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Analysis of Progress and Optimization Pathways for Hydrogen Production Technologies under Dual Carbon Goals

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Abstract: The development of green energy is rapidly progressing in pursuit of carbon peaking and carbon neutrality goals. Hydrogen production via water electrolysis is a crucial technology in the transition to clean energy, offering substantial value for research and optimization. This process facilitates the efficient conversion of renewable energy sources into hydrogen, thereby contributing to sustainable energy solutions. Thus, the paper examines the basics and technical classifications of water electrolysis for hydrogen production, hence providing a comprehensive review of the characteristics and roles of three main technologies, Alkaline Water Electrolysis (AWE), Solid Oxide Electrolysis Cells (SOEC), and Proton Exchange Membranes (PEM), in achieving carbon reduction goals. In addition, advances in hydrogen production via electrolysis are outlined, which highlights that technological improvements can be achieved by enhancing catalyst performance, optimizing electrolyzer design, as well as increasing the integration of renewable energy sources. The results demonstrate that as these technologies mature and scale, hydrogen production is poised to become an integral component of the green energy transition.

Keywords: Proton Exchange Membrane Electrolysis, Electrocatalysts, Hydrogen Production, Clean Energy, Energy Transition

1. Introduction

The global energy system has long relied on fossil fuels, such as coal and oil, which led to substantial greenhouse gas emissions that exacerbate climate change. At present, fossil fuels comprise about 78% of global energy consumption, resulting in substantial greenhouse gas emissions [1]. These emissions are a primary driver of climate change and contribute to a range of adverse effects, including health issues and ecological degradation [2]. Despite the positive shift to cleaner energy, many countries still face challenges such as energy shortages, environmental pollution and food security issues. Hydrogen energy, known for its clean properties and high energy density, has emerged as a promising solution [3]. The paper aims to explore more efficient and cost-effective technologies for hydrogen production and application. In particular, it focuses on enhancing water electrolysis methods to improve hydrogen extraction efficiency, reduce production costs, and address the challenges related to scaling up for widespread use. Through the examination of advances in electrolysis technology and the incorporation of both experimental analysis and cost evaluations, this research seeks to provide

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viable solutions that facilitate the broader adoption of hydrogen energy, as well as contributes to the potential to support large-scale hydrogen applications and help reduce global dependence on fossil fuels.

2. Overview of hydrogen production from electrolyzed water technology

2.1. Basic principles and classification of technologies

Hydrogen can be produced by decomposing water into hydrogen and oxygen via various electrolysis technologies, including Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Electrolysis (PEME), and Solid Oxide Electrolysis (SOE), with either renewable or non-renewable energy sources. AWE is preferred due to its simplicity, cost-effectiveness, and high safety. In the AWE process, water is decomposed into hydrogen and hydroxide ions at the cathode, and the hydroxide ions then move through the membrane to the anode, where they are oxidized to produce oxygen and release electrons to complete the circuit [4]. The membrane is crucial in this process as it boosts the stability and safety of the cell while preventing unnecessary side reactions, though it also increases the system's resistance. To improve the efficiency of AWE, advancements are needed in areas such as electrolyte conductivity, material replacement to reduce resistance, and the development of new catalysts. The core component of PEME is the exchange membrane, which uses a thin solid polymer electrolyte instead of traditional liquid electrolytes [5]. This membrane effectively isolates the anode and cathode, preventing side reactions between the fuel and electrode products [6]. SOE exhibits strong market competitiveness, showcasing exceptional thermodynamic and kinetic performance in high-temperature environments and renowned for its high efficiency. In contrast to other electrolysis technologies, SOE is a solid-state electrolyzer that provides exceptional lifespan and durability. It can also harness additional renewable energy sources for hydrogen production, thus yielding high hydrogen production rates. Given the high-temperature operation, research primarily focuses on its thermodynamic properties. In the future, SOE is expected to integrate with solar and renewable energy systems, boosting efficiency through optimization [7]. Table 1 presents a comparison of current hydrogen production methods, highlighting the strengths and weaknesses of various technologies and their respective applications [8].

