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Challenges and Prospects of Alkaline-based and Membrane-based Technologies for Green Hydrogen Production in South Africa

Simika Kanniappen, Racquel Sherise Lallie, Emmanuel Kweinor Tetteh and Sudesh Rathilal

Abstract**—** The continuous demand and utilization of fossil fuels raises global concern with excessive carbon dioxide (CO_2) emissions and climate change. Herein, transforming South Africa from a coal-based energy economy to a green economy alleviates the rising carbon footprint and temperature. Green hydrogen has captured global attention as a promising, clean energy for sustainable environment and economic growth via renewable energy sources (RES) and water electrolysis technologies. This study conducted a comprehensive review of challenges and prospects of water electrolysis technologies for South Africa. The operational factors and mechanisms of alkaline water electrolysis (AWE) and anion exchange membrane water electrolysis (AEMWE) were explored. Additionally, challenges and technoeconomic of the AWE and AEMWE systems powered by RES was highlighted. Findings of this study provide insight for development of green hydrogen production technology in South Africa.

Keywords**—** Green Hydrogen Production, Renewable Energy Source, Water Electrolysis Technology, Techno-Economic Analysis

I. INTRODUCTION

The depletion of non-renewable energy sources is a pressing concern and is a significant driver of climate change and the depletion of energy reserves. The current environmental emergency and energy crises are global challenges due to the combination of the impacts of climate change and heavy reliance on fossil fuels. Additionally, the exponential rise in fossil fuel consumption, to meet the demands of population and industrial expansion, is detrimental to the environment [1]. Climate change is the result of large amounts of greenhouse gases (GHGs) in the atmosphere.

Consequently, the growing GHGs present in the atmosphere increase the mean global temperature which in turn warms the globe (known as the greenhouse effect). GHG emissions are predominantly the product of burning of fossil fuels and contain significant concentrations of carbon dioxide, CO_2. The addition of CO_2 and infrared gases, such as ozone (O_3) and water vapor, to the atmosphere trap thermal radiation emitted by the sun and atmosphere which warms the earth's surface [2].

Currently, fossil-fuel-based energy sources, oil, coal and natural gas, dominate the global energy mix (Fig 1). Global primary energy production stems from 31.7%, 26.5% and 23.3% of oil, coal and natural gas sources respectively [3]. Therefore, it is imperative and the primary aim to introduce decarbonization technologies into energy mix. Herein, green hydrogen technologies have been identified as a prospective route for sustainability and economic development [4]. Green hydrogen production represents a clean solution to the current energy and environmental crises facing the planet. Green hydrogen involves the splitting of water into oxygen and hydrogen atoms, or the electrolysis of water, and requires the use of RES [5].

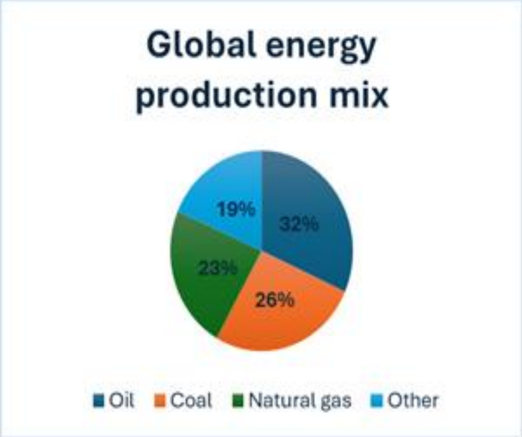

Fig 1: Global energy production mix.

Hydrogen represents a promising alternative to fossil fuels as an effective energy carrier [6]. Generally, thermochemical processes, involving heavy fossil fuels, have higher hydrogen production rates and are favored over biological routes. Comparatively, only 20-21% of hydrogen production is powered by RES and is left grossly underused [7]. To align with the climate change objectives set in the Paris Agreement, low-carbon techniques are being explored for upscale and commercialization. On par with sustainability and energy security, hydrogen can also be harnessed as a product via the use of solar, wind, sea and biomass energy [8].

