Challenges and Prospect of Solar-Powered Seawater Electrolysis for Green Hydrogen Production in South Africa: A Comprehensive Review

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***Abstract*—** The global energy transition towards achieving a sustainable energy landscape has generated attention once again on the potential decarbonisation solution provided by green hydrogen production across different sectors. Countries with abundant renewable energy resources, such as South Africa, are well positioned to capitalise on these opportunities presented by green hydrogen technologies. Seawater electrolysis is a green hydrogen production technology that is receiving increasing attention as a potential key technology to address climate change issues This review provides detailed insights into the current challenges and prospects of solar-powered seawater electrolysis for green hydrogen production in the South African context.

The review begins with an overview of green hydrogen production, including the basics of water electrolysis, the technologies involved, and compares the various electrolysis technologies: alkaline, proton exchange membrane (PEM), solid oxide electrolysis cell (SOEC), and membrane (AEM) systems. It then evaluates the status of green hydrogen development in South Africa, including the role of the government, players in industry, and skills development.

Techno-economics of green hydrogen production: Levelized Cost of Hydrogen (LCOH) and integrated renewable energy systems efficiency metrics are analysed. The review also explores the technical, infrastructural, and economic aspects of seawater electrolysis, including challenges like chlorine evolution, electrode corrosion, and transportation network constraints. Emerging research directions aimed at overcoming these challenges by designing selective catalysts, novel electrode designs and improving materials, are discussed.

The review highlights the importance of environmental aspects related to the deployment of seawater electrolysis technologies, which require comprehensive impact assessments for sustainable development. It concludes by suggesting priorities for future research that address efficiency, lifetime and cost-competitiveness with a view to supporting South Africa's transition to a green hydrogen economy.

***Keywords*—** Green Economy, Green Hydrogen, Renewable Energy, Seawater, Sustainable Energy Transition, Water Electrolysis.

I. Introduction

The global interest in green hydrogen production has gained significant momentum in recent years due to its potential to decarbonize various sectors, such as the transportation industry, and power generation sectors worldwide (Buttler and Spliethoff, 2018; Miller et al., 2020). Countries with abundance of renewable energy resources, such as solar and/or wind, are well-positioned to explore the opportunities presented by green hydrogen technologies (Vorosmarty et al., National & Dresp, 2010; 2019).

South Africa is one such region that is rich in abundant renewable energy resources, particularly solar radiation (Abbas et al. 2023). Nevertheless, fossil-fuel-based electricity generation is still a significant component of the current energy mix in South Africa, particularly coal (Zghaibeh et al, 2022). To address this challenge and align with global decarbonization efforts, the South African government has implemented several policies and frameworks for renewable energy and clean hydrogen production to overcome this bottleneck (Clarke et al., 2009; Li et al., 2018).nThe electrolysis of seawater is a potential green hydrogen production technology for countries with large shorelines and lots of solar/wind energy such as in the dry coastal regions of South Africa (Dionigi et al., 2016; Tong et al., 2020). This approach offers the potential to harness the inherent resources of the country while also contributing to the transition toward a more sustainable energy system (Nocera, 2019; Obata et al., 2018).

Green hydrogen produced by seawater electrolysis is hindered by numerous technical and economical constraints. These include the development of specialized electrocatalysts and membrane materials that can withstand seawater contamination effects and minimizing overall system costs to achieve competitiveness against conventional hydrogen production methods (Vos et al., 2018; Peter et al., 2020). Thorough Comprehensive environmental impact assessments will also be vital to ensure that sea water electrolysis technology deployment aligns with sustainable development goals and minimizes any adverse environmental consequences (d'Amore-Domenech et al., 2020; Lindquist et al., 2020).

