4 Anion Exchange Membrane Water Electrolysis (AEMWE)

AEMWE integrates the strengths of ALK and PEMWE by employing anion exchange membranes and non-precious catalysts (Ni-, Fe-, Co-based), thereby significantly reducing system costs[12]. It supports high current densities (0.2–1 A/cm², in some systems > 1 A/cm²), low internal resistance, and is well-suited for large-scale hydrogen production under alkaline conditions[11, 12]. Nevertheless, AEMWE remains in R&D, facing challenges in chemical/mechanical stability, conductivity, alkaline resistance, and membrane longevity (typically several thousand to ~12,000 hours), which is still lower than ALK (60,000–90,000 h) and PEMWE (20,000–60,000 h) targets[11, 12]. Additionally, impurities such as Cl^- or CO_2 in feedwater can impact performance[11].

2.3 Conclusion

Each of the four water electrolysis technologies has its own advantages and limitations. Alkaline water electrolysis is mature and suitable for large-scale, stable industrial applications. Proton exchange membrane electrolysis is well-suited for integration with renewable energy sources due to its fast response, though it remains relatively expensive. Solid oxide electrolysis offers high efficiency and can utilize high-temperature heat sources, but improvements in material and system stability are needed. Anion exchange membrane electrolysis offers cost advantages and strong development potential but still requires breakthroughs in materials and system design. In the future, selecting the most appropriate electrolysis technology based on specific application scenarios will be crucial for advancing the sustainable development of the hydrogen energy industry.

3. Advances in Electrocatalysts for Water Electrolysis

3.1 HER Catalysts

In the water electrolysis process, the hydrogen evolution reaction (HER) at the cathode is one of the key steps. To improve HER efficiency, researchers have developed various catalysts to optimize the adsorption and dissociation pathways of reactants and reduce the activation energy [10]. The main types of catalysts include noble metal catalysts, non-noble metal catalysts, and doped or composite material catalysts.

3.1.1 Noble Metal Catalysts

Noble metal catalysts, such as platinum (Pt) and ruthenium (Ru), exhibit outstanding catalytic performance in HER. Platinum is widely considered the most effective HER catalyst, with nearly zero hydrogen adsorption free energy (ΔG_H^*) in both acidic and alkaline media, enabling hydrogen generation with minimal energy barrier. Its excellent stability and corrosion resistance also contribute to its long service life. However, the high cost and scarcity of noble metals limit their application in large-scale hydrogen production[13].

3.1.2 Non-Noble Metal Catalysts

To reduce hydrogen production costs, researchers have focused on developing efficient non-noble metal catalysts. Transition metals such as nickel (Ni), molybdenum (Mo), cobalt (Co), and iron (Fe) have attracted attention due to their abundance and good electrocatalytic properties. For instance, molybdenum disulfide (MoS_2), a transition metal sulfide, demonstrates excellent HER activity. The catalytic performance of these materials can be further enhanced through nanostructuring and alloying strategies. A notable example is a cobalt-based $Co_3Mo_3N/Co_4N/Co$ heterostructure that achieves 1.58 V at 10 mA·cm^{-2} with nearly 100% retention over 100 h, outperforming commercial Pt/C—RuO_2 systems[14].

3.1.3 Doped and Composite Material Catalysts

Doping and the construction of composite materials are effective strategies to improve the performance of non-noble metal catalysts. Introducing non-metallic elements (such as nitrogen, phosphorus, and sulfur) can modify the electronic structure and surface properties of catalysts, thereby enhancing their catalytic activity and stability. For example, nitrogen-doped carbon membranes functionalized with Co/CoP Janus-type nanocrystals deliver exceptional HER activity and long-term stability in both acidic and alkaline environments[15]. Figure 4 is the stability assessment of HER catalysts.