In recent years, South Africa has been identified as one of the biggest contributors of GHG emissions, Data collected between 1990 and 2020 showed that the average annual GHG emissions in South Africa amounted to approximately 5200 tonnes per year [9] and climbing. As it stands, South Africa

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actively contributes to 3% of CO_2 emissions worldwide and 11% to national CO_2 emissions [10]. South Africa is the 7th largest coal producer worldwide and approximately 85% of the country's electricity is generated from coal-based energy [11]. South Africa has ranked among the top ten greenhouse gas producers globally due to the use of coal to meet power and energy needs. Additionally, 80% of GHG emission contributions are generated from South Africa's coal-based energy production. South Africa is also favorably rich in natural energy sources, specifically solar, wind and hydropower, with great potential for a green economy. Despite this, green hydrogen technologies combined with RES are still in infancy stages and require further development for upscale.

Green hydrogen generation powered by water electrolysis is presently acknowledged as the most promising hydrogen production technology [12]. The advancement of green hydrogen production addresses the 7th goal, Affordable and Clean Energy, from the 17 United Nations Sustainable Development Goals (UN-SDGs). Currently, South Africa is heavily reliant on the coal economy for fuel and power demands of the country [13]. Therefore, it is essential to find alternative methods for clean energy, like green hydrogen. Water electrolysis technologies are a sustainable, cost-effective, and clean method of green hydrogen production. However, there exist limitations regarding cost and efficiency. Additionally, water electrolysis is energy intensive and requires RES. Therefore, RES such as wind farms and solar energy will be considered due to its availability in South Africa. Despite the growing demand, knowledge gaps in environmentally beneficial hydrogen-based technologies are yet to be economically sound. Hence, the purpose of this study is to review water electrolysis technologies, namely alkaline water electrolysis (AWE) and anion exchange membrane (AEM), for green hydrogen generation in South Africa.

II. HYDROGEN PRODUCTION PATHWAYS

Hydrogen has surfaced as an effective energy carrier and potential fuel to mitigate the current strain on energy reserves. Conventionally, hydrogen is produced via thermochemical routes such as steam methane reforming, partial oxidation, gasification, pyrolysis, autothermal reforming, plasma reforming and biomass gasification [14]. Among the conventional methods, such as gasification, pyrolysis and steam methane reforming (SMR) techniques are mature [15], and with most biological routes achieve low hydrogen production rates.

Currently, hydrogen is categorized according to the method of production using a ranging color spectrum. The GHG emissions are found to be higher with the production of grey, brown and black hydrogen. Grey hydrogen is usually formed from processes involving fossil fuel use, specifically SMR. Black and brown hydrogen products form from the use of various types of coal (namely bituminous for black hydrogen or lignite for brown). Blue hydrogen occurs as a result of combining grey hydrogen and carbon capture technologies to decrease GHG emissions [16]. Purple and turquoise hydrogen production methods involve the utilization of nuclear energy and hydrocarbon splitting techniques respectively. Green hydrogen is obtained from renewable energy and produced largely via water electrolysis. Of interest, the use of alternate energy to fossil fuels comes with both environmental and economic benefit in industrial, commercial, transportation and residential sectors [17]. Therefore, a green economy founded on hydrogen promotes the mitigation of the ongoing environmental concerns, energy depletion and clears a path for sustainable energy production.

Furthermore, biomass and water are emerging as energy resources to produce hydrogen. The conversion of biomass to hydrogen is environmentally friendly and promotes a circular economy. However, this method has setbacks in terms of process complexity such as post-purification of hydrogen and carbon capture. Hence, the most suitable method for generating hydrogen is via water electrolysis, powered by RES, leading to zero GHG emissions [18]. The combination of RES with water electrolysis technologies results in green hydrogen as a prospective solution to the energy crisis.

III. RENEWABLE ENERGY SOURCES IN SOUTH AFRICA

RES has captured global interest as a leading alternative for the replacement of fossil fuel-based energy. RES exists in the forms of solar, wind, hydro, geothermal, ocean thermal energy conversion (OTEC) and biomass (Fig 2). RES represents a cost-effective and environmentally conscious candidate to alleviate the strain on fossil fuels and electrical grids. Recently, the global growth rate of photovoltaic (PV) cells and wind power has grown to 4% and 7% respectively [19]. Over the past 5 years, the mean increase in PV cells and wind power reached 27% and 13%. South Africa has great potential for the integration of renewable energy and in the process of discovering green hydrogen production via electrolysis technologies powered by RES. In terms of RES, South Africa has a growing abundance of solar and wind power outlets [20].