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II. Overview Of Green Hydrogen Production

Hydrogen has emerged as a promising energy carrier in the global push towards decarbonization and sustainable energy systems. Hydrogen is a promising fuel that can be generated from various sources, used in a wide range of sectors, and thus offers significant potential for reducing greenhouse gas emissions, and fossil fuel dependency (Rosero Chasoy et al., 2023). Hydrogen has gained importance for its potential to store energy and act as a transport mechanism for electrical energy and for clean combustion, which produces only water as a byproduct. Different hydrogen production methods are based on their carbon intensity. Grey hydrogen is derived from fossil fuels without any carbon capture, while blue hydrogen combines fossil fuels with carbon capture and storage. One of the attractive solutions is the production of green hydrogen; the focus of this review; obtained using renewable energy source in water electrolysis, resulting in zero direct carbon emissions (Bidattul Syirat Zainal et al., 2024). Green hydrogen has the potential to decarbonize hard-to-abate economic sectors such as heavy industry and long-distance transportation, providing significant environmental benefits (Rosero Chasoy et al., 2023). Water electrolysis represents a fundamental process in the production of green hydrogen. Water electrolysis is a method that uses electricity to dissociate water molecules into hydrogen and oxygen. If this electricity is from renewable sources (like wind or solar), the resulting hydrogen is designated as green hydrogen and is consistent with Power-to-X energy conversion and storage strategies. While the basic principle remains consistent, many technological approaches to water electrolysis have been developed, each with different properties and uses (Ponikwar, 2024).

A. Fundamentals of Water Electrolysis

Water electrolysis is a crucial process to produce green hydrogen, a clean and sustainable energy carrier. This section provides an in-depth analysis of the fundamental principles underlying water electrolysis, including its thermodynamic and kinetic properties, efficiency, and materials needed.

B. Thermodynamics of Water Electrolysis

The energy demand and viability of water electrolysis is based on the thermodynamics of the reaction. The standard Gibbs free energy change for the water-splitting reaction is 237.2 kJ/mol, which corresponds to minimum theoretical voltage of 1.23 V at standard temperature and pressure (Ursua et al., 2012). In practice, however, more energy is needed to overcome activation barriers among other losses, leading to a higher operational voltage. These extra energy inputs place a significant constraint on the thermodynamic efficiency of water electrolysis and must be accounted for in the design and optimization of electrolysis systems (Ponikwar, 2024).

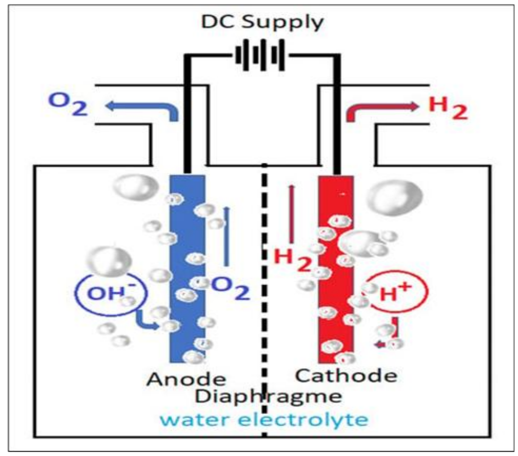

Fig. 1 Typical scheme for water electrolysis (Badea et al., 2022).

C. Kinematics and Mass Transport

The overall efficiency and performance of the water electrolysis process are also significantly impacted by the kinetics of the water electrolysis reaction and transport of reactants and products in the electrochemical system. Electrode material properties, catalyst loading, and operating conditions (such as temperature and pressure) govern the reaction kinetics (Carmo et al., 2013). The performance of an electrolysis system is also greatly affected by mass transport phenomena, including diffusion and convection of reactants/products, especially high current density (Carmo et al., 2013).

D. Efficiency Considerations

Water electrolysis efficiency is an important factor in assessing the overall feasibility and competences of green hydrogen production. The process is limited by several factors, e.g. thermodynamical limitations, kinetic overpotentials, ohmic losses and ancillary equipment consumption (e.g. compressors, pumps) (Buttler and Spliethoff, 2018). Research focused on the area of water electrolysis is still ongoing by seeking to make the process even more efficient, and develop advanced materials, optimize system design, and enhance energy management strategies (Buttler and Spliethoff, 2018).

