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Exploration of green hydrogen energy in Africa

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***Abstract*— Africa, although blessed with various renewable energy sources, is overly dependent on fossil fuels for the production of energy. And this over reliance has a lot of disadvantages, one of which is air pollution which consequently causes greenhouse emissions. The aim of this study is to understand the existing energy and green hydrogen energy state and challenges in Africa. The challenges facing the continent as it regards green hydrogen systems are multifaceted in nature, they are issues such as political, social and technical shortcomings. Some of these problems are as a result of the poor policies and frameworks established by energy stakeholders in the region. This work also reviews already functioning green hydrogen production systems globally in order to apply relevant methods and processes as a solution to the problems. Green hydrogen is basically hydrogen that is produced by water electrolysis using renewable and emission-free energy sources such solar, wind, geothermal, biomass, ocean, etc. Relevant findings from the works reviewed are that improved and new processes are beneficial, the levelized cost of hydrogen is relatively cheaper, the state of the renewable energy sources will directly affect the hydrogen to be produced, and that hybridization renewable energy sources slightly reduce hydrogen cost. Finally, it is recommended that energy data should be made available as it promote research and development in the energy industry.**

Keywords*— *Green hydrogen; Energy; Exploration; Africa

I. INTRODUCTION

The world's oil reserves will reach its peak in a few decades, at most, this has necessitated the need to find more sustainable energy sources to offset some of the political, economic, and environmental problems brought on by the world's excessive reliance on fossil fuels, the world will inevitably move toward a new energy economy centered on renewable energy sources [1].

Africa can be divided into three distinct energy-related areas as shown in Fig. 1. Nearly every home in North Africa has access to clean cooking, and the region is virtually totally powered. The country of South Africa, which is primarily electrified, has a similar scenario. However, the majority of people in the remaining sub-Saharan Africa (SSA)—600 million people—do not have access to electricity and still cook using solid biomass, which consists of wood and organic garbage (780 million) [2].

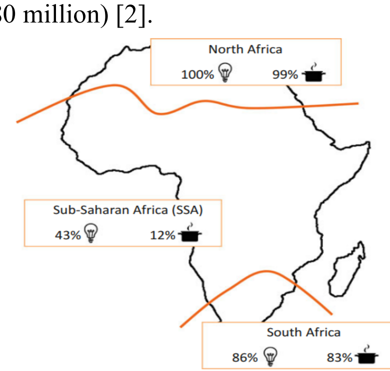

Fig. 1: Three energy zones in Africa [2].

This South Africa's high energy intensity per unit of GDP and continuous reliance on coal as the primary energy source make it one of the very few nations in Africa with unexplainably high greenhouse gas emissions. Currently, 67% of the nation's principal energy sources come from coal [3]. Because so much of the power in Southern Africa is produced in coal-burning facilities, the area is among the worst in the world for greenhouse gas emissions [4]. The use of inefficient energy sources by impoverished communities, which results in high levels of indoor air pollution with detrimental health effects, inappropriate policy instruments that do not minimize the negative impact of externalities, and finally, a lack of government commitment to privatization as a crucial tool in the economic reform process are the challenges facing the energy sector and are critical to South Africa's economic development [5].

Sub-Saharan Africa has an average of around 25% of the world's population having access to electricity, whether that is defined as power in the house or within certain geographic areas. Countries with access levels of 5% or less, such Chad, Somalia, Uganda, Sierra Leone, and Rwanda, are at the bottom of the scale, while Mauritania, Ghana, and South Africa are at the top, with access levels above 50% as displayed in Fig. 2 [6].

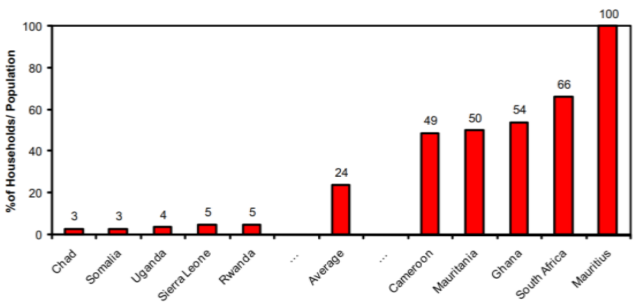

Fig. 2: Access rates for sub-Saharan African nations with the least and greatest electricity [6].