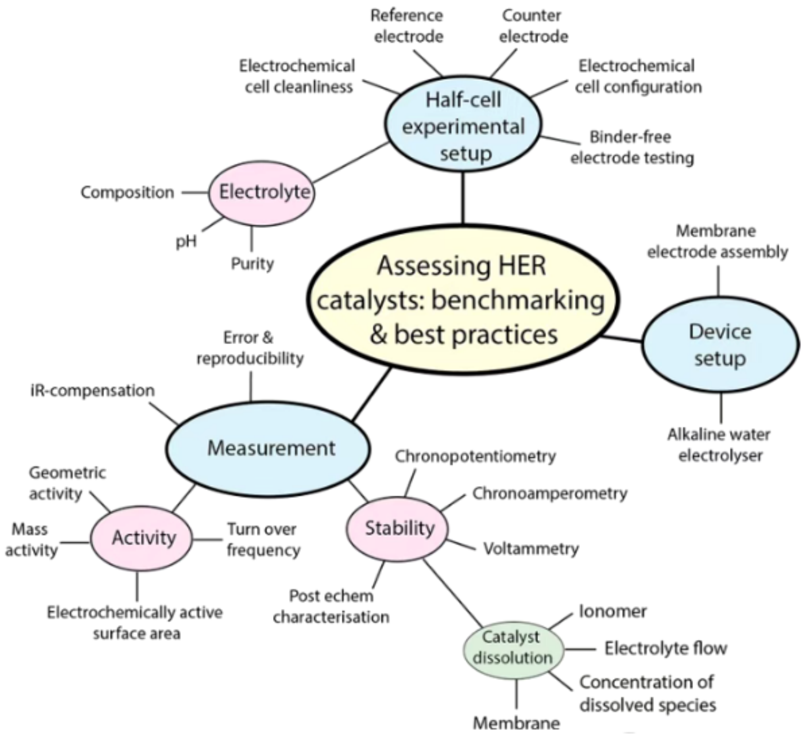

Figure 4: Stability Assessment of HER Catalysts

3.2 OER Catalysts

In water electrolysis, the oxygen evolution reaction (OER) at the anode is another key step. Due to its multi-electron transfer nature, OER suffers from slow kinetics, making it the rate-determining step of the overall reaction. To enhance OER efficiency, researchers have developed various catalysts, mainly including noble metal oxides and non-noble metal catalysts.

3.2.1 Noble Metal Oxide Catalysts

Noble metal oxides such as iridium dioxide (IrO_2) and ruthenium dioxide (RuO_2) exhibit excellent catalytic performance in OER. These materials offer superior conductivity and chemical stability, enabling low overpotential and high current density in both acidic and alkaline media. However, like in HER, the high cost and limited availability of noble metals hinder their widespread commercial application[16].

3.2.2 Non-Noble Metal Catalysts

Similar to HER, efforts have been made to develop cost-effective non-noble metal catalysts for OER. Transition metals such as nickel (Ni), iron (Fe), and cobalt (Co) are also applicable here. For example, nickel-iron layered double hydroxide (NiFe LDH) exhibits excellent OER activity in alkaline media and serves as a promising catalyst for AEM electrolyzers[17].

3.2.3 Structure-Tuned Catalysts

In recent years, structural tuning has become an important strategy for improving catalyst performance. Single-atom catalysts (SACs), in which metal atoms are dispersed on a support, maximize metal utilization and provide uniform active sites. For instance, anchoring Ir single atoms on NiFe LDH significantly improves OER activity and stability. Moreover, constructing heterostructures and applying interfacial engineering—such as introducing heteroatom doping or forming metal–nonmetal interfaces on carbon-based supports—can regulate the electronic structure and optimize the adsorption energy of intermediates, thereby enhancing catalytic activity[18].

4. Overview of Recent Patented Technologies in Catalysts

4.1 Analysis of Breakthrough Patent Cases

In recent years, water electrolysis for hydrogen production has made significant progress, particularly in catalyst development and electrolyzer design. The following are several representative patented technologies that have played key roles in enhancing system efficiency, reducing costs, and improving durability.

4.1.1 Smoltek: Corrosion-Resistant Nano-Structured PEM Catalyst Layer

Swedish company Smoltek has developed a porous transport layer (PTL) technology for the anode based on carbon nanofibers, aimed at reducing the use of the noble metal iridium. Utilizing atomic layer deposition (ALD), an ultra-thin layer of iridium is uniformly coated on the carbon nanofibers, significantly lowering iridium consumption. This technology has demonstrated excellent stability in 1000-hour continuous operation tests, with the anode's nanostructure remaining intact, indicating strong corrosion resistance[19]. Additionally, it improves electron transport efficiency and enhances catalytic activity, offering a viable solution for large-scale green hydrogen production.