E. Material Requirements and Specifications

Materials employed in water electrolysis systems are required to meet stringent requirements to ensure high performance, long-time stability and cost effectiveness. These range from the electrocatalysts, electrode materials, and membranes to the bipolar plates (Carmo et al., 2013). Ongoing research and development are focused on finding and optimizing novel materials that can increase water electrolysis technology's performance, stability, and scalability in terms of materials and processes (Carmo et al., 2013).

III. Comparative Analysis of Water Electrolysis Technologies

This section examines four primary water electrolysis technologies: Alkaline Water Electrolysis (AWE), Proton

Exchange Membrane (PEM) Electrolysis, Solid Oxide Electrolysis Cell (SOEC), and Anion Exchange Membrane (AEM) Electrolysis as depicted in figure 2. Each technology is analyzed in terms of its structural components, operational processes, and key characteristics.

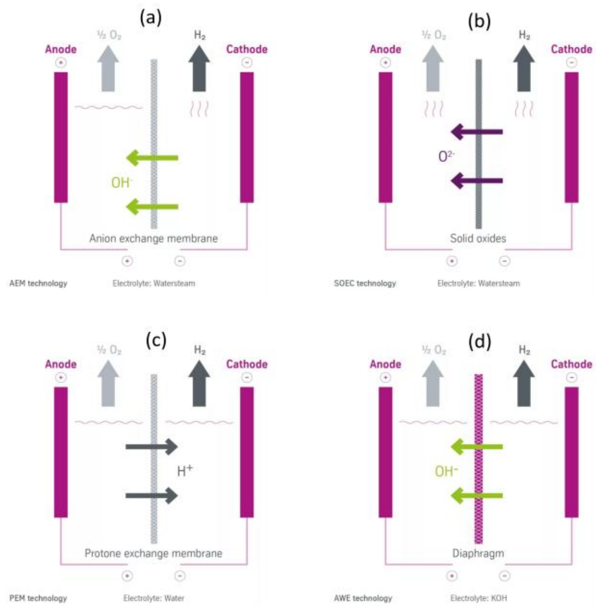

Fig. 2 Typical schematics of water electrolysis technologies (Sugawara et al., 2023)

A. Alkaline Water Electrolysis

Alkaline Water Electrolysis (AWE) is a mature technology for green hydrogen production utilizing an alkaline electrolyte, usually potassium hydroxide (KOH) or sodium hydroxide (NaOH), to facilitate ion transport and electrolysis (Fuchs, 2021). This matured technology operates within 70–90° C range and up to atmospheric pressure with suspended electrodes from half-cells separated by an ion conducting membrane permeable to hydroxide ions but not gasses (Amini Horri & Ozcan, 2024).

The AWE process can be described by the following electrochemical reactions:

At the cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

At the anode: $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$

AWE systems have strong long-term stability, relatively low capital expenditures, and achieve cell nominal efficiencies (HHV) of 50-80% (Amini Horri & Ozcan, 2024). They usually work at 1.8–2.4 V voltages with 0.2–0.5 A/cm² current densities while consuming 5.0–5.9 kWh/Nm³ (Amini Horri & Ozcan, 2024). These systems produce high purity hydrogen (99.5–99.99 %) and long stack life (up to 90,000 h) with a stack cost of 270 USD/kW (Amini Horri & Ozcan, 2024). Compared to other electrolyzer types, AWE tends to offer lower efficiency (even allowing for the lower capital costs associated with non-noble metal catalysts) and limited range of operation under dynamic conditions. Ongoing research aims to address challenges such as improving energy efficiency and reducing capital costs to enhance the economic competitiveness of AWE in the evolving hydrogen economy (Amini Horri & Ozcan, 2024).

