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# Advancements in Electrolyser Efficiency for Scalable Hydrogen Production from Renewable Sources

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## ABSTRACT

Hydrogen is increasingly recognised as a key component of decarbonised energy systems, mainly when produced via water electrolysis powered by renewable energy sources. However, its widespread use is limited by the current electrolyser technologies' low efficiency, high costs, and challenges with scaling up. This paper examines recent improvements in electrolyser efficiency across major types, including alkaline electrolysers (AEL), proton exchange membrane electrolysers (PEMEL), and solid oxide electrolysers (SOEL). It focuses on thermodynamic performance, material breakthroughs, operational conditions, and system integration approaches that boost energy efficiency and lower hydrogen production costs. Additionally, the study discusses hybrid setups and connection with intermittent renewables like solar and wind, emphasising dynamic operation, load management, and advanced control techniques. The paper ends with insights into research gaps, policy options, and future strategies for large-scale adoption of high-efficiency electrolysers in the global green hydrogen economy.

**Keywords:** Electrolyser Efficiency, Green Hydrogen, Renewable Energy Integration, Proton Exchange, Embrane (PEM), Alkaline Electrolyser, Scalable Hydrogen Production

## INTRODUCTION

Hydrogen is a vital carrier for storing, transporting, and distributing energy, and it has the potential to replace fossil fuels in many sectors (Xia et al., 2023). Hydrogen plays a key role in supporting various sectors during the shift to clean energy. Hydrogen production through electrolysis is central to expanding a clean hydrogen economy at the terawatt scale (Zhang et al., 2024). Different methods can be used to produce hydrogen, including water electrolysis, reforming of fossil fuels, and biomass gasification. Among these, electrolysis is the most adaptable and promising method for directly converting electrical energy into hydrogen. Improving electrolyser efficiency is essential to meet the demand for scalable hydrogen production from renewable sources. Water electrolysis involves splitting water into hydrogen and oxygen using electrical energy (Apata et al., 2024). It offers an attractive method for producing hydrogen without generating greenhouse gases or other pollutants. Electrochemical water splitting can be carried out with alkaline, proton exchange membrane, or solid oxide electrolysers. These three main types of electrolysers have significantly influenced the development of modern water electrolysis technologies over the past century, encompassing design, configurations, electrolytes, and materials. Key efficiency parameters such as energy efficiency, faradaic efficiency, and operational efficiency are crucial for developing innovative and effective electrocatalysts, electrolyte membranes, and electrodes.

### Overview of Hydrogen Production Methods

High front-end capital costs hinder the distribution of renewable energy; storage and transmission limits restrict access to supply variations. Hydrogen from water electrolysis is a promising solution for grid storage and transmission (B. Agyekum et al., 2022). This rapidly growing research field utilises processes such as water electrolysis, where electricity splits water into hydrogen and oxygen. Hydrogen can be used as a fuel or in hydrocarbon processes, such as methanol synthesis or methane reforming. The electricity for electrolysis can come from intermittent renewable sources, such as solar or wind power, or the electrical grid. Hydrogen is a promising alternative energy source due to its high energy density, ease of transportation, and emission-free production, making it a suitable replacement for fossil fuels. It can be used in fuel cells to generate electricity with higher efficiency than hydrocarbons (Nasser et al., 2022). This review focuses on water electrolysis powered by solar and wind energy, comparing electrolyser types, advantages, and disadvantages. An economic analysis examines the costs and challenges associated with it. Solar energy generally outperforms wind in hydrogen production. Despite high energy needs, catalyst issues, and cathode corrosion, innovations continue. Since 2005, patents on green hydrogen have grown, led by Japan and the U.S.