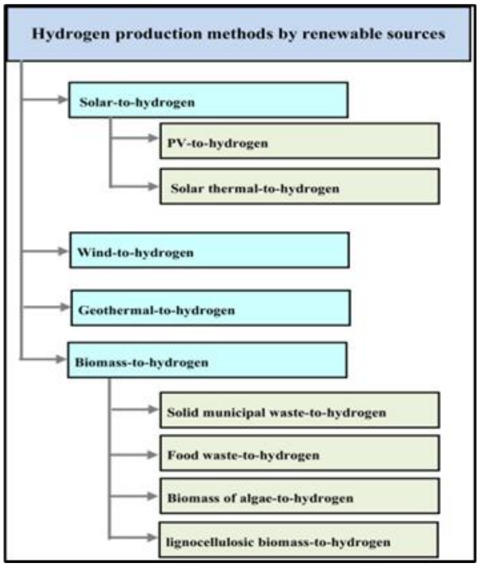

Fig 2: Conventional hydrogen production methods via renewable energy sources [21].

South Africa is in the process of growing its renewable energy sector for hydrogen generation. The transition from a coal-dependent economy to a sustainable energy mix is imperative to mitigate the current energy crisis. The renewable energy technologies, such as wind power and solar-driven, required to drive green hydrogen production in South Africa will be considered in this review.

A. Solar Energy

Solar energy is abundant in South Africa and has shown great promise as a RES. The most promising route for generating electrical energy from solar radiation in South Africa is via the use of PV cells. In South African, PV cells are used for several applications such as lighting, domestic appliances, telecommunications, and water pumps. PV panels are made with silicon which aids in the direct conversion of solar to electrical energy [22]. PV systems operate based on the photo-electric effect whereby electrons are emitted from a material’s surface, usually a semi-conductor, due to the exposure to light of a specific wavelength [23]. The utilization of solar-powered PV systems has a wide range of benefits in terms of being renewable and sustainable, and having little environmental impacts. PV systems are also very versatile and scalable for a variety of applications while offering economic benefits such employment creation [24]. Currently, rooftop solar PV panels (Fig 3) are the most common in South African countries such as the Western Cape, Gauteng, and Kwa Zulu-Natal. The biggest challenge of using solar energy for electricity generation that requires rapid mitigation is the issue of long-term energy storage. The cost of PV modules used to be a major concern but has begun to decline in recent years. Hence, PV cell and PV panel technologies are growing in interest and potential for relieving the stress on power and electrical grids.

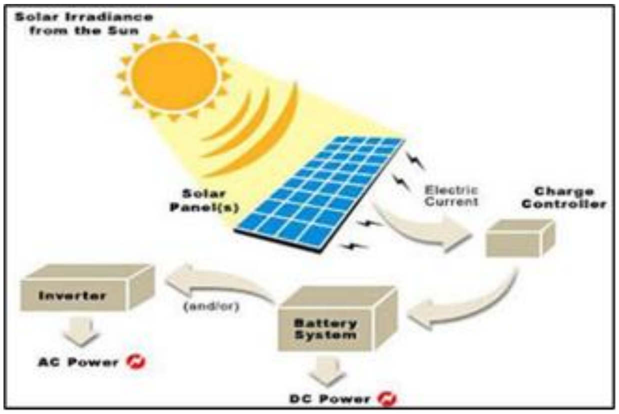

Fig 3: Photovoltaic (PV) solar panel [25].

B. Wind Energy

Wind energy systems (Fig 4) have been present in South Africa for decades and was initially utilized for agricultural activities on farms. In 2002, ESKOM was able to establish the country's first wind farm (27 MW Klipheuwel wind farm) to assess the promise of wind energy for electricity generation. This wind farm provides approximately 20000 South African citizens with 86000 MWh per year and has aided in a significant decrease of 24080 tonnes and 481600 tonnes in annual carbon emissions and lifetime carbon emissions, respectively [26]. Since the installation of the first wind farm, various wind farms have been built over the years for the water needs of domestic and farming activities. However, the use of wind energy for electricity and power generation remains sorely unexplored. There exist some technical and environmental challenges that hinder the utilization and expansion of wind farms.

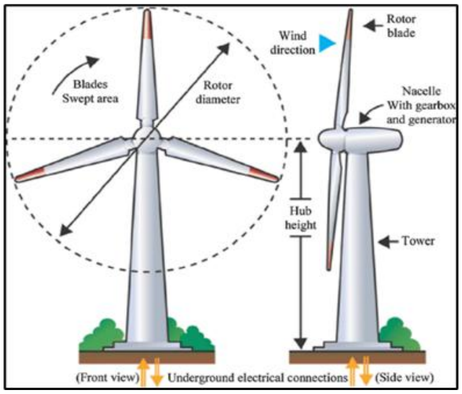

Fig 4: Schematic of wind energy system [30].