4.1.2 TiO_2-Supported NiFe Oxide Composite Catalyst

NiFe-based catalysts are of interest for the oxygen evolution reaction (OER) in water electrolysis due to their low cost and good conductivity. By supporting NiFe oxides on titanium dioxide (TiO_2), a composite catalyst is formed that exhibits improved conductivity and stability. This catalyst shows excellent catalytic activity and long-term stability at high current densities, making it suitable for industrial applications. Moreover, the introduction of TiO_2 helps to optimize the electronic structure of the catalyst, further lowering the OER overpotential and enhancing overall energy efficiency[20].

4.1.3 Dry Cathode Electrolyzer System Design

Traditional water electrolysis systems often use wet cathode designs, which may result in gas mixing and energy loss. This patent proposes a dry cathode electrolyzer system that improves gas separation efficiency and reduces energy loss through optimized cell structure design. Furthermore, the dry cathode design reduces system complexity and maintenance costs, making it well-suited for integration with renewable energy sources to achieve efficient and environmentally friendly hydrogen production[21].

4.2 Analysis of Breakthrough Patent Cases

The rapid development of water electrolysis hydrogen production is the result of close collaboration between patented technologies and academic research. The practical application of patented technologies drives deeper academic inquiry, while academic innovations provide theoretical support for patent development. This mutually reinforcing relationship accelerates the industrialization of water electrolysis technologies[22].

The transformation potential and application prospects of patented technologies ensure efficient and low-cost hydrogen production. For example, the corrosion-resistant nano-structured PEM catalyst layer developed by Smoltek extends the lifespan of the electrolyzer by enhancing catalyst durability. The patented TiO_2-supported NiFe oxide composite catalyst achieves high-performance OER, boosting overall hydrogen production efficiency[19-20].

Meanwhile, academic research contributes theoretical foundations and experimental data in catalyst materials, electrolyzer design, and system integration. These findings guide the development of patented technologies, ensuring their feasibility and practicality. At the same time, the implementation of patented technologies provides validation platforms for academic research, promoting the integration of theory and practice[22-23].

5. Research Progress in Electrolyzer Systems and Control Strategies

5.1 Optimization of Electrolyzer Design

The optimization of electrolyzer design aims to enhance system performance and stability. Researchers have made notable progress through improvements in membrane electrode assemblies (MEAs) and interface regulation:

1) MEA Optimization: The MEA is the core component of an electrolyzer, and its performance directly affects system efficiency. By optimizing catalyst layer thickness, porosity, and conductivity, the hydration state and ionic conductivity of the proton exchange membrane are improved, thereby enhancing overall electrolyzer performance[24].

2) Interface Regulation: The interfacial properties between electrodes and the electrolyte are critical to electrolyzer performance. By introducing nanostructured materials, applying interface modification, and utilizing interface engineering techniques, the contact area between the electrode and electrolyte is increased, interfacial resistance is reduced, and the stability and efficiency of the electrolyzer are improved[25].

5.2 Intelligent Control Systems

The introduction of intelligent control strategies helps improve the energy efficiency and response speed of water electrolysis hydrogen production systems. Current research focuses on several control aspects:

1) Adaptive Control: To address the intermittency of renewable energy sources, adaptive control strategies are developed to dynamically adjust operating parameters of the electrolyzer in real-time, maximizing the utilization of renewable energy and improving energy efficiency[26].

2) Predictive Control: By utilizing weather forecasts and historical data to predict renewable energy output, electrolyzer operation strategies can be adjusted in advance, ensuring stable operation under varying conditions[27].

3) Fault Diagnosis and Prediction: Machine learning and data mining techniques are applied to analyze operational data of electrolyzers, enabling real-time monitoring of system health, early warning of potential failures, and ensuring system reliability and safety[28].

5.3 Integration with Renewable Energy Sources

Integrating water electrolysis systems with renewable energy sources such as solar and wind power is a promising approach to achieving green hydrogen production. However, this integration presents several engineering challenges:

1) Power Fluctuation: The stochastic and intermittent nature of renewable energy leads to unstable power input to electrolyzers, which may result in performance degradation and reduced lifespan. To address this, researchers have proposed power balancing strategies across multiple electrolyzers, optimizing operating time to enhance system stability and lifespan[29].