Sub-Saharan Africa will require major installed generating capacity expansion and considerable infrastructure upgrades in order to fulfill the region's rising energy demand. More than half a billion people are predicted to lack access to electricity by 2040 at the present rate of electrification and population increase, and complete access to electricity is not likely to be achieved in the region until 2080. Because of this, there is a complicated and ongoing electrical deficit throughout Sub-Saharan Africa [7].

Renewable energy resources are still mostly unexplored in North Africa, despite the recent introduction of several clean energy policy measures. Also, that large-scale solar power exports to the European Union are now being worked on, and while there hasn't been much support from Arab political regimes thus far, there is hope that renewable energy will be widely adopted throughout North Africa [8]. The Middle East and North Africa has some of the lowest domestic costs in the world for both primary energy and electricity, which gives an impression that financial incentive is required for alternative energy sources, such as nuclear power and renewable energy [9].

Green hydrogen is regarded as one of the most promising technologies for energy generation, transportation, and storage. The most abundant and basic element in the universe is hydrogen. It has the largest specific energy content of all conventional fuels, hydrogen can be easily incorporated into the global energy delivery system than other energy storage methods. Green hydrogen can be created using water electrolysis, which is an alternative to fossil fuels. If all electricity needed to power the process comes from renewable sources, greenhouse gas emissions may be avoided when water is divided into hydrogen and oxygen using an electric current [10]. Due to its high mass energy density, low weight, and ease of electrochemical conversion, hydrogen can be used to transport energy across sectors and geographical areas via fuel cells, pipelines, or freight ships in the form of liquid fuels like ammonia. It can also be burned for heat, used as a reagent in the production of synthetic fuels, or used as a chemical feedstock [11]. In the hydrogen-economy paradigm, green hydrogen is the cleanest energy resource with the highest gravimetric energy density (about 142 MJ kg^{-1}) and is predicted to displace fossil fuels that have detrimental impacts on the environment [12].

After hydrogen is created, it is kept in designated tanks before being fed into a fuel cell, where it combines with oxygen once again to produce electricity and water as a byproduct. However, the economic feasibility has emerged as the main worry rather than the environmental effect. Furthermore, the goal of green hydrogen will be undermined if the power needed for electrolysis is not produced sustainably by burning fossil fuels.

This review tries to investigate and examine the present state and future of green hydrogen in Africa. It focuses on the potentials of green hydrogen in solving the energy problems in Africa. It encompasses the types, sources, application and advantages of green hydrogen for energy production in Africa as well as the challenges facing the use of green hydrogen in Africa. This is specifically why green hydrogen is a way forward for the energy sector in Africa. Exploring green hydrogen in Africa wouldn’t be possible without understanding the various processes and sources of green hydrogen, thus this work critically looks at the production of green hydrogen in various parts of the world which will be a background for identifying the potential and consequentially the challenges that comes with it.

II. AFRICA’S GREEN HYDROGEN CHALLENGES

The use of green hydrogen in Niger is doubtful owing to the higher prices of hydrogen as an energy vector for country's still expanding domestic coal and oil industries [13]. The current hydrogen energy policies and renewable energy resources of the Southern African Development Community's (SADC) was examined. There is still a low demand for hydrogen in Southern Africa and obstacles remain in the way of Africa's efforts to use renewable energy resources as a means of transformation to a green economy. This can be achieved through advance research and commercialization. This obstacle involves policy frameworks that are institutional, financial, political, technical, and socioeconomic in nature [14].

Previous study by Brauner et al. [15] compares perspectives from Germany and Africa in order to find areas of agreement that may serve as a foundation for collaboration as well as identify contrasts ideas for green energy and hydrogen that could lead to conflict. The findings showed that although everyone agrees that there must be a quick switch to renewable energy, the African side does not envisage green hydrogen being exported right away. Furthermore, enhancing the continent's potentials to address the inadequate energy availability for industry and population is the main issue of African stakeholders. The legislative, policy, and strategy documents pertaining to the energy sector and hydrogen energy that are currently in the Economic Community of West African States (ECOWAS) region were examined by Ballo et al. [16]. According to the study, there are currently no official hydrogen policies or bylaws in place in any of the ECOWAS member states.