Table 1: Comparison of current hydrogen production methods

Attribute	AWE	PEMWE	SOE
Electrolysis Type	Alkaline	Polymer electrolyte	Solid oxide
Electrolyte	NaOH/KOH	Solid polymer electrolyte	Yttria stabilized Zirconia
Electrode	Ni	Pt, Ir	Ni
Charge carrier	OH^-	H^+	O^{2-}
Anode reaction	$2OH^- \rightarrow \frac{1}{2}O_2+2e^-+H_2O$	H2O$\rightarrow \frac{1}{2}O_2$+2H++2e+–	$O_2 \longrightarrow \frac{1}{2}O_2+2e^-$
Cathode reaction	$2H_2O+2e^- \rightarrow H_2+2OH^-$	$2H^++2e^- \rightarrow H_2$	$H_2O+2e^- \rightarrow H_2+O^{2-}$
Overall reaction	$H_2O \rightarrow H_2+\frac{1}{2}O_2$	$H_2O \rightarrow H_2+\frac{1}{2}O_2$	$H_2O \rightarrow H_2+1/2O_2$
Current normal density	0.3–0.7A·cm^{-2}	1.5–2.5 A·cm^{-2}	0.5–1 A·cm^{-2}
Operating temperature	50–90°C	50–90°C	700–850°C
Voltage range	1.5-3V	1.5-2.5V	1.0-1.5V
Workinging pressure	1–30 bars	1–70 bars	1bar
H2 purity	99.5%–99.9998%	99.9%–99.9999%	99.90%
Development status	Commercial	Mature	R&D

Table1: (continued)

Respond rate (From min load to full)	10min	10s	N/A
System size	0.25–760 Nm^3H_2/h 1.8–5300kW	0.01–240 Nm^3H_2/h 0.2–1150 kW	N/A
Electrode area	10 000–30 000cm^2	1500cm^2	200cm^2
The stack efficiency	75-85%	75-85%	85-95%
System efficiency (HHV)	65-77%	60-80%	80-90%
The single battery decay rate	<0.5%/1000h	<1%/1000h	<1%/1000h
The degradation rate of the stack	N/A	<2%/1000h	<2%/1000h
System lifetime	>80000h	>50000h	>20000h

2.2. The role of water electrolysis in hydrogen production under dual carbon goals

As global fossil fuel reserves are projected to decline after 2050, reliance on traditional energy sources is becoming unsustainable. Rising fossil fuel consumption and greenhouse gas emissions highlight the urgent need for alternative energy solutions [9]. The energy transition necessitates policy changes that position hydrogen as a vital energy carrier. Policy support can encourage enterprises and research institutions to increase investment in hydrogen technology research and development, and promote innovation and breakthroughs in hydrogen technology.Therefore, developing supportive policies for hydrogen production and infrastructure is crucial for long-term sustainability and achieving climate commitments [10]. The efficiency of hydrogen production via water electrolysis can be significantly enhanced through the development of advanced catalysts, optimization of electrolyzer cell design, and improved integration of energy systems. Furthermore, the advancement of cost-effective catalysts and membrane materials to reduce dependence on precious metals can substantially lower the overall cost of hydrogen production [11]. In short, hydrogen production via electrolysis supports dual carbon goals by transforming the energy structure, improving efficiency, and promoting low-carbon development. With technological advancements and falling costs, water electrolysis is set to become a key element of the future energy landscape. Table 2 outlines the advantages and challenges of water electrolysis for hydrogen production in various scenarios [12-15].

Table 2: Advantages and disadvantages of electrolysis water hydrogen production technology

Water electrolysis technology	**Advantages**	**Disadvantages**
Alkaline water electrolysis (AWE)	• Well mature Technology • Conventional technology • Inexpensive electrocatalysts • lower cost • Long-term stability	• Current densities is low • corrosion susceptible electrolyte
Proton exchange membrane electrolysis (PEM)	• Commercialized technology • Current densities is high • High purity of the gases • Compact system design • Quickly response	• Precious catalysts are used • Noble metal electrocatalysts • Less duration • High cost
Solid oxide electrolysis (SOE)	• High working temperature	• Limited stability