Wind farms pose serious threats to the environment and surrounding habitats in terms of habitat fragmentation, noise pollution and the depletion of water and land resources. The erection of the wind turbines, in migration corridors or in biodiverse areas, are injurious to avian and bat life [27] [28], as they can fly directly into the rotating blades. Wind farms are also visually unappealing and can decrease the aesthetic landscape value of an area during construction. Overcoming these critical drawbacks involves implementing extensive environmental impact assessments in conjunction with tactful selection of sites, and active stakeholder support [29]. The prospects and benefits of using wind energy can only be attained once the technical and environmental issues are addressed.

IV. WATER ELECTROLYSIS TECHNOLOGIES

Water electrolysis technologies are significantly advantageous for green hydrogen production with high purity products with zero carbon emissions and can be powered by RES [6]. During water electrolysis, the reactant (water) undergoes dissociation and is split into separate oxygen and hydrogen via the application of DC current. The equations below describe the principal dissociation reaction of water at the anode and cathode during the water electrolysis process.

$$\text{Anode: } H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+ + 2e^- \qquad \textit{(Equation A)}$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2(g) \qquad \textit{(Equation B)}$$

$$\text{Overall reaction: } H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(\mathrm{g}) \qquad \textit{(Equation C)}$$

Among hydrogen generation technologies (Fig 5), there are four widely used water electrolysis systems of interest: proton exchange membrane (PEM), alkaline water electrolysis

(AWE), anion exchange membrane (AEM) and the solid oxide electrolyser cell (SOEC).

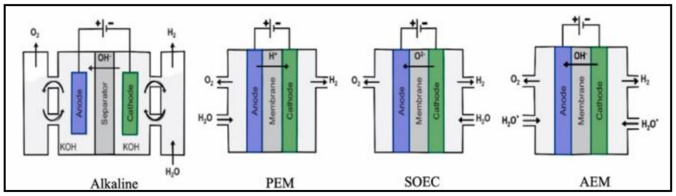

Fig 5: Conceptual setups of typical water electrolysis cell technologies [32].

V.Factors Affecting Green Hydrogen Production In Water Electrolysis Technologies

Among the variety of water electrolysis technologies available for hydrogen generation, AWE and AEM have gained significant attention for high energy production efficiencies and cost-effectiveness. AWE systems are the most readily available technology to reach large-scale commercialization. Alkaline electrolysers are relatively inexpensive due to the exclusion of membranes and noble catalysts for effective operation [51]. The AEM water electrolysis (AEMWE) system has captured mass interest for combining key benefits of the AWE and PEM technologies at low costs [52]. Additionally, both the AWE and AEM technologies operate at low temperatures, yield high purity products and are relatively inexpensive when accounting for the incorporation of RES power. Hence, it is imperative and beneficial to investigate the two technologies for green hydrogen production.

A. Factors Affecting Green Hydrogen Production in AWE and AEMWE Systems

To effectively improve the hydrogen production efficiency of the AWE and AEMWE systems, key parameters and operating conditions must be investigated. These factors include electrolyte concentration, current density, temperature and pressure. Their collective impacts on hydrogen production efficiency are selected to address gaps in research.

1) Electrolyte Concentration

Electrolyte concentration is a primary factor affecting the performance of AWE systems. Trends in research show that electrolyte concentration and cell voltage have an inverse correlation. The electrochemical reactions occurring within the AWE require high electrolyte concentrations which decreases the cell voltage [53]. The drop in potential can be explained by the increase in electrical conductivity occurring when electrolyte concentration is increased. Hence, the energy required by the system is significantly reduced. However, it is important to note that this trend does not hold for the continuous increase of electrolyte concentration. Beyond a particular electrolyte concentration value, conductivity begins to fall due to a growing excess of ions in the solution.