**The Role of Electrolysis in Hydrogen Production**

Electrolysis plays a crucial role in hydrogen production, particularly when powered by renewable energy sources. Hydrogen can be generated through electrolysis using solar, wind, or other renewable energies, offering a sustainable route to clean energy. Advances in electrode technology and electrolyser design have enhanced performance and cost-effectiveness, making hydrogen produced via electrolysis integral to green hydrogen production pathways aimed at decarbonization and energy transition targets (B. Agyekum et al., 2022). Several electrolyser technologies are currently available, including Alkaline, Proton Exchange Membrane (PEMEL), anion exchange membrane (AEM), and Solid Oxide Electrolysers, each with varying degrees of technological maturity. The nature of the energy source dictates the quality of hydrogen and its environmental impact; renewable energy sources provide a carbon-free option. Due to the variable and intermittent nature of renewable energy generation, surplus power can be converted into hydrogen through electrolysis, allowing for storage and subsequent reconversion to electricity via fuel cells. Among these technologies, PEM electrolysis exhibits a rapid response and maintains high efficiency at partial loads, rendering it particularly well-suited to fluctuating energy inputs such as wind power. Nevertheless, challenges persist in integrating electrolysers with renewable energy systems, particularly regarding operational limits and overall integration efficiency (Patella et al., 2023).

Alkaline water electrolysis, utilising advanced technology, holds significant potential for large-scale production of green hydrogen powered by renewable energy. The process comprises two half-cell reactions: the oxygen evolution reaction (OER) and the hydrogen evolution reaction (HER). The OER is notably more challenging from both thermodynamic and kinetic perspectives. Selecting electrocatalysts that are durable, abundant, and effective for the OER remains an outstanding challenge; the electrocatalyst surface and its interaction with water, reaction intermediates, hydrogen, and oxygen govern catalytic performance. Efforts to enhance intrinsic activity through phase segregation, defect engineering, and surface activation of transition-metal-based electrocatalysts, particularly those based on cobalt, are ongoing. Overcoming these challenges is essential to enable the large-scale production and utilisation of green hydrogen (Tüysüz, 2024).