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Table 2: (continued)

	• Inexpensive electrocatalysts • High reaction • High efficiency	•Less duration • Under development • Limited scale

3. Latest developments in water electrolysis for hydrogen production

3.1. Advances in catalysts

Catalysts are crucial in hydrogen production via water electrolysis. Their selection depends on factors such as activity, lifetime, electrical conductivity, specific surface area, and chemical stability. At present, commonly used catalysts are mainly categorized into noble metal catalysts, transition metal oxide catalysts and non-precious metal catalysts (NPMC). However, the high cost and scarce reserves of noble metal catalysts limit their application, and transition metal oxide catalysts are currently mainly used [16]. Nickel-based oxides play an important role in hydrogen production from electrolytic, and cobalt and iron oxides also perform well in alkaline media. Literature shows that nickel oxide has the highest catalytic efficiency and iron oxide has the lowest efficiency [17]. Precious-based metal catalysts such as platinum and its alloys have high activity in cathodic hydrogen-extraction (HER) and anodic oxygen-extraction (OER) reactions, but their industrial application is limited due to very low platinum reserves and high cost [18]. To improve its stability and utility, researchers have dispersed it as single atom catalysts (SACs) to increase the catalytic active sites [19]. As the PEM market grows, the demand for platinum continues to rise and the research focus shifts to non-precious metal catalysts.

There are various types of NPMCs, including transition metal/nitrogen/carbon catalysts, mainly nickel, iron, molybdenum, and cobalt. Under the same current density, the catalytic overpotential of nickel-based catalysts is lower, and doping other elements can modulate their electronic structure to enhance activity and stability [20]. Non-metallic catalysts are mainly carbon materials, which possess abundant raw material sources and low cost, but their instability under acidic conditions limits the development [21]. However, nonmetallic catalysts show good stability in voltage cycling experiments, but the working potential range and H_2O_2 generation time are limited. PEM electrolytic cells are more difficult to develop nonprecious metal catalysts in acidic environments, so platinum and its alloys are still predominant in large-scale electrolytic cells [22]. In recent years, significant progress has been made in catalyst research. Through nanostructure design and surface engineering, the catalyst surface area and active sites are increased to boost the catalytic performance. Low-cost nanostructured metal phosphide catalysts exhibit excellent physicochemical properties with high activity, stability, and conductivity, thus showing potential as electrolysis catalysts [23]. The electronic structure of the catalysts is optimized by means of alloying, doping and interfacial engineering to further enhance the catalytic activity and stability.

Different electrolysis rules correspond to different catalyst requirements. Given that the PEM electrolytic cell is subjected to a prolonged period of operation within a strongly acidic environment with pH=2, most of the non-precious metal ions will combine with the ions in the electrolyte, which will affect the proton conduction efficiency. Therefore, the research of PEM electrolytic cell catalysts mainly focuses on noble metals such as platinum, iridium and ruthenium, as well as titanium-based oxides or new catalyst materials alloyed with transition metals. Bimetallic catalysts hold promise for future PEM applications given the specificity of electrolyte [24]. Emphasis should be placed on the development of new materials and synthesis methods to improve the performance of non-precious metal catalysts in order to compete with precious metal catalysts and to ensure long-term stability,

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improve hydrogen production efficiency and reduce costs. Table 3 summarizes the properties of some catalysts and their applications in hydrogen production from electrolytic water [25-34].

Table 3: Major catalyst details

Anode catalyst	Cathode catalyst	Cell area (cm^2)	Cell temp (C)	E(V)	current density (Acm^{-2})
Ti/IrO_2	$PANI/Ni_2P$	8	80	1.82	1
Ru/Ni	CeO_2	10	80	1.84	20
Ni2P/NiMoP	Pt	–	80	1.35	10
Ir/FeNiP	Pt/C	5	80	1.42	1
Ag/Ti	Pt/C	10	80	1.8	16
Ir-black	Pt/C	15	90	1.6	10
IrO_2– Pt/C	Pt/C	–	80	3.8	2.5
Ir_6Ag_9NTs/C	Pt	5	80	1.57	10
Li/MgO	Pt/C	5	90	–	–
$SrTi_{0.67}Ir_{0.33}O_3$	Pt/C	5	80	1.7	1

