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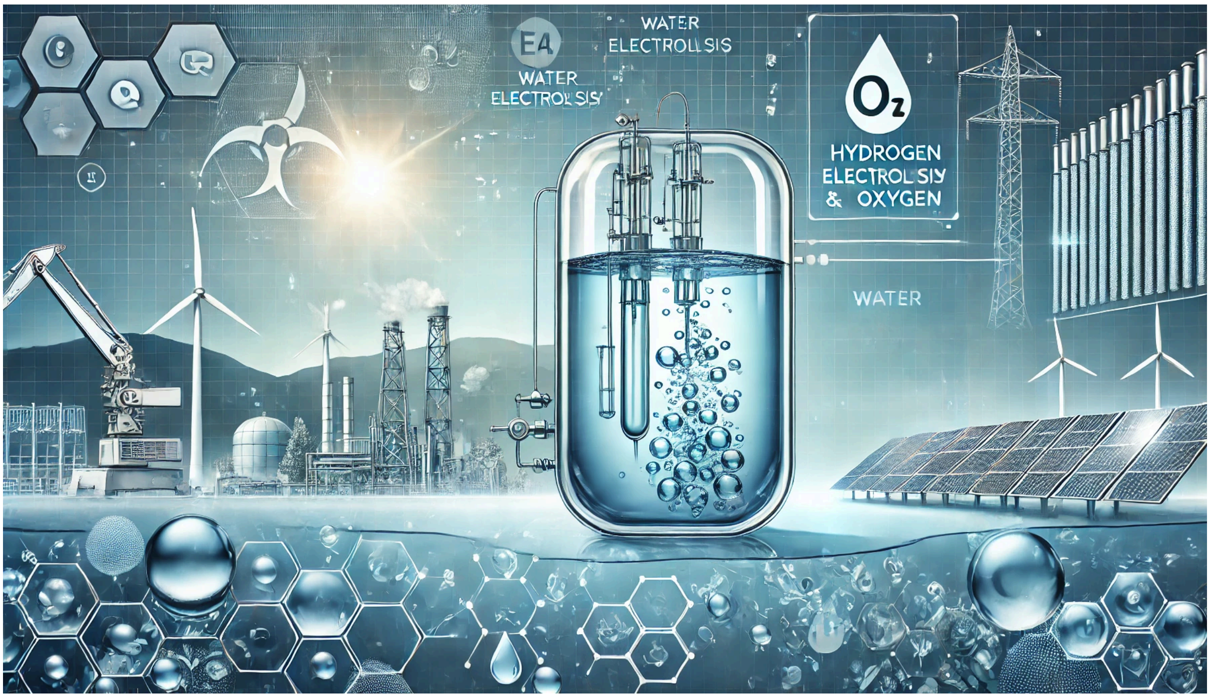
Research
Report

The current state of water electrolysis technology



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Summary

Water electrolysis technology represents a critical component in the production of green hydrogen, a clean and sustainable energy carrier essential for various industrial applications and the transition to renewable energy sources.

The technology involves the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases through the application of an electrical current, utilizing different types of electrolyzers such as Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Water Electrolysis (PEMWE), and Solid Oxide Electrolysis (SOE). Each type of electrolysis technology offers unique attributes in terms of efficiency, operating conditions, and material requirements.

The evolution of water electrolysis technology has been marked by significant advancements in catalyst materials and manufacturing techniques. Early dependence on noble metal catalysts posed economic and sustainability challenges, prompting research into earth-abundant, non-precious metal catalysts to reduce costs and improve environmental impact. Innovations in manufacturing processes, such as atomic layer deposition and 3D printing, have further optimized the performance and reduced the production costs of electrolysis cells. Current research focuses on understanding the degradation mechanisms of catalysts under operational stresses to enhance the durability and efficiency of water electrolysis systems[1][2].

Despite its potential, water electrolysis technology faces several challenges, including the high capital and operational costs, integration with renewable energy sources, and the need for improved stability and efficiency of catalyst materials. Faradaic efficiency, stability under oxidative conditions, and energy efficiency are crucial parameters influencing the overall viability of electrolyzers. Advanced studies on noble and non-noble metal catalysts, as well as innovative hybrid configurations, aim to address these challenges, making hydrogen production more economically feasible and sustainable[1][3][4].