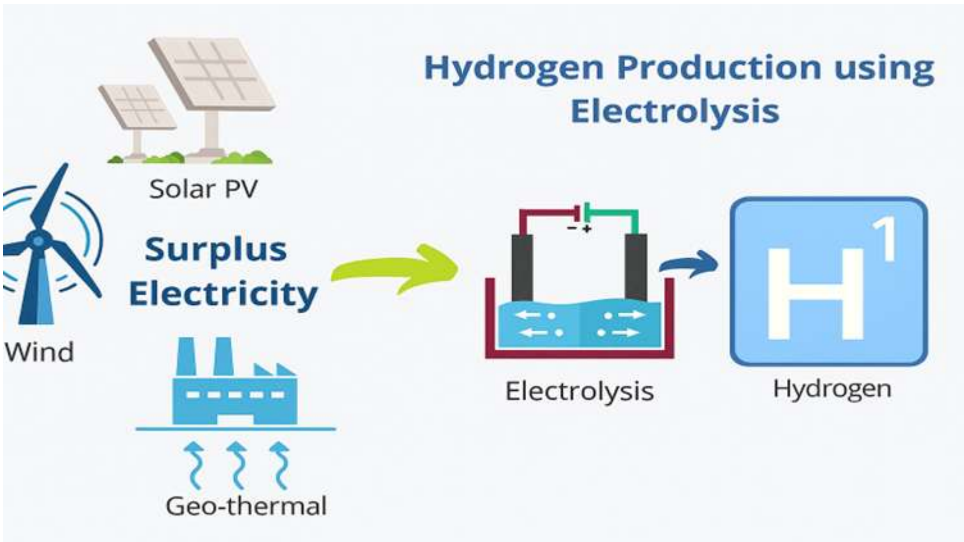


Fig. 1: Electrolysis in Hydrogen Production

### Types of Electrolysers

The four mainstream electrolysis technologies for hydrogen production from water are alkaline electrolysis, polymer electrolyte membrane (PEM) electrolysis, solid oxide electrolysis, and anion exchange membrane (AEM) electrolysis. Alkaline and PEM electrolysers hold dominant market share positions, each at Technology Readiness Level (TRL) 9. In contrast, solid oxide and AEM electrolysers are at TRL 6 and 7, respectively (Xia et al., 2023). Alkaline electrolysers have been commercially used since the 1930s. They comprise a cathode and an anode separated by a porous diaphragm, with 20–40 wt.% aqueous alkaline electrolyte flowing internally. Essential components include a diaphragm, electrodes, a catalyst, and electrolytes. Alkaline electrolyte is typically circulated through the electrolyser or stored externally, with periodic replenishment required. Common electrolytes comprise KOH (20–40%) or NaOH (40%) (Zhang et al., 2024). Hydrogen evolution occurs at the cathode, and oxygen evolution at the anode. Although older than PEM electrolysers, alkaline technologies can be scaled to higher capacities, including those exceeding 100 MW and multiple hundred MW commercial systems. The older alkaline design is currently considered to have lower capital costs than PEM projects. PEM electrolysers operate at elevated temperatures ranging from 20 to 80 °C. Hydrogen evolution occurs at the cathode, while oxygen reduction takes place at the anode, both separated by an electrolyte membrane assembly. The catalyst, often platinum or iridium (assisted by other components), is embedded in the electrodes. The cell incorporates a polymer membrane that functions as both an electrolyte and a separator. Water supplied to the anode optimises the proton reduction reaction. PEM developments began in the 1960s, but they emerged commercially much later than alkaline technology. Recent advances have focused on reducing and substituting expensive components such as iridium catalysts and Nafion membranes.

### Alkaline Electrolysers

Alkaline water electrolysis for hydrogen production is popular due to its simplicity and low cost. These electrolysers, used in industry, operate at 60–80 °C with an alkaline electrolyte (e.g., KOH, NaOH, LiOH), producing hydrogen and oxygen when a voltage is applied. Their performance is not much affected by renewable energy intermittency compared to PEM electrolysers. Detailed methods, reactions, and applications are analysed (Tüysüz, 2024). Renewable energy-driven alkaline electrolysis is suitable for large-scale hydrogen production, but variable RESs cause poor low-load performance due to structural and electrical issues. A multi-mode self-optimisation strategy enhances efficiency and extends operation from 30-100% to 10-100% load, enabling improved RES hydrogen production. Three methods exist: solid oxide, proton exchange membrane, and alkaline electrolysers. Solid oxide types operate at high temperatures, face stability and sealing issues, and are in R&D (Xia et al., 2023).

### Proton Exchange Membrane Electrolysers

Proton Exchange Membrane (PEM) electrolysers have overcome some of the fundamental material limitations of alkaline electrolysers, enabling high-pressure operation and efficient operation with single-pass feedwater. They are currently widely used in commercial electrolyser systems. Because PEM electrolysers employ solid polymer electrolytes, they require very pure feedwater (typically 0.05 micromhos/cm) to avoid membrane contamination. The overall systems possess high turndown ratios, ranging from 10% to 100% of rated load, and rapid start-up, which is achieved within 5 minutes. PEM designs enable operation at high current density and produce relatively high-purity hydrogen (>99.9995% H2) at pressures between 15 and 30 MPa (Chisholm et al., 2020). Decoupled electrolysis of water, which provides hydrogen and oxygen in real-time and continuously, is crucial for hydrogen storage and utilisation. This can be achieved in a proton exchange membrane cell with an electron-coupled proton buffer (ECPB) comprising silicotungstic acid (Liu et al., 2024). Decoupled electrolysis enables accurate control of hydrogen production and reduces crossover between hydrogen and oxygen. The use of an ECPB provides several advantages over traditional electrolysers, including the suppression of gas crossover, greater tolerance to non-deionised feed water, and a decrease in markers of membrane degradation.