III. Pathway to Green Hydrogen Production

The According to Shiva and Lim [17], water electrolysis is an emission-free method that uses energy to split water electrochemically in order to produce green hydrogen. The following is the fundamental reaction of water electrolysis:

$$H_2O + Electricity\ (237.2\ kJmol^{-1}) + Heat\ (48.6\ kJmol^{-1}) \rightarrow H_2 + \frac{1}{2}O_2 \quad (1)$$

Based on the electrolyte, operating environment, and ionic agents used, there are four different types of water electrolysis technologies: (i) Alkaline water electrolysis; (ii) anion exchange membrane (AEM) water electrolysis; (iii) proton exchange membrane (PEM) water electrolysis; and (iv) Solid oxide water electrolysis. All methods, however, follow the same working principles. The electrochemical water splitting process in an alkaline water electrolysis is made up of two distinct half-cell processes, such as the oxygen evolution reaction (OER) at the anode and the hydrogen evolution reaction (HER) at the cathode. One mole of hydrogen (H_2) and two moles of hydroxyl ions (OH^-) are first produced during the alkaline electrolysis process at the cathode side of the process. The H_2 that is produced can be removed from the cathodic surface, and the remaining hydroxyl ions (OH^-) are transferred to the anode side through the porous separator under the influence of an electric circuit between the anode and cathode. As seen in Fig. 3, the hydroxyl ions (OH^-) are discharged at the anode to create one water (H_2O) molecule and one oxygen (O_2) molecule.

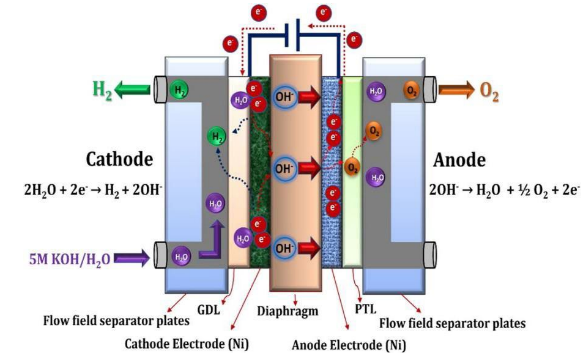

Fig. 3: Diagram illustrating the basic principles of alkaline water electrolysis [17]

Green hydrogen, also known as renewable hydrogen, is created by electrolysis with the use of renewable energy sources. It produces almost no carbon dioxide and doesn't require carbon capture and storage. Direct connection of the electrolyzer to the renewable energy source is necessary to achieve a zero-carbon footprint. Using water electrolysis technology, electrical power produced from renewable resources is transformed into high-purity hydrogen, chemical energy that can be stored. Green hydrogen is more expensive than gray or blue hydrogen because renewable power is more expensive. Due to conversion losses and the cost of the electrolyzer, the final product's price will always be more than the power consumed to manufacture it. The routes for the manufacture and use of green hydrogen are presented in Fig. 4. However, because of the surplus of renewable energy and the planned growth of the hydrogen market in the upcoming years, it is anticipated that the cost of producing green hydrogen will decrease as the cost of renewable energy reduces (Agaton et al., 2022).

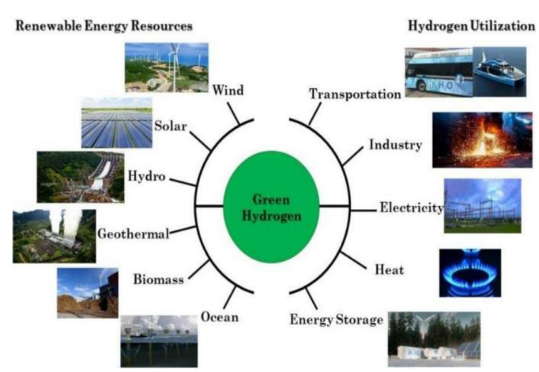

Fig. 4: Routes for the manufacture and use of green hydrogen [12].