For membrane-based technologies, liquid electrolytes are favored due to their ability to reduce ohmic resistances between the membrane and catalyst layer as well as enhance the reaction kinetics [59]. It is widely understood that higher electrolyte concentrations are frequently associated with higher conductivity and rapid ionic mass transfers to the electrodes [60]. Therefore, effectively improving the hydrogen production rate. Using performance curves, it was found that cell voltages decline with an increase in electrolyte concentration. Conversely, reductions in the electrolyte concentrations lead to a decrease in the AEM performance. This trend indicates that higher concentrations of alkaline electrolyte solutions significantly enhance the ionic conductivity of the membrane [61]. Additionally, higher alkaline conditions, due to higher electrolyte concentrations, yield lower ohmic resistances. This result is directly linked to the improved membrane conductivity, that is, the increase of charge transfer (due to growing ion concentration) within the membrane. Thus far, electrolyte concentrations (specifically potassium hydroxide) between 0.5 and 1M exhibited the best performance for AEMWE systems [63].

2) Current Density

Current density variation is key to accurately predicting hydrogen production efficiencies of AWE systems [54]. The current density values are used directly informs on the hydrogen production rate. Current density can be described as a function of temperature. As the temperature of the system increases, current density also experiences an increase. This result can be attributed to the effect on temperature on the reaction kinetics. At higher temperatures and cell densities, the total cell potential, cell voltage, is subject to decreasing. Hence, the drop in cell voltage accounts for lowering of power required and in turn increases system efficiency [55].

The current density of AEM technologies is an indicator of its stability and efficiency [62]. Similarly to the AWE, higher current densities are favored for optimizing the performance and durability of AEMWE. Zhegur-Khais and company conducted a study revealing that the time constant of the de-carbonation decreases as current densities increase [63]. Operating at low current densities can lead to the degradation of the ion exchange membrane, therefore, significantly decreasing the performance and efficiency [64].

3) Operating Temperature

The operating temperature is one of the factors informing on the true system efficiency of the AWE system. As temperature increases, the reaction kinetics accelerate which in turn decreases the cell voltage. The decline in cell voltage allows for reductions in the energy consumed. The efficiency of the AWE cell increases with the decrease of energy required. Thus, it can be said that the performance of the cell increases with the rise in temperature. Higher temperatures can increase the system efficiency provided that the current density values are relatively high [56]. The system efficiency can also be gradually increased by consistently reducing the temperature gradient throughout the AWE stack. Increasing the operating temperature is an effective way of reducing the system's internal resistance [57].

Higher electrolyte temperatures facilitate higher performances in AEMWE systems. [61]. The increase in performance due to rises in temperature is attributed to the lowering ohmic potentials and overall improved reaction kinetics. The reduction of ohmic potential at elevated temperatures increases the movement of hydroxide (OH-) ion [67] within the membrane thus increasing the rate of reaction. This means there is a higher diffusion coefficient of OH- ions within the electrodes. Consequently, the increase of temperature also speeds up catalytic activity because of the rapid electron transfer occurring. Hence, the optimized performance of the AEM is dependent on the increase of temperature.

4) Operating Pressure

Pressure control can be instrumental in reducing the load of AWE stacks. At low temperatures, the cell voltage starts to decline as pressure increases [58]. At high operating pressures lower the cell voltages (over potential) by the improvement of bubble kinetics. It is found that using a larger pressure (however not exceeding 20 bar) also heightens the hydrogen product gas without the use of a desiccant device [56].

Operating conditions, such as pressure, is critical for achieving high performances in AEMWE. Operating pressure is a key parameter that informs on the cell performance as well as acting as an indicator for suitable mechanical considerations. Maintaining the appropriate pressure within the membrane electrode assembly (MEA) allows for enhanced performance of the anode and cathode. Xu and colleagues' states that the change in performance is dependent on MEA mechanism [66]. The increase of the internal MEA results in increased thickness of the gas diffusion lay (GDL) at the cathode, which improves the performance at both the anode and cathode. By optimizing the operating pressure, the contact between the GDL and catalyst can be enhanced which further improves the performance of the AEMWE system. However, extreme pressure can cause water leakage in the AEM, therefore, finding an optimal range is key to avoid mechanical and internal damage. Wijaya, Im and Nam suggest that the optimal pressure (approximately between 0.5 and 1.8 MPa) suppresses the internal and the charge resistances which promotes a higher performing system [67]. Higher operating pressure within the AEM also impacts the thermodynamic reversible voltage (given by the Nernst equation) and can restrict the rate of diffusion between the membrane and electrodes. This result can cause increased losses in diffusion, gas crossover and cell polarization, thereby decreasing the performance to a minimum.