### Solid Oxide Electrolysers

Solid oxide electrolysers offer a promising approach to producing hydrogen using renewable energy efficiently. They use steam at high temperatures (700–900°C), which simplifies systems and requires less electrical energy (less than 1 volt) compared to room temperature. The turbine exhaust's thermal energy can meet a significant portion of the energy needs. These electrolysers operate in the reverse manner of solid oxide fuel cells, utilising a water-splitting process that involves an electrolyte and electrodes to influence performance. Metal-supported cells show good long-term performance with low resistance, and voltage–current responses are measured under different steam pressures. Most performance decline happens in the first 24 hours, then stabilises. Large-scale hydrogen storage and synthetic fuel production from hydrogen and $CO_2$ are key for integrating renewable energy, supported by Fischer–Tropsch synthesis and infrastructure development.

**Energy Efficiency Metrics for Electrolyser Performance**

A comprehensive electrochemical analysis of the three-electrode system examined its inherent activity, the impact of metal toxicity, and stability. This was performed using the rotating disk electrode technique over a potential range of −1 to +2 V versus a carbon electrode in galvanostatic mode (Patella et al., 2023). The evaluation of Fe–Mo electrodes highlighted noble-metal-free frameworks that outperform the benchmark Pt/C (60 μg Pt cm−2) at overpotentials of 290–300 mV in acidic media. Efficiency, defined as $\eta = 3.52 \times V / E$, links the standard condition hydrogen volume (V) to electrical energy consumption (E), serving as a key indicator of electrolyser performance and stability under varying power inputs (Xia et al., 2023). The system efficiency ($\eta$) for the lab-scale electrolyser is calculated as $\eta = 3.52 \times V/E$, with V as the accumulated hydrogen volume under standard conditions and E as the electric energy used. Data supporting these results are available upon request from the corresponding author (Xia et al., 2023). Alkaline water electrolysis is among the most advanced methods for producing green hydrogen. It is increasingly regarded as the most practical option for large-scale hydrogen generation from clean energy sources (Tüysüz, 2024). Typically, electrolyser units convert 65–70% of electrical input into hydrogen, with 30–35% lost as heat to the environment. Improving system energy efficiency will reduce electricity use, currently accounting for about 60–75% of operational costs (OPEX), and enhance the capacity for sustainable hydrogen production.

**Improvements in Faradaic Efficiency and Operational Performance in Electrolyser Technology**

The efficiency of a lab-scale electrolyser system is calculated with $\eta = 52 \times V/E$, where V is the hydrogen volume at standard conditions, and E is the energy used, derived from water vapour-corrected measurements. Calculating V and E assesses system efficiency (Xia et al., 2023). The rising global demand for hydrogen underscores the need for safe and affordable methods of producing it. Water electrolysis is the leading method for producing green hydrogen, unlike methane pyrolysis or geothermal hydrogen, which face scalability issues. Alkaline electrolysers are preferred for their economic benefits, as they operate at atmospheric pressure with non-precious catalysts and require easy maintenance. However, maintaining a stable, high-efficiency current is challenging due to market growth and fluctuations in renewable power, which can lead to voltage overshoot, reactive power issues, and inverter faults, affecting continuous operation. Consistent current is crucial since catalyst activity varies, and power instability reduces efficiency. The slowness of oxygen evolution limits overall efficiency, primarily influenced by the anode's performance. The process splits water into hydrogen and oxygen ions, with system efficiency depending on current and water splitting efficiency. Understanding how electricity is converted to hydrogen through the transport of hydroxyl ions across membranes is vital. Progress hinges on analytical tools to optimise procedures and reduce energy consumption. Large-scale hydrogen production is essential for decarbonising heavy industries. Electrolysis, powered by renewables, is the most promising green hydrogen method, involving HER at the cathode and OER at the anode. Commercial electrolysers mainly use alkaline or PEM technology (Xia et al., 2023).