B. Proton Exchange Membrane

Proton Exchange Membrane (PEM) electrolysis is a unique way to make hydrogen. It works in an acidic environment and uses a solid membrane that conducts protons and acts as an electrolyte and gas separator (Fuchs, 2021). Unlike Alkaline Water Electrolysis (AWE), PEM systems use a membrane electrode assembly (MEA). This consists of a polymer membrane placed between catalyst-coated electrodes, allowing protons to move while stopping electron flow (Amini Horri & Ozcan, 2024). PEM electrolyzers operate at lower temperatures (around 80°C) and higher pressures, providing better efficiency (50-83%) and faster response times than AWE systems. They are known for high current densities, compact design, and producing high purity hydrogen, making them good for fuel cell applications and use with renewable energy sources. However, PEM electrolyzers need costly noble metal catalysts, especially at the anode, which is a hurdle for widespread industrial use. Even with this issue, PEM technology is being scaled up for industrial use, building upon its historical use in scientific applications (Amini Horri & Ozcan, 2024).

The PEM electrolysis process can be described by the following electrochemical reactions:

At the anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$

At the cathode: $2H^+ + 2e^- \rightarrow H_2$

C. Solid Oxide Electrolysis

SOEC (Solid Oxide Electrolysis Cell) is a high temperature electrolyzer, which is basically a solid oxide ceramic material and acts as an electrolyte. A typical solid oxide ceramic material is yttrium-stabilized zirconia (YSZ) (Fuchs, 2021). Electrochemical cells operate at high temperatures, 500°C to 1,000°C, where hydrogen gas is formed in a process called water splitting at the cathode, while the oxygen ion (O^{2-}) is moved through the solid electrolyte at the anode for oxidation. This hot function of the reaction is an additional advantage for the co-production of hydrogen and high-temperature steam or heat which is very useful to the system in the case of the drawing of steam or heat.

SOEC is a technology that is based on ceramics that are highly capable of withstanding very high temperatures, high efficiency, and sensitivity to temperature fluctuations. SOEC was mainly used in scientific and niche applications in the past but at present, it is in the demonstration phase of industrial applications. However, technology faces challenges related to material durability and long-term stability, positioning it primarily in the research and development stage. Despite these hurdles, SOEC is a great performer in the high-temperature field; thus, it opens new possibilities in the industrial sector, as this technology can be used in hydrogen and high-grade heat applications (Amini Horri & Ozcan, 2024).

The SOEC process can be described by the following reactions:

At the cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$
At the anode: $O^{2-} \rightarrow ½O_2 + 2e^-$

D.Anion Exchange Membrane

Anion Exchange Membrane (AEM) electrolysis is considered the most promising technology in this field to replace alkaline electrolysers because it uses an alkaline solution to supply the hydroxide ions and an anion exchange membrane to separate the anode and cathode. During the AEM process, the water migrates from the anode to the cathode, which is where it is split up to form hydrogen and hydroxide ions. The hydroxide ions thus formed then proceed to travel in the reverse direction to the anode where they participate in the formation of oxygen and water (Amini Horri & Ozcan, 2024).

The AEM electrolysis process can be described by the following reactions:

At the cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
At the anode: $2OH^- \rightarrow ½O_2 + H_2O + 2e^-$

AEM electrolysis is currently in the research and development stage, but it is possible that it may provide very high current density, which is the current challenge for this technology, namely, the membrane's life and the system overall efficiency.

Table 1 provides a comprehensive overview of the prominent characteristics of electrolysis technologies. This comparative analysis explains the distinct advantages and limitations of each method, facilitating a nuanced understanding of their respective roles in the evolving landscape of hydrogen production.