The future of water electrolysis technology is promising, with expectations for significant cost reductions and technological advancements. By 2030, a substantial decrease in the capital costs of Solid Oxide Electrolyzers (SOEL) and other electrolysis technologies is anticipated, driven by production scale-up and innovation. These advancements are essential for achieving deep decarbonization targets and making green hydrogen competitive in the energy market. Continuous research and development efforts are crucial for improving the performance and deployment of water electrolysis systems, ultimately supporting the broader energy transition and sustainability goals[2][5][6].

History

The evolution of water electrolysis technology has seen significant advancements from its inception to modern-day applications. Initially, water electrolysis relied heavily on the use of noble metal catalysts, which were essential due to their high activity and selectivity. However, the dependency on these precious metals posed economic and sustainability challenges, leading to a concerted effort in the scientific community to discover innovative catalyst materials.

Current research prioritizes the development of earth-abundant, non-precious metal catalysts that offer high activity, selectivity, and stability, aiming to reduce costs and improve the technology's environmental footprint[1]. In addition to material innovations, advancements in manufacturing techniques have played a crucial role in the progress of water electrolysis. Emerging fabrication methods such as atomic layer deposition, 3D printing, and electrospinning have enabled unprecedented control over the nanostructure of components within the electrolysis cells. These technologies not only optimize functionality but also contribute to significant reductions in production costs[1].

The continuous research and development in this field have highlighted the need for a deeper understanding of degradation mechanisms of catalyst materials under operational stresses. Such studies are essential for enhancing the durability and efficiency of the catalysts, which are critical for the long-term viability of water electrolysis technology[1].

As the field advances, researchers have also been focusing on comparing the efficiency factors of different electrolysis technologies. For example, theoretical predictions suggest that proton exchange membrane (PEM) electrolysers could achieve efficiency factors of up to 94%, although this remains a theoretical figure at this time[7].

Looking forward, the article outlines future research directions aimed at improving the performance and durability of water electrolysis systems, paving the way for their widespread implementation. This includes addressing the challenges and trends associated with current and future technologies, some of which are still in the research phase but are expected to gain prominence in the coming years[2].

Principles of Water Electrolysis

Water electrolysis is a fundamental electrochemical process that involves the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases through the application of an electrical current. This technology is essential for producing green hydrogen, a clean energy carrier. The electrolytic process occurs in a device known as an electrolyzer, which comes in various types based on the electrolyte used and the operating conditions.

Types of Water Electrolysis

Water electrolysis technologies are broadly categorized into three main types: alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and solid oxide electrolysis (SOE).

Alkaline Water Electrolysis (AWE)

In AWE, the electrolyte typically consists of an aqueous solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH) with a concentration of 20-40%[8]. The electrolysis cell comprises an anode and a cathode separated by a gas-impermeable membrane, which allows the passage of hydroxyl ions (OH^-) while preventing the mixing of hydrogen and oxygen gases[9]. Nickel-based materials are commonly used for the anode, while cobalt-based oxides are preferred for the cathode[1]. AWE usually operates at temperatures between 70 and 90 °C and current densities of around 400 mA cm^{-2}[10][1]. The technology is known for its stability, low investment costs, and high efficiency, making it suitable for industrial-scale applications[11].

Proton Exchange Membrane Water Electrolysis (PEMWE)

PEMWE utilizes a solid proton-conducting membrane instead of a liquid electrolyte. This membrane, often made from a material like Nafion®, allows protons (H^+) to pass through while blocking electrons, thus facilitating the electrolysis process in an acidic environment[11][7]. Water is supplied to the anode, where it is oxidized to produce oxygen, protons, and electrons. The protons migrate through the membrane to the cathode, where they are reduced to form hydrogen gas[11]. PEMWE can operate at high current densities (-2 to -3 A cm^{-2}) and typically functions at temperatures between 50 and 80 °C[9]. This technology is historically rooted in scientific research and is currently scaling up for industrial applications[11].

Solid Oxide Electrolysis (SOE)

SOE operates at much higher temperatures (typically above 800 °C) compared to AWE and PEMWE. The process uses a solid oxide or ceramic electrolyte that conducts oxygen ions (O^{2-}). At the cathode, water is reduced to hydrogen gas and oxygen ions, which migrate through the solid electrolyte to the anode. There, the oxygen ions are oxidized to form oxygen gas[9]. The high operating temperature of SOE allows for greater efficiency in converting thermal energy to chemical energy, making it suitable for integration with high-temperature heat sources[12]. While SOE is still in the demonstration phase for industrial applications, it presents a cost-effective approach to water electrolysis when such heat sources are available[11].