2) System Coordination: The coordinated operation of renewable energy generation systems, energy storage systems, and water electrolysis units is crucial. Researchers have developed control strategies that prioritize hydrogen production from stored renewable energy, optimizing system parameters to improve overall energy utilization efficiency[30].

6. Current Challenges and Future Directions

While water electrolysis technology has made significant progress in improving efficiency and material innovation, further development must proceed along multiple dimensions to achieve high-efficiency, cost-effective, and sustainable hydrogen production.

1) Cost Issues: Currently, the cost of electrolysis equipment, including energy consumption, system maintenance, and component replacement, remains a major barrier. To reduce overall costs, it is essential to accelerate the development of novel low-cost materials such as non-noble metal catalysts and cost-effective membrane materials. Standardizing and modularizing electrolyzer design can reduce manufacturing difficulty and costs. Additionally, scaling up production and achieving economies of scale will help lower the unit cost of hydrogen production.

2) System Integration Challenges: A lack of system integration is one of the key factors affecting the stability and efficiency of water electrolysis. Coordinated operation between electrolysis systems and renewable energy sources such as wind and solar power requires highly adaptive control systems. Future developments should focus on establishing intelligent energy management systems to achieve dynamic coordination between hydrogen production units, the power grid, and energy storage systems. Electrolyzers should also be adaptable to varying environmental conditions to meet diverse application needs.

3) Durability and Stability Issues: Long-term operation often leads to performance degradation due to material aging and electrode corrosion. Strengthening the corrosion and aging resistance of core electrolyzer materials is essential. The development of intelligent predictive maintenance and fault diagnosis systems will enable early detection of potential issues, timely risk mitigation, and prolonged equipment lifespan.

References

[1] Xu Y, Zhang B. Recent advances in electrochemical hydrogen production from water assisted by alternative oxidation reactions[J]. ChemElectroChem, 2019, 6(13): 3214–3226.

[2] Luo Y, Zhang Z, Chhowalla M, et al. Recent advances in design of electrocatalysts for high-current-density water splitting[EB/OL]. arXiv:2202.07322, 2022. https://arxiv.org/abs/2202.07322

[3] Anwar S, Saleem M, Hussain A, et al. Recent development in electrocatalysts for hydrogen production through water electrolysis[J]. International Journal of Hydrogen Energy, 2021, 46(26): 16517–16539.

[4] Rossmeisl J, Logadottir A, Nørskov J K. Electrolysis of water on oxide surfaces[J]. Journal of Electroanalytical Chemistry, 2005, 607(1-2): 83–89.

[5] Sheng W, Zhuang Z, Gao M, et al. Correlating hydrogen evolution reaction activity in alkaline media with hydrogen binding energy on monometallic and bimetallic catalysts[J]. Nature Communications, 2015, 6: 5848.

[6] Trasatti S. Work function, electronegativity, and electrochemical behaviour of metals: III. Electrolytic hydrogen evolution in acid solutions[J]. Journal of Electroanalytical Chemistry, 1972, 39: 163–184.

[7] Tran P D, Zhang J, Chen L, et al. Current status of developed electrocatalysts for water splitting technologies: from experimental to industrial perspective[J]. Nano Convergence, 2025, 12.

[8] Delmoné F, Carta M, Ruiz K, et al. Electrolysis of water on oxide surfaces[J]. Journal of Electroanalytical Chemistry, 2005, 607(1–2): 83–89.

[9] Tan H, Tang B, Lu Y, et al. Engineering a local acid-like environment in alkaline medium for efficient hydrogen evolution reaction[J]. Nature Communications, 2022, 13(1): 2024.

[10] Zhang C, Yu Y, Grass M E, et al. Mechanistic studies of water electrolysis and hydrogen electro-oxidation on high temperature ceria-based solid oxide electrochemical cells[J]. Journal of the

American Chemical Society, 2013, 135(31): 11572-11579.

[11] Tran P D, Zhang J, Chen L, et al. Current status of developed electrocatalysts for water splitting technologies: from experimental to industrial perspective[J]. Nano Convergence, 2025, 1.

[12] Zhou W, Jia J, Lu J, et al. Recent developments of carbon-based electrocatalysts for hydrogen evolution reaction[J]. Nano Energy, 2016, 28: 29-43.

[13] Wu D, Kusada K, Yoshioka S, et al. Efficient overall water splitting in acid with anisotropic metal nanosheets[J]. Nature Communications, 2021, 12: 1427.