VI. TECHNO-ECONOMIC ANALYSIS OF WATER ELECTROLYSIS TECHNOLOGIES FOR GREEN HYDROGEN PRODUCTION

Green hydrogen production techniques are still under development. In terms of cost-effectiveness, green hydrogen production methods are currently more expensive than fossil-fuel-based energy methods. Techno-economic analyses gauge the feasibility and economic viability of a proposed model. It requires estimations of the system efficiency and specific energy consumption. A techno-economic analysis investigates the potential and economic viability of the AWE and AEMWE systems for green hydrogen production using RES.

TABLE 1: SUMMARY OF TECHNO-ECONOMIC PARAMETERS FOR AWE AND AEMWE OBTAINED FROM PREVIOUS STUDIES.

Type of technology	**Energy source**	**Hydrogen production rate**	**Levelized Cost of Hydrogen (LCOH)**	**References**
AWE	Solar PV, onshore and offshore wind	5.8-ton, 6.56 ton and 9.86 ton	8.41 \$/kg, 7.02 \$/kg and 7.75 \$/kg	[68]
	Wind and solar energy	0,7437-25,875 kg/yr	7.49–7.59 \$/kg	[32]
AEM	Wind, PV system and electrical grid	-	86,94, 88.76 and 81.56 \$/kg	[69]
	Wind and solar-generated electricity	215 kg/hr	3.64 \$/kg	[70]

Techno-economic analyses also require mathematical modelling to emulate the mass and energy conversions occurring within the electrolyzers. Energy and mass transfer equations are included below for the system modelling of the AEMWE and AWE.

A. Mathematical modelling equations for anion exchange membrane water electrolysis.

Cell Voltage

$$E_{cell} = E_{rev} + \eta_{act} + \eta_{ohm} + \eta_{diff} \tag{1}$$

Reversible Cell Voltage

$$E_{rev} = E^{0}{}_{rev} + \frac{RT}{2F} \ln\left(\frac{\rho_{H_2} \rho_{O_2}^{0.5}}{a_{H_2O}}\right) \tag{2}$$

Butler–Volmer equation

$$\eta_{act} = \frac{RT}{2a_a F} \sinh^{-1}\left(\frac{j}{2r_a j_{0,a}}\right) + \frac{RT}{2a_c F} \sinh^{-1}\left(\frac{j}{2r_c j_{0,c}}\right) \tag{3}$$

Ohmic Overpotential

$$\eta_{ohm} = IR_{tot} = I(R_E + R_E) \tag{4}$$

Mass Balance (cathode side)

$$n^{c}_{H_2,out} = n^{c}_{H_2,in} - \frac{jA_{cell}}{2F} \tag{5}$$

$$n^{c}_{H_2O,out} = n^{c}_{H_2O,in} - \frac{jA_{cell}}{F} - n^{trans}_{H_2O} \qquad (6)$$

Mass Balance (anode side)

$$n^{a}_{O_2,out} = n^{a}_{O_2,in} - \frac{jA_{cell}}{4F} \qquad (7)$$

$$n^{a}_{H_2O,out} = n^{a}_{H_2O,in} - \frac{jA_{cell}}{2F} - n^{trans}_{H_2O} \qquad (8)$$

Energy Balance of Cell

$$H_{a,in} + H_{c,in} + W_{cell} = H_{a,out} + H_{c,out} \qquad (9)$$

B. Mathematical modelling equations for alkaline water electrolysis

Cell Voltage

$$V_{cell} = V_{rev} + V_{act,c} + V_{act,a} + V_{ohm} + V_{diff} \qquad (10)$$

Reversible Cell Voltage

$$V_{rev} = V^{0}{}_{rev} + \frac{RT}{2F}\ln\left(\frac{\rho_{H_2}\rho_{O_2}^{0.5}}{a_{H_2O}}\right) \qquad (11)$$

Butler–Volmer equation

$$V_{act,k} = \frac{RT}{na_kF}\sin^{-1}\left(\frac{J}{J_{0,k}}\right) + \frac{RT}{na_kF}\sin^{-1}\left(\frac{1}{1-\theta}\right) \qquad (12)$$

Ohmic Overpotential

$$V_{ohm} = (R_c + R_a + R_{ele} + R_{mem} + R_{bubble}) \times I \qquad (13)$$

Total mass balance AWE stack

$$\frac{dm}{dt} = \sum mf_{ele,i} - \left(\sum mf_{ele,j} - \sum r_s\right) \qquad (14)$$

Mass Balance (cathode side)

$$mf_{cat,j} = mf_{cat,i} + mf_{H_2} - mf_{H_2O,con} \qquad (15)$$

Mass Balance (anode side)

$$mf_{an,j} = mf_{an,i} + mf_{O_2} - mf_{H_2O,prod} \qquad (16)$$

Energy Balance of Cell

$$\frac{dT}{dt} = \dot{Q}_{loss} - \dot{Q}_{liq} - \dot{Q}_{amb} \qquad (17)$$

The levelized cost of hydrogen (LCOH) and levelized cost of energy (LCOE) is calculated as a metric for determining the efficiency and competitiveness over time (which can be calculated using equations found below).