Performance Metrics

Key performance indicators for water electrolysis include the current density, operating temperature, and cell voltage, which influence the overall efficiency and stability of the electrolyzer. For instance, AWE typically achieves a polarization voltage ranging from 1.

Current Technologies

Water electrolysis, a critical method for hydrogen production, encompasses several technologies, each with unique attributes and challenges. The primary types of water electrolyzers are Alkaline Electrolyzers (AEL), Proton Exchange Membrane Electrolyzers (PEMEL), Solid Oxide Electrolyzers (SOE), and Anion Exchange Membrane Electrolyzers (AEM).

Alkaline Electrolysis (AEL)

Alkaline electrolysis is one of the most established methods for hydrogen production, dating back to the 19th century [5]. This technology is commercially mature, low-cost, and stable, typically operating between 20–80 °C and up to 30 bar pressure, with process efficiency ranging from 62–82% [9]. Alkaline electrolyzers utilize charged Raney nickel electrodes immersed in a potassium hydroxide (KOH) electrolyte, separated by a diaphragm permeable only to OH− anions. This configuration ensures the separation of product gases while maintaining stable operation [9].

Proton Exchange Membrane Electrolysis (PEMEL)

PEM electrolysis is a commercially available technology capable of operating at high current densities (−2 A cm−2 to −3 A cm−2) between 50–80 °C [9]. Unlike alkaline electrolyzers, PEMEL uses a thinner polymer electrolyte membrane, Nafion®, which provides excellent proton conductivity (0.12 ± 0.04 S cm−1) and quicker input response [9]. This technology is particularly suited for projects with high renewable variability and limited space, such as offshore projects [6].

Solid Oxide Electrolysis (SOE)

Solid oxide electrolysis, initially developed in the 1980s by Dönitz and Erdle, stands out for its high efficiency and ability to operate at high temperatures (500–850°C) [5][6]. SOE uses water in the form of steam and converts electrical energy into chemical energy with high efficiency [5]. Solid oxide electrolysis cells (SOECs) operate at the thermoneutral point (1.23 V), achieving stack efficiencies close to 100% [6]. Despite the challenges in scaling up due to the high-quality and reliable ceramic technology required, SOECs are already achieving the MW scale, making them viable for deployment and further development [6].

Anion Exchange Membrane Electrolysis (AEM)

AEM electrolysis is the least developed among the discussed technologies but holds significant potential. AEM operates in an alkaline medium, similar to AEL, but uses a membrane technology akin to PEMEL, allowing for the use of inexpensive materials and a smaller footprint [6]. Although there are currently few commercial AEM products, the potential efficiency and cost advantages make it a promising area for future research and development [6].

Applications

Water electrolysis technology has various applications, predominantly in the production of hydrogen, which can replace natural gas as a heat source in industrial processes requiring high temperatures, such as in the steel and cement sectors. These industries may need to adapt or replace their equipment but do not require highly pure hydrogen [5].

Energy Storage

Hydrogen storage plays a crucial role in the energy sector. Current storage options include compressed gas, cryogenically frozen or liquefied gas, and chemical storage methods such as metal hydrides and ammonia [5]. Storing hydrogen as a compressed gas is currently the most common method, despite requiring substantially more space compared to other storage technologies. Nonetheless, it offers advantages such as simple operation, low costs, and rapid (dis)charge cycles [5].

Synthetic Fuels Production

Currently, synthetic fuels are produced by steam reforming of fossil hydrocarbons (mainly methane) and by coal or biomass gasification. Additionally, coal liquefaction through direct processes like co-processing and dry hydrogenation is used, where coal is directly converted to liquid synfuel, avoiding the initial conversion to syngas [5]. The integration of water electrolysis in synthetic fuel production allows for the generation of green hydrogen, reducing reliance on fossil resources.

Industrial Applications

Hydrogen produced through water electrolysis is widely utilized in industrial applications. This includes the manufacturing of fertilizers, petroleum refining processes, and in the chemical and petrochemical industries [5]. For example, hydrogen can be used in fuel cells, which are essential for modern industrial processes. Water electrolysis provides a renewable means to produce the hydrogen required for these applications, thereby supporting sustainability efforts.