A. Production through biomass energy

Bioethanol is an intriguing feedstock that may be utilized for hydrogen generation by steam or autothermal reforming, according to Bion et al. [18], who developed nanocatalysts for the synthesis of green hydrogen from bioethanol. However, because the impurities have a significant effect on catalytic activity and stability, the heavy alcohols, esters, acids, and N compounds present in the raw feedstock need to be purified at a high cost. Therefore, it would be ideal to find a way to use the raw feedstock without seriously degrading the catalyst.

Mosca et al. [19] developed and assessed a membrane-assisted method for producing green hydrogen from feedstock using bioethanol. The Palladium-membrane separation processes are integrated in the most appropriate reaction steps to modify the basic Steam Ethanol Reforming (SER) process scheme in a membrane aided process. The evaluation of the membrane aided process, which was set up in three different designs (Open architecture, Membrane Reactor, and Hybrid architecture), yielded a clear indication of increased process performance in terms of efficiencies and hydrogen yields. follows.

B. *Production through solar energy*

The concentrator photovoltaic-electrolysis (CPV-E) setup according to Khan et al. [20] had a STH efficiency of 28% at 41 suns. They also conducted a thorough techno-economic analysis, which revealed that although CPV cells are expensive, the levelized cost of hydrogen is only \$5.9 kg^{-1}, which is comparable to the cost of hydrogen from c-Si solar farms (\$4.9 kg^{-1}). Lastly, they reported on the sensitivity analysis of factors affecting both CPV and alkaline electrolyser systems. Their findings showed how CPV technology may be used to produce green hydrogen on a massive scale, potentially replacing hydrogen produced from fossil fuels.

Using hourly data, Armijo and Philibert [21] presented a techno-economic modeling for the flexible synthesis of hydrogen and ammonia from water, air, and ideally coupled solar and wind energy. They came to the conclusion that, when the impact of raising the load factor on the electrolyser outweighs the rise in electricity prices, hybridizing solar and wind power can lower the cost of producing hydrogen by a few percent.

A brand-new dynamic simulation model was introduced by Barone et al. [22] to assess the energy efficiency of solar-powered systems used to produce green hydrogen. A parabolic solar dish collector connected to appropriate thermo-chemical reactors is the system's primary component. Their findings show that a considerable amount of hydrogen, between 1.19 and 1.64 m3/year, may be achieved by the system under investigation.

C. *Production through wind energy*

The Republic of Djibouti's utilization of wind energy for power and the creation of green hydrogen was studied by Dabar et al. [23]. They examined the wind speed characteristics using wind data measured at five meteorological stations between 2015 and 2019 and carried out the techno-economic analysis of five wind farms with a combined capacity of 450 MW. They did this by using techniques like the levelized cost of energy production, the levelized cost of green hydrogen production (LCOH), sensitivity analysis, Monte Carlo simulation, and economic performance indicators. According to their findings, green hydrogen may be produced at a competitive cost, with LCOH ranging from 1.79 to 3.38 US dollars per kilogram H_2. Additionally, their sensitivity analysis revealed that the factor capacity, interest rate, and initial investment cost are the three economic analysis criteria that are most important.

The potential for producing green hydrogen from wind energy in the United States (Fig. 5) its use in power generation, and the possibility of replacing grey and blue hydrogen for industrial use was examined by Sedai et al. [24]. According to the study, in order to completely replace grey hydrogen in the US industry and meet the current demand of 10 million metric tons of hydrogen annually, a wind farm with a capacity of approximately 130 gigawatt-hours must produce green hydrogen. This estimation holds true for regions with wind resources comparable to Lubbock and Texas.