**Materials Science Innovations**

Materials science innovations, such as Pd-Co electrodes for hydrogen generation, are vital for advanced electrolysers. Limited conventional fuel availability and environmental concerns are increasing interest in alternative fuels. Electrochemical systems are considered for hydrogen production, storage, and energy conversion (Patella et al., 2023). While water electrolysis using renewable energy is sustainable, large-scale green hydrogen production remains costly due to high energy demands. Efforts focus on cost-effective, high-productivity solutions for renewable energy storage at terawatt scales. Improvements via stress optimisation have boosted electrolysis efficiency (Liu et al., 2024). Decoupled water electrolysis (DWE) enables

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temporally/spatially separated reactions, allowing for membrane-free operation and overcoming traditional limitations. Early DWE utilised redox couples but faced low efficiency. Recent cycles, however, separate oxygen evolution into sub-reactions, achieving 98.7% HHV efficiency and facilitating scalable, membraneless green hydrogen production.

**Catalyst Development**

Efficient catalyst development is crucial for enhancing electrolyser performance and scaling up the production of green hydrogen. While alkaline water electrolysis is mature, optimising catalyst activity, durability, and cost, especially for oxygen evolution reaction (OER), remains crucial. Investigations focus on reaction mechanisms and in situ techniques to monitor surface intermediates and changes in the catalyst (Tüysüz, 2024). Contaminants such as iron and carbonates can deactivate catalysts, hindering their large-scale use, especially with nickel–iron active sites. Developing transition metal-based cathodes aims to replace costly precious metals with earth-abundant options that are active, stable, and economical. Goals include improving the kinetics of the hydrogen evolution reaction (HER), resistance to poisoning, lifespan, charge transfer, and active surface area (Li et al., 2023). Transition metals, such as nickel, cobalt, and molybdenum, are promising due to their availability and catalytic properties. Different water electrolysis methods—such as alkaline, PEM, and solid-oxide—have trade-offs. Effective catalysts must function across a wide range of pH and temperatures, thereby reducing reliance on expensive metals. Strategies include synthesising multifunctional nanomaterials and designing electrode architectures with hierarchical, open-pore structures to increase surface area and enhance mass transport, thereby exposing active sites for improved performance. Overall, catalyst research integrates understanding, contamination control, and structural design to enable scalable and decarbonising applications.

**Membrane Technologies**

Membrane separation techniques underlie versatile approaches to decarbonising hydrogen production through electrochemical water splitting, enabling hydrogen flows commensurate with commercial electrolysers. In electrolytes with near-neutral pH, polyoxometalate redox mediators and flow-cell designs enable a continuous cycle for decoupled water electrolysis (DWE), with the kinetically facile evolution of hydrogen and oxygen carried out in separate cells simultaneously (Slobodkin et al., 2024). Compared to conventional DWE methods using soluble or solid redox couples, this differentiation achieves current densities of 750 mA $cm^2$ at 1.73 VRHE with an electrolytic efficiency of 98%, a record high that capitalises on the elimination of thermal cycling. Meanwhile, catalyst longevity surpasses 600 h, supporting steady-state operation. These conditions promote a more rigorous evaluation of membrane technologies, which remain a focal point of investigation due to their relevance to cost and resource scarcity.

**Electrode Materials**

Reviews cover the performance of electrode materials for water electrolysis, emphasising corrosion resistance, electrochemical activity, conductivity, and material abundance for both anodes and cathodes. Morphology affects performance, and polarisation curves, influenced by various conditions, are used as metrics. Lab-scale efficiency is measured by the electrical power input relative to hydrogen's heating value, which requires rigorous testing under realistic conditions. Industrial focus shifts to cost minimisation, with design prioritising catalysts with high surface areas, system optimisation, and configurability. Future electrolyser designs aim for multi-mode operation, resource localisation, and flexible storage, enhancing efficiency and scalability (Zhang et al., 2024; N. Colli et al., 2019).

**Integration with Renewable Energy Sources**

An alkaline electrolyser system with a capacity of up to 3 kW and an output of 9 $Nm^3/h$ $H_2$ was designed and constructed to demonstrate the technical feasibility of coupling alkaline electrolysis with renewable energy sources. The electrolyser configuration ensures efficient electrochemistry and uniform flow distribution in the potential range of −0.6 to 0 V_RHE. Despite the small test scale and frequent load variations (which alleviate degradation), the galvanostatic test with a high cell voltage indicates only slight degradation after a 3350 h lifetime test under intermittent DC power from photovolatics (PV), wind, an electrolyser stack, and balance of

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plant (BoP) components (Xia et al., 2023). The system comprises dynamic power electronic converters, electrolyser stacks, and ancillary components, and its efficiency meets the efficiency requirements of hydrogen production from aqueous electrolysis coupled to renewable power generation.