3.2. Innovations in electrolyzer design

At present, PEME stands out as one of the most widely adopted methods of hydrogen generation and effective techniques for generating hydrogen via water electrolysis. The PEM electrolyzer possesses several distinctive features. In particular, due to its low internal resistance and highly active catalyst, it can operate at high current densities (typically more than 1 A/cm^2), hence increasing the hydrogen production efficiency [35]. The PEM electrolyzer has the capability of fast startup and shutdown, which allows it to quickly adapt to power fluctuations and seamlessly integrate with other renewable energy sources. In addition, its compact structure stems from the design of the solid electrolyte and thin-film electrode assembly, which facilitates integration and deployment [36]. PEME produces hydrogen with a purity of more than 99.999%, which makes it suitable for a variety of applications, and it consumes a relatively low amount of energy, with some technologies able to reduce power consumption to 3.2 kWh/standard square meter, which is significantly superior to alkaline electrolysis, which consumes 5 kWh/standard square meter [37]. Thus, PEM electrolyzers have a modular design for easy maintenance and expansion.

Key components of a PEM electrolyzer include the membrane electrode assembly (MEA), gas diffusion layer (GDL), and bipolar plate (BPP). The MEA, made by hot pressing, consists of a catalyst layer, proton-exchange membrane, and GDL. However, this method is costly and can cause membrane dehydration and deformation. Improvements include simultaneous hot pressing of catalyst ink onto the membrane before pressing the GDL [38]. Current research on MEA focuses on enhancing catalyst efficiency, reducing the use of precious metals, improving proton conductivity and membrane durability, and optimizing GDL structure. PEM must be kept moderately hydrated to maintain high proton conductivity and optimal hydrogen production. However, excessive water can reduce reaction efficiency, so a steady-state equilibrium must be maintained [39]. The GDL transports reactive gases to the catalyst layer and removes liquid water. It is hydrophobically treated, with a micropore layer coated on the base layer to form an effective diffusion structure, typically made of carbon fibers. The base layer is usually composed of carbon fibers, while the microporous layer is composed of carbon nanoparticles mixed with hydrophobic materials [40]. In order to improve the drainage effect of GDL, a certain mass fraction of PTFE solution is commonly used [41]. The addition of PTFE enhances the drainage function of GDL, and the optimization of its distribution has become the focus of research.

Experiments show that increasing PTFE content improves the hydrophobicity of GDL materials, and GDL performance directly influences electrochemical reactions and hydrogen production efficiency.

Bipolar plates (BPPs) play an important role in PEMs, including providing mechanical support for membrane electrodes, heat dissipation, and removal of excess water [42]. Ideal bipolar plates should have excellent thermal conductivity, low contact resistance, easy processing and cost effectiveness. To improve the stability performance, polymer blends are used to enhance the strength. Related research focuses on surface modification of metallic bipolar plates using techniques like PVD to enhance corrosion resistance and conductivity, as well as the development of composite plates with improved strength, corrosion resistance, and reduced weight and cost [43]. Also, the development of automated production lines is enhancing the production efficiency and quality control of bipolar plates.

3.3. Energy integration and optimization

Achieving peak carbon and carbon neutrality goals requires the full integration and optimization of energy systems to increase the efficient use of clean energy. Integrating renewable energy sources, such as wind, solar and natural gas, with electricity can improve energy utilization and significantly reduce greenhouse gas emissions and drive a transition in energy production and consumption. Energy flows can be managed more efficiently to cope with fluctuations in renewable energy sources through improvements in system efficiency [44]. For example, as Europe's largest economy and GHG emitter, Germany has implemented a bold energy policy to actively transition to sustainable energy. Through major investments in wind and solar energy, Germany has significantly increased the share of renewables in its energy mix, plans to phase out coal by 2038, and is climate neutral by 2045. The success of this transition lies in reducing carbon emissions, decreasing dependence on fossil fuels, and promoting new industries to drive jobs and economic growth [45]. Meanwhile, China is actively developing its hydrogen energy industry, with the *Medium- and Long-Term Development Plan for the Hydrogen Energy Industry (2021-2035)* outlining key goals. Despite rapid economic growth, China faces significant environmental challenges, with per capita carbon emissions among the highest globally. In 2020, China committed to peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, despite challenges in economic restructuring and industrial upgrading [46].