Power-to-Fuel Configurations

In power-to-fuel configurations, hydrogen generated from water electrolysis can be stored and later used to produce synthetic fuels. This system is beneficial in ensuring a steady supply of energy, especially during periods when renewable energy sources are not available. For instance, hydrogen can be produced using surplus energy from renewable sources, stored, and then utilized in fuel cells to generate electrical and mechanical energy as well as heat, thus ensuring continuous production of emissions-free energy [5].

Fuel for Internal Combustion Engines

Hydrogen is also recognized as a viable fuel for internal combustion engines, offering a clean alternative to traditional fuels. Hydrogen combustion produces only water vapor as its major oxidation product, making it an environmentally friendly option. While hydrogen provides three times the energy per kilogram compared to gasoline, its low density in gaseous form remains a challenge for storage and transport [5].

Challenges and Limitations

Water electrolysis technology, while promising for sustainable hydrogen production, faces several challenges and limitations that need to be addressed for its broader adoption and economic viability.

Faradaic Efficiency and Turnover Frequency

Faradaic efficiency is crucial for understanding the efficiency of electrons transferred to the electrode surface for the electrochemical reaction. It is defined as the ratio of the experimentally detected quantity of H_2 or O_2 to the theoretically calculated quantity based on chronoamperometric or chronopotentiometric analysis. Experimental values are typically measured through gas production analysis using methods like water–gas displacement or gas chromatography. The minimum theoretical overpotential of 0.37 eV illustrates the inherent energy barriers that need to be overcome for efficient electrolysis [3].

Stability and Durability

The stability of electrocatalysts is a key factor determining the practical lifetime of electrolyzers. This is typically tested through accelerated degradation tests involving cyclic voltammetry (CV) at higher scan rates, chronoamperometry (CA), or chronopotentiometry (CP) at a given current density or voltage. Current research focuses on assessing the stability of electrocatalysts and two-electrode electrolyzers over thousands of CV cycles and extensive CP or CA durations. For industrially relevant hydrogen production, electrolysers must operate at high current densities (e.g., 0.5 to 2 A cm^{-2}) to achieve appreciable H_2 production rates while maintaining stability for thousands of hours to years [10].

Energy Efficiency

Energy efficiency is another critical parameter for evaluating electrolyzer performance. The cell-level energy efficiency, which considers only the electricity input, is calculated using several factors including the measured hydrogen production rate, power supplied by the direct-current power supply, applied current and voltage, Faraday's constant, and the heating value of reaction enthalpy. This comprehensive approach highlights the importance of optimizing both the energy inputs and the operational parameters of the electrolyzers [1].

Cost Considerations

The cost of hydrogen production through electrolysis is significantly influenced by the capital and operational costs of the electrolyzer.

Current estimates for capital costs vary depending on the technology used:
- ALK electrolysis ranges from USD 200 to USD 600 per kW,
- PEM electrolysis from USD 500 to USD 1000 per kW, and
- SO electrolysis from USD 1000 to USD 3000 per kW.

Reducing these costs through technological improvements, scalability, and standardization is essential for making hydrogen production more economically feasible [4].

Integration with Renewable Energy

Integrating electrolyzers with renewable energy sources presents additional challenges, such as the need for large PV surfaces for significant hydrogen production at major industrial sites. For instance, in steel production, around 0.2 to 0.3 m^2 of PV surface per kg of H_2 is necessary, translating to substantial areas when scaled up. Improving the efficiency of hydrogen processes and blending green hydrogen in existing industrial processes are potential solutions, but require thorough evaluation and optimization [13].

Research and Development

The research regarding various production technologies for water electrolysis is extensive, addressing current commercial technologies as well as future technologies that are still in the research phase but expected to be significant in the coming years[5].

The study of catalyst materials, both noble and non-noble metals, has been a focal point of recent advancements. Noble metals like Rh, Au, Pt, and Pd-based catalysts have shown promise as bi- or tri-functional electrocatalysts for the oxygen evolution reaction (OER), hydrogen evolution reaction (HER), and oxygen reduction reaction (ORR)[3]. Conversely, earth-abundant oxide and (oxy)hydroxide electrocatalysts, particularly Ni–Fe based compounds, have attracted significant interest for OER, demonstrating their utility in industrial-scale development[1].

Catalyst Development

Noble Metal Catalysts

Research has expanded beyond Ir and Ru to include other noble metals such as Rh, Au, Pt, and Pd, which have been developed as bi- or tri-functional electrocatalysts. These catalysts are promising for OER, HER, and ORR applications, showcasing notable performance improvements in electrochemical reactions[3].