**Solar Energy Integration**

A 4-kW PV-powered water electrolyser and firewood stove hybrid system has been developed for rural households. It uses local standards and potentiostat systems to boost efficiency. When sunlight decreases, the electrolyser recovers energy from firewood, saving fuel and ensuring a sustainable power supply. Hydrogen, a clean energy source, is hard to store and transport because of its high volume. Storing hydrogen chemically in stable materials, such as Li-ion alloys, offers a solution. Solar thermal energy can supplement electrolysis, with international support from the US and Europe, due to the challenges of hydrogen storage. Concentrated solar power, although costly on its own, facilitates thermal and photovoltaic integration, thereby reducing overall costs. PV electrodes are effective; standalone systems with separate hydrogen and oxygen cells driven by PV modules achieve high efficiency and scalability. External PV supplies enable hybrid photoelectrochemical cells to achieve better efficiency and facilitate easier fuel management. Current systems with separate electrodes show good stability.

**Wind Energy Integration and Hydro Energy Integration**

Wind energy is becoming increasingly vital in the renewable sector, particularly offshore wind for the production of green hydrogen. Unique offshore features enable lightweight energy transmission and maximise costly resources. While full deployment is promising, research is needed on scaling floating foundation systems, grid integration at high energy levels, and system behaviour during periods of low electricity prices. Risks include permitting, supply chain, and regulatory issues (Xia et al., 2023). Hydropower is crucial, with excess energy diverted for hydrogen production. Climate change may reduce hydropower, creating opportunities for energy storage and management. Ice cover impacts wind and hydropower in the Nordic and Siberian regions, causing low discharge and shutdowns. Hydrogen with hydropower can stabilise these grids. Transitioning to a carbon-neutral supply chain requires investment in green hydrogen, which can be produced locally or imported, depending on the specific needs and resources available. Since 2017, hydrogen and ammonia infrastructure have expanded, with efforts to standardise equipment. The hydrogen economy is expected to grow rapidly and sustainably, despite fluctuating energy prices following the pandemic.

**Economic Factors and Operating Expenses of Electrolyser Systems**

Hydrogen production can be decentralised, with off-grid solutions offering cost benefits. An operating optimisation model indicates that wind- and solar-based energy systems, with hydrogen shares reaching double digits, can gain advantages from off-grid projects compared to fully integrated designs (Tries et al., 2023). The efficiency of electrolyser systems is given by $\eta = 3.52 V/E$, where V is the total hydrogen volume (L) at standard conditions, and E is the electric energy used (kWh) (Xia et al., 2023). An electrolyser splits water into hydrogen and oxygen by applying an electric current. Key electrolyser types include alkaline, proton exchange membrane, and solid oxide, forming the basis for many technologies. Challenges involve improving efficiency, power density, durability, and cost, all of which are interconnected and essential for expanding the use of renewable energy. Choosing electrolyser systems can enhance stability and extend operational durations, thereby reducing maintenance and downtime, while also simplifying design and minimising the number of components. Standalone and hybrid systems can adjust hydrogen and oxygen flows to meet different or simultaneous demands. Improved efficiency means more product with less energy, lowering costs and boosting sustainability. Alkaline water electrolysis (AWE) is presently the most cost-effective technology for producing green hydrogen from renewable resources. An analysis focusing on the economic viability of current alkaline electrolyser technology, which maintains stable operation across a wide range of power inputs, emphasises the assessment of operational costs to exploit the full potential of renewable energy management and recycling. The operational cost (OPEX) can be calculated using the expression

OPEX=CCwCw^T + EC_EI + PC_P + MC_i

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where CCw, EC_E, PC_P, and MC_i denote the capital cost, electricity cost, plant cost, and maintenance cost, respectively, for each component referenced by subscript w, that is, the electrolyser, inverter, transformer, and rectifier (Xia et al., 2023).