The integration of hydrogen with various energy systems is crucial to realize a diversified energy mix, as hydrogen can serve as a bridge between electricity and heat [47]. The ongoing advancements in hydrogen production technologies are expanding the potential of hydrogen to serve as a central element in energy integration. Governments worldwide are increasingly acknowledging hydrogen's strategic importance due to its potential to enhance energy efficiency, reduce costs, and function as a critical enabler in the transition to a low-carbon energy system [48]. Improving energy efficiency, reducing costs, and advancing hydrogen technologies will help countries achieve carbon neutrality, with hydrogen playing a key role in addressing climate change and resource depletion.

4. Optimized pathways for hydrogen production and application

4.1. Efficiency upgrade

The efficiency of hydrogen production is constrained by several factors, primarily including operating temperature, current density, and membrane material performance. Appropriately increasing the temperature and current density can significantly boost hydrogen production rates. However, excessive values may result in higher energy consumption and overheating, which can negatively impact overall efficiency and stability. Elevated temperatures can lower electrolysis voltage and accelerate reaction kinetics; however, beyond a critical threshold, it may adversely affect the chemical and mechanical stability of the membrane, leading to potential degradation. For example, Nafion

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membranes lose stability above 120℃, impacting electrolysis efficiency [49]. Similarly, though higher current densities enhance hydrogen production, they also increase DC energy consumption and may induce overheating of the electrolyzer, highlighting the need for efficient thermal management to prevent potential damage to the equipment. [50, 51]. The proton conductivity of membrane materials is a critical factor for PEM electrolysis efficiency. Enhancing proton conductivity can effectively reduce electrolysis voltage, thus decreasing energy consumption and improving hydrogen production rates. Furthermore, the chemical stability and selective permeability of the membrane directly impact long-term stability and hydrogen purity. Therefore, developing new membrane materials with high conductivity, excellent chemical stability, and low cost is key to improving PEM electrolysis efficiency. Advancements in materials science and technology, coupled with the optimization of operating conditions, enhancement of membrane performance, and improvement in thermal management, will collectively propel PEM electrolysis toward becoming a dominant method for green hydrogen production, thereby contributing to global carbon neutrality objectives.

4.2. Cost reduction

The high cost of PEME is mainly driven by the use of precious metal catalysts, particularly Pt, which is prone to dissolution in acidic hydrogen production media, reducing catalytic efficiency. To lower catalyst costs, researchers have explored alternatives such as non-precious metal and alloy catalysts, including Pt-Cu alloy catalysts. The de-alloying of copper in Pt-Cu alloys enhances their surface activity and durability under cycling conditions, extending the catalyst's lifespan [52]. Furthermore, nanoporous alloying technology effectively reduces platinum loss and enhances catalytic performance. Other corrosion-resistant materials, such as metal carbides, oxides, and nitrides, also show potential in helping to reduce overall catalyst costs. PEM, the core component of PEME, are costly primarily due to the use of fluoropolymers (e.g., Nafion membranes). While Nafion membranes offer excellent proton conductivity and chemical stability, their high cost limits the widespread application of PEME. Therefore, developing low-cost alternative membrane materials is key to reducing PEME costs. Materials such as PTFE and polyvinylidene fluoride (PVDF) can serve as alternatives under certain conditions. Despite their performance not fully matching that of Nafion, they offer advantages in cost and stability [53]. PEMWE have emerged as a leading technology for hydrogen production due to their high efficiency, variable power operation, and high current density [54]. However, bipolar plates, which are crucial components of electrolyzers, are both costly and prone to corrosion in acidic, wet conditions. Corroded metal may release ions that poison the catalyst and proton membrane, reducing hydrogen production efficiency. Coating metal bipolar plates can effectively prevent corrosion and enhance their durability [55]. In addition, optimizing the flow field design of the electrolyzer is crucial for improving efficiency. By increasing the number of parallel flow channels, the design minimizes pressure loss, improves reactant and product transport, and enhances overall efficiency [56]. Moreover, integrating PEMWE with renewable energy sources like solar and wind can greatly enhance energy efficiency and lower production costs. Policy support, particularly in the form of R&D subsidies, plays a critical role in advancing technology and reducing costs. With continued technological advances and supportive policies, the cost of PEME is expected to drop significantly, fueling the growth of the hydrogen industry and advancing global energy transition and carbon neutrality objectives.