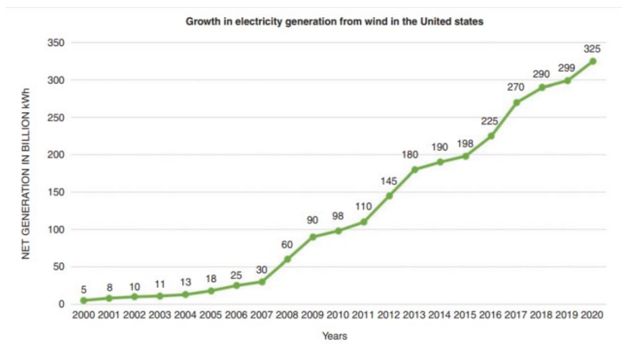

Fig. 5: Twenty years wind energy increase rate in the United States [14]

Ayodele and Munda [25] used of real wind speed measured at 60 m anemometer height to examine the feasibility and capacity of producing hydrogen from South Africa's wind energy resources. Sensitivity assessments were also carried out to provide an understanding of the potential impacts of wind turbine operating parameters on the price of producing hydrogen. The results of the sensitivity analysis showed that, in comparison to other wind turbine characteristics, rated wind speed significantly affects the cost of producing hydrogen.

D. *Production through ocean energy*

Pérez-Vigueras et al. [26] conducted a feasibility analysis of green hydrogen generation using marine energy. This analysis provides information on the ideal electrolyzer for marine environments, the most cost-effective storage medium, and the ideal operating conditions for offshore wind farms. When compared to gray hydrogen generation, the green hydrogen production method from marine systems has been shown to be more environmentally friendly and viable.

The technical and financial viability of using wave energy in Portugal to produce green hydrogen was examined. The goal was to replicate the creation of hydrogen utilizing energy from solar power plants and AW-Energy's wave energy converters. It was discovered that in the majority of common weather situations, the flexible operation of wave energy converters created by AW-Energy can decrease solar power fluctuation [27].

Another study by Blanco-Fernández and Pérez-Arribas [28] suggested using marine energy to extract hydrogen from water. They came to the conclusion that the impact of long submarines piping to the coast would be lessened if hydrogen-obtaining equipment were positioned in the ocean. Moreover, this will pave the path for the creation of hydrogen-powered ships.

While offshore renewable energy resources hold enormous promise for the global energy supply chain, Gondal [29] noted that offshore power still has a higher levelized cost of energy than conventional electricity. In Gondal's work, a unique totally offshore method of using carbon sequestration and storage in combination with electrolysis to complete the methanation process was presented as shown in Fig. 6. There was also a suggestion for a man-made island to house the entire offshore power-to-gas process. It was discovered that the suggested configuration is capable of efficiently managing the energy generated offshore and transferring it to onshore demand centers using conventional natural gas pipeline infrastructure.

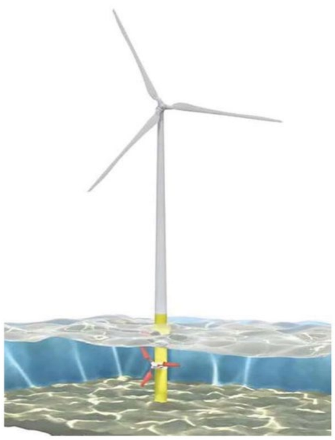

Fig. 6: Combined offshore wind wave energy system [29]

E. *Production through geothermal energy*

Alirahmi et al. [30] examined a multi-generation system powered by geothermal energy in the creation of green hydrogen, which generates electricity, hydrogen, oxygen, and cooling (Fig. 7). The findings showed that the system's output parameters increased with the temperature of the geothermal well. The findings show that the system can generate 4,696 MWh of electrical power annually, which is sufficient to meet the energy needs of 160 homes. Finally, an ideal scenario with 37.85% energy efficiency a system cost rate of 15.09 USD/h was achieved through multi-objective optimization.