**Market Potential for Green Hydrogen**

Green hydrogen, produced via water electrolysis using renewable energy, offers a sustainable option. Electrolysers support power-to-gas, grid balancing, energy storage, and energy-intensive industries. Initiatives like the EU's IPCEI test diverse electrolysis applications. Global assessments identify opportunities across various locations for producing green hydrogen from abundant renewable sources and efficient electrolysers (Baral & Šebo, 2024). Analyses show electrochemical conversion maximises profits from hydropower, geothermal, solar, and biomass (Matute et al., 2022). Large-scale electrolyser deployment provides cost-effective solutions for future hydrogen needs. Studies support the integration of intermittent renewables, with a focus on solar and wind, which complement electrolysers well. Investments in electrolyser technology foster development at all scales — from grid plants to off-grid facilities, improving efficiency and sustainable design, and strengthening hydrogen's economic viability.

**Environmental Impact**

The increase in greenhouse gas emissions caused by climate change has led to a significant rise in global temperatures. Moreover, as fossil fuel reserves continue to decline, sustainable energy resources have become essential alternatives to meet the growing global energy demand. Hydrogen energy production from renewable energy sources (RESs) through the electrolysis of water is among the most promising methods, featuring high energy efficiency, low operating costs, and environmentally friendly advantages (B. Agyekum et al., 2022). Conventional electrolysers comprise an electrolytic cell connected to a diaphragm or membrane, a power supply, and a water reservoir. RESs, including photovoltaic (PV) solar, wind, and hydropower, can be directly connected to electrolysers as an initial step towards increasing the production of green hydrogen (Xia et al., 2023).

**Carbon Footprint Analysis**

In the context of hydrogen production from solar and wind energy, melilite membrane electrolysers mitigate the intermittent nature of electricity. The carbon footprints of solar-driven high-temperature electrolysis systems can be assessed to guide further development. A techno-economic analysis considers solar-driven high-temperature electrolysis for hydrogen and synthesis gas production via three configurations. Thermal systems generate heat and electricity using concentrated solar power. Electrical arrangements employ photovoltaics and electrical heaters, while hybrid designs combine both. The hybrid concept achieves a hydrogen cost of 9/kg and scales favourably. An optimal operating temperature of 1350 K balances heat losses against cell potential; low pressure enhances system efficiency and cost-effectiveness. Thermoneutral operation is observed across a broad range of temperatures and pressures. Water conversion is optimised to avoid electrode mass transport limitations, supporting large fuel production. Synthesis gas with a 2:1 $H_2$:CO molar ratio results from controlling inlet ratios, temperature, and pressure. Coupling solar energy with renewable energy-driven high-temperature electrolysis presents a viable route to scalable solar-fuel output, utilising both concentrated solar power and photovoltaics (Lin & Haussener, 2017).

**Life Cycle Assessment**

Life Cycle Assessment (LCA) is a widely recognised and practical approach to evaluating the environmental impacts of solutions within complex systems, such as hydrogen production. It facilitates understanding intricate frameworks with multiple processes or subsystems, supporting informed decision-making for sustainable development. The literature indicates that hydrogen production and storage systems powered by renewable electricity have yet to achieve sustainability levels that rival or surpass those of conventional methods, such as steam methane reforming (Imran Amran et al., 2017). Using wind and solar energy for hydrogen production shows promise for decreasing primary energy use and emissions, but these systems need further optimisation. Concerns about hydropower, pumped storage regulation, and the environmental impact of PEM electrolysers — particularly when they involve off-site production — highlight the need for research into design and operational strategies that maximise P2G potential without harming sustainability (Isabel García Herrero et al., 2017). Multiple renewable-based production methods are currently under study, but their industrial adoption remains limited. In this context, LCA is the most suitable tool for identifying current bottlenecks and suggesting best practices to promote sustainable solutions.