TABLE 1: ROUGH CHARACTERISTICS OF THE CONVENTIONAL WATER ELECTROLYSIS TECHNIQUES

Characteristic	Alkaline Electrolysis (AE)	Proton Exchange Membrane (PEM)	Solid Oxide Membrane (SOM)	Anion Exchange Membrane (AEM)
Technology Readiness Level	Mature/commercialized	Mature/commercialized	R&D	R&D
Operating temperature (°C)	70-90	50-80	600-1000	40-60
Operating pressure (bar)	~Atmospheric	<40	<5	<35
Nominal voltage (V)	1.8-2.4	1.8-2.2	0.80-1.6	1.4-2.0
Nominal current density (A/cm²)	0.2-0.5	0.6-3.0	0.1-3.9	0.2-2.0
Electrolyte/membrane	KOH solution (25-30 wt.%)	Generic PEMs (PFSA)	YSZ or GDC	Generic AEMs (DVB polymers)
Commercial separator	Zirfon™, polysulfone, polyphenylene sulphide polymers	Nafion™	YSZ/GDC Pellets	Fumatech™
Common electrocatalysts	Nickel-coated perforated stainless steel	Iridium/platinum	Nickel-YSZ/LSM-YSZ	Nickel foam or carbon cloth
Cell nominal efficiency (HHV) (%)	50-80	50-83	80-100	52-67
Specific energy consumption (kWh/Nm³)	5.0-5.9	5.0-6.5	3.7-3.9	Unknown
Hydrogen purity (%)	99.5-99.9	99.9-99.9	99.9	99.9-99.9
Stack lifetime (h)	<90,000	<20,000	<20,000	<5000
Stack cost (USD/kW)	270	400	>2000	Unknown

Adapted from (Amini Horri & Ozcan, 2024).

All the technologies to be examined are alkaline electrolysers, which are the most mature and established. However, their lower efficiency has been the driving force to the development of alternative technologies that are employed in various applications to replace the alkaline system.

Proton Exchange Membrane (PEM) and Anion Exchange Membrane (AEM) electrolysers are electrolyzer types that can give you more efficiency and they are also more compact compared to their alkaline counterparts. These advantages, however, are offset by the requirement for more expensive

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materials in their construction, which translates to higher capital expenditures (Amini Horri & Ozcan, 2024).

Solid Oxide Electrolysis Cell (SOEC) technology emerges as the most efficient among the examined methods. However, it faces significant challenges that need to be resolved especially the high-temperature operational requirements and the higher associated costs expenditures (Amini Horri & Ozcan, 2024).

This comparative analysis demonstrates the intricate interrelationship between technological maturity, efficiency, compactness, and economic efficiency in the field of electrolysis. As research and development efforts continue, it is anticipated that these emerging technologies will further evolve, potentially altering the balance of advantages and limitations observed in the current state of the art expenditures (Amini Horri & Ozcan, 2024).

IV. Current of Green Hydrogen in South Africa

A. Advancing green hydrogen production in South Africa

South Africa has an emerging but growing green hydrogen infrastructure and facilities, with a few pilot projects and demonstration plants, such as the Hydrogen Valley Initiative in Mpumalanga (Mazumder et al., 2021). The country also has hydrogen filling stations and a small hydrogen-powered transportation system consisting mainly of vehicles in the Western Cape province (Villarreal Vives et al., 2023). However, the progress of green hydrogen is still at the initial stage of concept due to the absence of the necessary information and research on the technologies of green hydrogen production in the South African context, as well as technological barriers to the acceptance of this new energy source (Tetteh et al., 2024).

Nevertheless, there is a risen curiosity in green hydrogen if the factors like research publications from 2013 to 2023 are considered (Tetteh et al., 2024). The implementation of these projects will take on a two-pronged strategy further (CSIR, Meridian Economics, and KfW Development Bank, 2021). The Development of well-informed evidence-based policies will be the main instruments, supporting, and encouraging green hydrogen projects, and be followed by the favourable framework of the regulatory environment for them to flourish. At the same time, bringing knowledge and awareness to the public sector through the educational and awareness campaigns in the context of stakeholders' interactions with the different energy sectors will not only lure investors away from the national economy but also most probably international organizations. These moves ought to be accompanied by the integration of renewable energy resources such as South Africa's dominant solar and wind resources with the hydrogen production technologies. By leveraging these clean energy sources, the country can establish a sustainable and efficient green hydrogen production ecosystem, positioning itself as a leader in this emerging industry (Villarreal Vives et al., 2023).