[14] Liu Y, Wang L, Hübner R, et al. Cobalt-based Co3Mo3N/Co4N/Co metallic heterostructure as a highly active electrocatalyst for alkaline overall water splitting[EB/OL]. arXiv:2404.14427, 2024. https://arxiv.org/abs/2404.14427

[15] Wang H, Min S, Ma C, et al. Nitrogen-doped nanoporous carbon membranes functionalized with Co/CoP Janus-type nanocrystals as hydrogen evolution electrode in both acid and alkaline environment[EB/OL]. arXiv:1705.03756, 2017. https://arxiv.org/abs/1705.03756

[16] Vinodh R, Palanivel T, Kalanur SS, et al. Recent advancements in catalyst coated membranes for water electrolysis: a critical review[J]. Energy Advances, 2024, 3: 1144–1166.

[17] Hagesteijn KFL, Jiang S, Ladewig BP. A review of the synthesis and characterization of anion exchange membranes[J]. Journal of Materials Science, 2018, 53: 6459–6489.

[18] Lee J, Lee SA. Unlocking the potential of chemical-assisted water electrolysis for hybrid water splitting[J]. Ind. Materials, 2025, doi:10.1039/D4IM00163J.

[19] Smoltek AB. Corrosion protection technology for nanostructured PEM catalyst layers[EB/OL]. [2024-05-01]. https://www.smoltek.com/technology/hydrogen/corrosion-protection/

[20] Wang J, Xu K, Zhang J, et al. Enhanced OER performance of titanium dioxide-supported NiFe oxide composite catalysts in alkaline media[J]. Electrochimica Acta, 2021, 390: 138858. DOI:10. 1016/j.electacta.2021.138858.

[21] Kwon Y, Lee J, Cho H. Design and optimization of a dry cathode electrolysis system for efficient hydrogen production[J]. Journal of Power Sources, 2023, 570: 233495. DOI:10. 1016/j. jpowsour. 2023. 233495.

[22] Zhao Y, Zheng L, Zhang X, et al. Integrating academic research and patent innovation: A pathway to scalable water electrolysis[J]. Energy Reports, 2022, 8: 992–1004. DOI:10. 1016/j. egyr. 2022.07.046.

[23] Lee S A, Jun S E, Park S H, et al. Single atom catalysts for water electrolysis: from catalyst-coated substrate to catalyst-coated membrane[J]. EES Catalysis, 2024, 2(1): 49-70.

[24] Carmo M, Fritz D L, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis[J]. International Journal of Hydrogen Energy, 2013, 38(12): 4901–4934. DOI:10.1016/j.ijhydene. 2013. 01. 151.

[25] Lin Y, Shen P K, Lu J. Interface engineering of electrocatalyst layers for efficient water splitting: From materials to devices[J]. Advanced Materials, 2021, 33(19): 2008636. DOI:10.1002/adma. 202008636.

[26] Li Y, Yu H, Yang C, et al. Adaptive control strategies for PEM electrolyzers integrated with fluctuating renewable power sources[J]. Renewable Energy, 2022, 185: 1303–1315. DOI:10. 1016/j. renene. 2021.11.032.

[27] Liu J, Wang X, Zhang L, et al. Model predictive control of electrolyzers based on renewable energy prediction data[J]. Applied Energy, 2021, 282: 116136. DOI:10.1016/j.apenergy.2020.116136.

[28] Lu Q, Wu J, Han L, et al. Fault diagnosis for PEM water electrolyzers using machine learning

approaches[J]. Journal of Power Sources, 2022, 533: 231363. DOI:10.1016/j.jpowsour.2022.231363.

[29] Habib M M, Yousef B A, Al-Sulaiman F A. Power management strategy of hybrid PV-wind-electrolyzer system for efficient hydrogen production: A review[J]. International Journal of Hydrogen Energy, 2020, 45(15): 8755–8775. DOI:10.1016/j.ijhydene.2020.01.107.

[30] Bensadok K, Khellaf A, Loubar K, et al. Control strategy for the integration of renewable energy sources with water electrolysis: A review of recent developments[J]. Renewable and Sustainable Energy Reviews, 2023, 175: 113156. DOI:10.1016/j.rser.2022.113156.