LCOH

$$LCOH = \frac{CAPEX\ \sum_{i=1}^{N}\frac{OPEX}{(1+r)^{t}}}{\sum_{i=1}^{N}\frac{P_{H_2}}{(1+r)^{t}}} \qquad (18)$$

LCOE

$$LCOE = \frac{CAPEX\left(\frac{WACC(1+WACC)^{d}}{WACC(1+WACC)^{d}-1} + OPEX_{rel}\right)}{P_{el,nom}AFLH} \qquad (19)$$

VII. CHALLENGES AND PROSPECTS OF GREEN HYDROGEN PRODUCTION IN SOUTH AFRICA

A. Challenges

The integration of renewable energy sources to generate electricity for green hydrogen production has limitations resulting from their natural features [76]. The drawbacks of solar energy lie with grid integration and stability and the geographical and climate changes. The existing grid is currently not yet capable of managing the integration of solar power and the extreme cost of improvement and maintenance. Technologies for the storage and supply of excess energy produced, for sparsely sunny days, are still under research and development stages due to the high expense. Despite, the copious sunlight in the South Africa regions, the exposure to solar radiation fluctuates across different areas. The optimal locations for solar plants are often far from urban city centers which will create the need for costly transmission lines. For wind energy, two significant technical issues exist: the location of the wind farms and variations in wind pattern. Wind farms are often erected in remote which creates difficulties in connecting to the main power grids. Large amounts of the energy produced is left unused or lost as a result. The solution to this challenge is expensive transmission lines to link urban areas and wind farms, therefore increasing the cost of the overall installation [77]. The second major challenge is the varying wind speeds. The output wind power relies heavily on and is directly proportionate to the wind speed of the area. With the usage of a stable power grid, the varying wind speeds lead to fluctuations in the voltage which is costly to manage. The inconsistency causes either surplus or deficient power production which disrupts the power grid [78]. Despite the recent development, formidable setbacks hinder the progress of water electrolysis technology for upscale and economic viability [79]. Key challenges for advancing water electrolysis technologies in South Africa exist in terms of cost, energy consumption and electrolyser efficiency for cost-effective operation. Alkaline-based electrolysis technologies, even when powered by RES, currently experience one main limitation in terms of high gas impurity in the part-load range [80]. This can cause a severe breach in safety due to contamination of foreign gases. Poor alkaline durability and low ionic conductivity of membranes have been identified as the greatest challenges in membrane-

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based systems (specifically in AEMWE systems). Despite these hindrances, there is still great potential in the development of AWE and AEM technologies for green hydrogen production. By understanding and overcoming these challenges, the future of sustainable green economies can be attained.

B. Prospects

Green hydrogen technologies are a prospective route towards sustainability and cost-effective energy generation. Green hydrogen for energy generation, transportation and storage has gained global interest [81]. For most countries, especially South Africa, a green hydrogen-based economy represents a shift away from fossil fuel-based energy and towards the use of renewable energy. The green hydrogen as a product itself can be implemented in various sectors in South Africa such as refineries, chemical and transport industries. Renewable energy sources for powering green hydrogen technologies are still in their infancy but is generating a large following among many countries. Recent innovative studies investigating solar–wind hybrid power systems instead of the individual energy sources for hydrogen production technologies have arisen [82]. AEM technologies have stood out for being low cost and high performing when compared to typical water electrolysis technologies [73]. AEMWE technologies are the most recent in terms of investment, research and development. AWE is the most economically viable and consistent technology available for upscale and commercialization. AWE currently dominates the market as a mature water electrolysis technology due to its substantial capacity and low investment cost. The coupling of RES with AWE and AEMWE systems are promising attempts to bridge the gaps between cost-effectiveness and low-carbon-based energy usage for green hydrogen production.

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