B. Government and Industry Participation

The South African government has identified the strategic importance of green hydrogen for the growth of the country and has accordingly taken the necessary measures to support its production processes. Some of the notable initiatives are the inclusion provisions in the Integrated Resource Plan (IRP) 2019 and the development of a Hydrogen Society Roadmap by the Department of Mineral Resources and Energy (DMRE) (Hydrogen Europe, 2024). Also, the government has adopted different incentives and schemes of funding to promote new projects in green hydrogen (Villarreal Vives et al., 2023).

The industrial sectors of South Africa like Sasol, Eskom, and Anglo American are primarily in the green hydrogen development process with pilot projects and plans to invest in hydrogen production and related infrastructure as well (Hasan & Genç, 2022). Furthermore, South Africa has also signed agreements with countries such as Germany and the Netherlands to continue its green hydrogen collaboration activities on a global scale (Hydrogen Europe, 2024). These collaborations facilitate the exchange of best practices, access to funding, and the integration of South African green hydrogen initiatives with global value chains.

C. Skills Development and Capacity Building

Other than that, green hydrogen will also develop the skills and capacity building capacities of South Africa through the Hydrogen South Africa program which provides training and gives education in collaboration with universities and technical colleges (Hasan & Genç, 2022). These efforts are crucial in developing the necessary expertise and talent to drive the country's transition to a green hydrogen economy.

Overall, South Africa's green hydrogen landscape is characterized by a combination of government support, industry participation, international collaborations, and skills development initiatives, all of which are collectively aimed at advancing the production and utilization of this clean energy carrier within the country (Hasan & Genç, 2022).

V. Techno Economic Analysis

The techno-economic situation of green hydrogen production is a complex and changing business sector that involves multiple technological routes and economic issues. These factors, in turn, play a major role in the revolution and the formation of the new industry. The most recent analyses show that the Levelized Cost of Hydrogen (LCOH) for solar-based systems range from 4.6 to 7.31 $/kg. Nonetheless, the graphs point to the possibility of decreasing such costs to 2.92 $/kg in certain regions by 2030 (Gado, Nasser, and Hassan, 2024).

The technological equipment, in particular Proton Exchange Membrane (PEM) systems, has efficiency levels that range from 50 to 83%, operating at lower temperatures despite requiring premium materials. Integrated renewables systems have been thoroughly analyzed which have shown excellent prospects in terms of efficiency. The integrated wind-solar-OTEC (Ocean Thermal Energy Conversion) system that was devised in the paper titled "The Energy-Ecological Symbiosis of RES: the case of a Novel Integrated Wind-Solar-Otec System" managed to achieve overall system energy efficiency by 45.3% and exergy efficiency of 44.9%

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(Ishaq et al., 2019). In the system, the OTEC power generation cycle illuminates its energy efficiency of 4.5% and exergy efficiency of 12.9%. On the other hand, CuCl thermochemical production for hydrogen, which is the second process within the cycle, was responsible for 35.2% of energy efficiency and 36% exergy efficiency. The integration of the reverse osmosis (RO) desalination plant has exhibited superior performance with 73.3% energy efficiency and 34.6% exergy efficiency.

The introduction of large-scale PEM electrolyser systems with heat recovery presents another significant technological advancement. Villarreal Vives et al. (2023) analysed a 10 MW PEM electrolyser system integrated with a heat recovery system and Organic Rankine Cycle (ORC). Their findings revealed hydrogen production capacity of 181.3 kg/h (equivalent to 7,143.2 kW using H2 HHV), adding that the cooler extracts heat from PEM stacks and flows by the gas streams that removed 2,827 kW of waste, thus, the system operation from 71.4% to 98%. The inclusion of specific offshore wind power of £0.057/kWh is connected to the lowest LCOH of £110.73/MWh H2 (HHV) regeneration with heat recovery.