**Case Studies of Successful Industrial Implementations and Pilot Projects**

A new multi-mode, self-optimising electrolysis converter for alkaline electrolysers enhances performance under renewable energy conditions. Its efficiency, $\eta = 3.52 \times V/E$, relates hydrogen volume (V) to energy (E) (Xia et al., 2023). Paired with a modular, multi-channel AC–DC converter with SiC devices, it offers high efficiency and reliability. Closed-loop controllers manage current variables for smooth mode switching, including low-load conditions. This ensures high efficiency and optimal operation of commercial alkaline electrolysers for renewable hydrogen. Industrial hydrogen generators support grid stability and should be integrated with heat engines to enhance their effectiveness. Despite ongoing advances, progress in electrolyser tech is limited (Xia et al., 2023). Cities like London aim for net-zero carbon by 2030 and soon after, become carbon-free. Upgrading urban water systems involves installing lined sewer tunnels, which are dried by ventilation and dehumidification, and then sealed. Similar systems could remove water vapour post-venting for hydrogen electrolysis, creating a renewable fuel. Carbon-free water electrolysis, particularly membrane technology, has multiple pilot projects worldwide, advancing the production of green hydrogen from renewable sources. Examples include 2,000 PV panels for solar hydrogen in Australia, Florida's Cape Canaveral Hydrogen Initiative utilising Power Tower solar energy, and a 320 MW solar farm in Ningxia, China, which produces electricity and green hydrogen. Plans include adding batteries to mitigate solar variability, forming the world's most extensive hybrid energy storage system that combines batteries and hydrogen at a solar plant.

**Obstacles, including economic and regulatory challenges, in addition to future directions for electrolyser research.**

Alkaline water electrolysis (AWE) remains the most mature and scalable method for producing green hydrogen (Xia et al., 2023). However, energy-intensive steps in production, storage, and transportation pose significant challenges (Tüysüz, 2024). Commercial AWE units are limited by size and sluggish dynamic response, particularly for offshore applications. Emerging approaches, such as direct seawater electrolysis, offer promise but require stable, low-cost electrode materials (Zhang et al., 2024). Solar-driven electrolysis, whether via PV or CSP, holds significant potential for large-scale applications but is constrained by high capital costs and inefficient electrolytes (Lin & Haussener, 2017). Research is focusing on improving dynamic response, catalyst stability, and system efficiency under variable loads (Xia et al., 2023). Advanced catalysts for the oxygen evolution reaction (OER), a deeper understanding of reaction mechanisms, and scalable fabrication methods are crucial for reducing costs. Impurities such as iron in KOH must also be considered. Future progress hinges on enhancing system durability, reducing costs, and addressing the intermittency of renewables. Hybrid designs incorporating $CO_2$ electrolysis, novel materials, and improved system modelling are accelerating the transition to fossil-free hydrogen production.

# CONCLUSION

The production of green hydrogen from renewable sources has attracted significant attention for decarbonising hard-to-electrify industries and enabling large-scale, long-term energy storage. Water electrolysis (AWE) is a mature key technology for hydrogen generation; however, its efficiency still requires considerable improvement to become competitive with traditional steam methane reforming (SMR). Careful and precise evaluation of AWE efficiency is crucial for determining the viability and cost competitiveness of green hydrogen systems. To characterise the energy consumption in water electrolysis, it is essential to consider the potential at the working current, taking into account significant voltage discrepancies (rather than the thermoneutral voltage), and to account for intermittent operating modes resulting from the fluctuating nature of renewable energy sources. These performance and operating modes are rarely addressed in existing studies but significantly impact the techno-economic assessment and overall feasibility of green hydrogen production. These challenges, and their influence on the hydrogen production cost, are analysed based on the experimentally measured dynamic response of a commercial 5 kW alkaline electrolyser exposed to various intermittent profiles. (Xia et al., 2023)

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