4.3. Systems integration and scale-up

The global energy transition is accelerating. While dependence on non-renewable energy sources persists, the environmental issues associated with fossil fuels are becoming increasingly severe. In this context, system integration plays a crucial role by combining power generation, heating, cooling, and natural gas systems, thereby improving the centralized management and distribution efficiency of energy systems [57]. Significant progress has been made in integrating hydrogen energy into power systems, promoting bidirectional conversion between electricity and hydrogen, and expanding the range of hydrogen applications [58]. As an important medium for energy transition, hydrogen not only supports electricity and heat generation but serves as an energy storage solution, effectively addressing the challenges posed by the intermittency of renewable energy sources [59]. Currently, hydrogen energy systems are being piloted in regions rich in wind and solar resources, with related infrastructure construction steadily progressing [60]. These systems ensure stable power supply and reduce energy losses caused by periodic fluctuations in wind energy [61]. Figure 1 indicates the rise of renewable energy in global hydrogen production from 2015 to 2021, highlighting a shift in production structure.

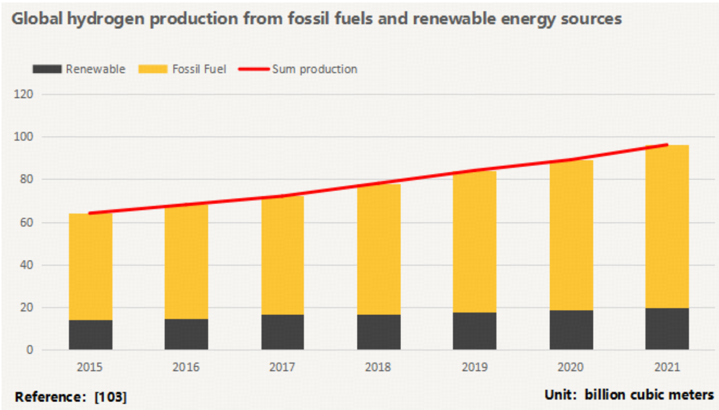

Figure 1: Global hydrogen production from fossil fuels and renewable energy sources, 2015-2021

Hydrogen production can quickly respond to grid demands, ensuring that power supply remains unaffected during power outages. As technology advances, hydrogen production and storage costs are expected to decrease, while efficiency improves, driving greater integration of the hydrogen industry and innovation chain. PEME technology, through catalyst and membrane optimization, is set to greatly improve efficiency [61]. Thus, accelerating the development of hydrogen supply networks and energy integration systems is essential to expedite the energy transition.

5. Conclusion

This study summarizes the application and future potential of PEME for hydrogen production. The results indicate that key areas of PEME technology advancement include catalyst optimization, proton exchange membrane performance enhancement, MEA updates, and electrolyzer design enhancements. Researchers have worked to reduce platinum usage while increasing the use of high specific surface area alloy nanoparticles to improve catalytic efficiency and durability. In addition, as the hydrogen energy market expands, large-scale production is expected to reduce costs and enhance technology competitiveness. Integration of PEM electrolysis with renewable energy sources, such as solar and wind, will further improve energy efficiency and reduce hydrogen production costs. However, the paper is limited by its focus on a single hydrogen production method and reliance on a literature review, lacking empirical support, which may limit its applicability. Future research should focus on comparing hydrogen production technologies to identify the optimal solution, particularly through the development of cost-effective, high-performance proton exchange membranes. In addition, exploring policy impacts on the hydrogen market and promoting international cooperation are key future directions.

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