Non-Noble Metal Catalysts

Earth-abundant catalysts, especially Ni–Fe based oxides and (oxy)hydroxides, are prevalent in OER applications due to their affordability and effectiveness. However, their stability under highly oxidative conditions in alkaline solutions remains a challenge[1]. For example, Hu et al. synthesized nanostructured nickel iron diselenide (NixFe1−xSe2) as a precursor for generating highly active nickel iron oxide catalysts, which exhibited excellent OER activity with a low overpotential of 195 mV for 10 mA cm−2[1].

Innovations in Catalyst Stability

Recent studies have focused on improving catalyst stability by integrating novel materials and manufacturing techniques. For instance, Lou et al. explored the use of 'accessional ionomer coatings' to enhance the architecture of membrane electrode assemblies (MEAs), leading to improved cell performance and durability. This approach has proven effective in reducing overpotential and degradation over extended operation periods, highlighting significant advancements in electrolyser stability and efficiency[1].

Hybrid Configurations

Hybrid catalyst configurations, such as those combining cost-effective NiFe catalysts with noble metals like Ir, have demonstrated increased catalytic activity and durability. T. H. Kwan et al. developed a multi-functional catalyst-coated membrane (CCM) for proton exchange membrane water electrolysis (PEMWE), which optimized iridium catalyst utilization and reduced hydrogen crossover, thereby enhancing overall electrolysis efficiency[1].

Advanced Manufacturing Techniques

Advances in fabrication methods are crucial for optimizing CCM components. Techniques such as atomic layer deposition, 3D printing, and electrospinning offer unprecedented control over nanostructures, potentially reducing production costs while enhancing functionality. Hrbek et al. presented an innovative dry process for manufacturing low-loading CCMs, achieving high performance with significantly reduced noble metal loading through simultaneous plasma etching and cerium oxide deposition[1].

Material Innovations

Future research is directed towards discovering innovative catalyst materials that minimize dependence on noble metals. The development of hydrogen bond-dominated polybenzimidazole (PBI) semi-interpenetrating network membranes for alkaline water electrolysis (AEMWE) exemplifies such efforts. Qiu et al.

Future Prospects

The future of water electrolysis technology holds considerable promise, particularly in the context of achieving deep decarbonization targets.

As highlighted in the research, advancements in AEM-WE (Anion Exchange Membrane Water Electrolysis) are essential for addressing the most critical aspects of current limitations and mapping out potential routes for overcoming these challenges.

The development status of AEM-WE underscores the need for further fundamental understanding and targeted research to achieve the desired improvements[14][10].

In terms of economic viability, significant reductions in the capital costs of Solid Oxide Electrolyzers (SOEL) are anticipated.

While current costs are high, fluctuating above EUR 3000/kW, experts project a substantial decrease to EUR 750/kW by 2030, driven by production scale-up and technological advancements[5].
These reductions are crucial for making green hydrogen more competitive in the market. The review suggests that by 2030, a notable growth in the deployment of electrolysis technologies can be expected, spurred by lower CAPEX and OPEX, and consequently, reduced Levelized Cost of Hydrogen (LCOH). This progress will be driven by further reductions in renewable electricity costs and advancements in electrolysis technologies[6].

The specific suitability of different technologies will also play a critical role; for example, alkaline technologies are more appropriate for large-scale projects with minimal space and renewable variability constraints, whereas PEM technologies are better suited for high renewable variability and limited space scenarios[6]. Moreover, the overall production and application of hydrogen are expected to grow significantly.

Despite global hydrogen production growing by only 2-3% to reach 95 Mtonnes in 2022, the production of low-emission hydrogen remains minimal. The installed capacity of electrolyzers is still limited, emphasizing the need for further deployment and technological enhancements[4].

Future research directions are pivotal for improving the performance and durability of technologies like Solid Oxide Electrolysis Cells (SOECs), facilitating their widespread implementation. These research efforts aim to bridge the gap between current capabilities and future requirements, thereby contributing to the broader energy transition[2].

Finally, reaching net-zero targets demands substantial changes in the energy industry's operational framework. Hydrogen has the potential to achieve deep decarbonization if produced sustainably and cost-effectively[8]. Ongoing advancements in electrolysis technology are essential to meet these ambitious goals, and continuous updates in cost data, industry reports, and project-specific details will be necessary to stay abreast of the evolving market dynamics and technological progress[4].

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