Regional analyses have also played a vital role in showing us how the feasibility and the economics of the geographical areas are different from each other. Investigations in Iraq have examined the systems of hydrogen production from solar and wind power along various system strategies, taking the different wind turbine sizes, solar panel types, and the dynamics of the electrolyzer as constraints (Hasan & Genç, 2022). In the same vein, the study conducted in Bangladesh through HOMER Energy software has been able to develop the most optimal system configurations such as the addition of a 12.2 kW solar PV system, 20 lead-acid batteries, and a 3.42 kW inverter/converter (Mazumder et al., 2021).

The standardization of economic assessment tools has advanced through initiatives such as the Levelized Cost of Hydrogen (LCOH) calculator developed by Hydrogen Europe (2024). This too has so far been one of the main fields of investigations and successes. It ensures overall production costs from the hydrogen facts fully transparent, thus prioritizing green hydrogen from water electrolyses at low temperatures including alkaline and PEM technologies. It enables assessment of renewable hydrogen production cost-effectiveness across various electricity sources, including grid connection, photovoltaics, and wind power installations Gado, Nasser and Hassan, 2024).

Solar powered systems have shown the superiority in hydrogen production over wind-based alternatives which were implemented in Africa’s context (Gado, Nasser and Hassan, 2024). The discoverability of this finding is very important in regional implementation strategies and technology selection. The collective evidence from these studies have shown that integrated renewable energy approaches, system efficiency optimization and cost-competitiveness are the main factors for the growth of green hydrogen technologies.

VI. Challenges And Future Prospects

The optimization of seawater electrolysis for green hydrogen production encounters multiple technical, infrastructural, and economic challenges while at the same time it also offers possibilities for sustainable energy development. The main technical barriers involve chlorine evolution at the anode, electrode corrosion, mineral scaling, and much lesser energy efficiency when compared to freshwater electrolysis (Halder et al., 2024; Tetteh et al., 2024). The electrolysis technologies themselves present further barriers with each having its specific limitations. Alkaline water electrolysis (AWE) systems are not only characterized by small current densities but also by low gas purity, limited dynamic operation capabilities, and the decay caused by carbonate growth on electrodes (Agyekum et al., 2022). Even though Proton Exchange Membrane (PEM) electrolysis holds a lot of promise, it faces obstacles in dealing with the very acidic operational environment, the immaturity of its components, and the high costs and durability issues (Agyekum et al., 2022). Solid Oxide Electrolysis (SOEC) systems add rather to the above issues by requiring extensive laboratory setups, exhibiting limited durability, and necessitating the use of complicated designs (Agyekum et al., 2022).

Infrastructure construction becomes another major problem especially in South Africa where limited hydrogen storage and transportation networks need substantial investment in the development of effective solutions. On the other hand, the plentiful solar energy resources in the region may provide a unique opportunity for market development and job creation in the green hydrogen sector. Significant knowledge gaps are still present in the following areas: long-term performance assessment of the hydrogen production process, the pre-treatment process, catalyst development, life cycle and techno-economic analyses (Halder et al., 2024; Tetteh et al., 2024).

Future research directions focus on addressing these limitations through multiple approaches. Current studies that focus on (non-selective) reactors and reshape technology to enable new possibilities of the creation of electrodes should result in better efficiency/longer duration, also meanwhile, the recent integration of renewable energy sources (particularly offshore solar farms) allows calculations for optimized performance. New methods are being evaluated to include the application of pulsating electric fields and ultrasonic fields as a means to increase the efficiency of renewable energy-based hydrogen production (Agyekum et al., 2022) Moreover the new materials, system design optimization, and energy management strategies which are the most important things for overall system efficiency and competitiveness, will be the key focus areas (Butler and Spliethoff, 2018). Economically, South Africa has the potential to develop a green hydrogen market, leveraging its solar resources and creating jobs, while environmentally, this technology offers significant benefits including reduced carbon emissions and decreased pressure on freshwater resources, potentially playing a crucial role in the country's transition to a more sustainable energy landscape as research progresses and infrastructure develops.

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