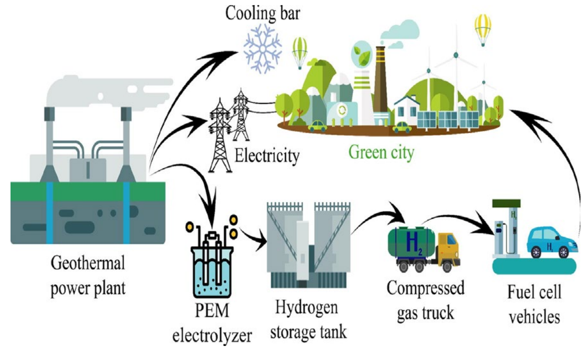

Fig. 7: Geothermal-green hydrogen system [30]

A model for producing green hydrogen from medium-temperature geothermal sources was presented [31]. Due of its substantial geothermal and water resource potential, the Zilan area in Turkey's Van region was selected by the model as a good location for the generation of hydrogen and power from low- to medium-temperature geothermal sources. Based on 2022 data, the hourly hydrogen production potential at this site utilizing a 1.4 MW ORC plant was assessed to be 18.6 kg by the model's findings. Based on 2050 forecasted data, this production potential is expected to grow to 28 kg. A techno-economic study of this compact green hydrogen generation method was also carried out, and the results showed that in the upcoming years, green hydrogen will be comparatively less expensive.

The goal of Arslan and Yilmaz's [32] study is to create models that use thermodynamics and thermoeconomics analysis to evaluate the possibility for producing green hydrogen from Turkey's geothermal resources. Thermodynamic study examines the thermophysical characteristics of geothermal fluids and looks at the viability of using the heat that is available to produce hydrogen via electrolysis. The Afyon Geothermal electricity Plant (AFJES) generates 4132 kW net electricity at 110°C using 150 kg/s of geofluid as a result of the performance analysis. The power plant's unit costs for producing hydrogen and electricity are 1.684 $/kg and 0.01671/kWh, respectively.

Rahmouni et al.'s [33] research focuses on the method of producing hydrogen by water electrolysis utilizing the energy produced by a geothermal power plant that employs CO2 as a heat transport fluid. The levelized cost of electrolytic hydrogen is estimated and the potential for hydrogen generation is assessed using a numerical simulation. The findings indicate that the process has a strong chance of manufacturing geothermal hydrogen. It can produce around 22 kg/h of electrolytic hydrogen at a temperature of 296 K and a mass flow rate of 40 kg/s for a geothermal carbon dioxide source. Economically speaking, the majority of the entire cost of producing hydrogen (more than 90%) is attributed to the costs of the electric energy system.

IV. Conclusion and Research Directions

The exploration of green energy in Africa is indeed important as it creates room to understand the existing state, challenges and, most importantly the opportunities of green hydrogen energy in Africa. Moreover, due to the present energy challenges, the advantages of green hydrogen energy as an alternative is enormous.

With Africa's present state of energy infrastructure and frameworks, it may be concluded that the continent still has a long way to go. Because, the challenges are multifaceted, they are political, social and technical amongst others, and issues need to be addressed fundamentally before any progress can be made in the application of green hydrogen. However, since the concept of green hydrogen energy is about efficiently producing hydrogen from renewable energy sources, there is definitely hope for the continent. Africa happens to be blessed with a wide range of renewable energy sources that can be tapped to produce green hydrogen. By understanding existing methods and policies used by other countries, optimizing them and applying similar principles, a green hydrogen energy future is very possible.

Several works that focused on producing green hydrogen from biomass, solar wind, ocean and geothermal sources has been captured in this study. These applicable works brought about significant results such as:

i. Improved and efficient processes for green hydrogen production. Additional, novel methods proved beneficial.

ii. Relatively lower levelized cost of hydrogen (LCOH) when renewable energy sources are considered.

iii. Increase in the capacity of renewable energy sources will in turn lead to an increase in green hydrogen production, in order to meet any proposed demand. Also, specific renewable energy production factors such as configurations, parameters, optimization, etc., affect the production cost.

iv. Superimposing several renewable energy sources can slightly reduce the cost of hydrogen production.

If these relevant conclusions can be adjusted where necessary and used to tackle the green hydrogen and general energy challenges in Africa, then it will be advantageous for the overall development of the region and the world at large. It is recommended that energy stakeholders in the continent be more generous with energy data in order for more accurate and region-specific research to be done.

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