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A Comprehensive State-of-the-Art Survey on Green Hydrogen Economy in Sub-Saharan Africa

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Abstract: Rapid increase in urbanization and industrialization due to increase in human population has led to increase in global warming resulting to climate change that affects the ecosystem. Unusual natural disasters such as cyclones, storms, floods, weather fluctuations, rising seal levels, transitional ecosystems and coastal disruptions are major adverse effects of climate change. There are huge worrisome concerns and uncertainties about the future of the planet earth due to climate change caused by high carbon emissions. Global aggressive policies in control of Carbon-dioxide (CO_2) emissions from several combustion mechanisms have paved way for alternative/ clean energy sources. Green hydrogen is a promising means of clean energy sources for commercial power generation stations and other crucial systems such as hydrogen fuel cell vehicles (HFCVs) , motors, drives, backup power for buildings, and also serving as a source of electrical energy for remote locations. The goal of this study is to review the current level of Sub-Saharan African nations' preparedness to adopt green hydrogen as a way to mitigate local energy supply issues and strengthen their individual economies.

Keywords: climate change; electrolysis; fossil fuels; global warming; green energy production; hydrogen fuel cell vehicles; hydrogen storage systems; renewable energy sources; sustainable development goals

1. Introduction

Sub-Saharan Africa (SSA) as shown in Figure 1 [1], is a region that has a population up to 1.2 billion [2], with more than 66 % of the population without access to electricity supply and many others with unreliable electricity supply [3]. Over the next several decades, SSA will be primarily responsible for the increase in global population, with some other regions witnessing a decline in population [4]. According to [5], about 50% of 41 member countries in SSA region have no access to electricity. They rely mostly on unprocessed biomass, such as wood, charcoal and waste as the main sources of energy for cooking and house warming.

In fact, 2 out of 3 people in SSA lack access to modern energy services [6]. Such persistent inadequate supply of energy has crippled the region's economy and has adversely affected its health services as well as its education development goals.

Moreover, SSA's per capita energy consumption (excluding South Africa) stands at 180 kWh, compared to that of USA and Europe, which are 13000 kWh and 6500 kWh respectively [3].

Barasa M. et al [7], suggests that a 100% renewable source based energy system is a practical solution to energy supply problems in SSA in both technical- and economical-wise.

The fundamental related challenges towards adequate renewable energy supply in SSA in general is the lack of technical know how in harnessing the abundance energy [8]. However, the technical potential for producing affordable green hydrogen in SSA is high as indicated in [9].

The primary source of green hydrogen is renewable energy such as Solar PV, wind or hydro via the process of electrolysis[10]. Excess generated renewable energy can be converted to green hydrogen (via the process of electrolysis), which can safely and easily be stored in hydrogen storage tanks [11].

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Such converted energy can serve multiple purposes such as hydrogen fuel cell vehicle application [12–14], bridging low production of renewable energy during rainy season or winter period [11].

Green hydrogen production policy and strategy framework has been in precise, adopted by Economic Community of West African States (ECOWAS) during their 90th ordinary council of ministers session, which took place in Bissau, Guinea Bissau on the 6th to 7th of July, 2023. Such energy was classified by ECOWAS as a clean and sustainable energy that is capable of decarbonising industrial, transport, power and agricultural sectors [15].

The green hydrogen is the best alternative energy for vehicles and other electrification applications due its zero emission characteristics [10]. Grid connected Electric Vehicles' (EVs) charging points do not promote the global zero emission target, especially from a grid network that is dominated by fossil fuel based generation systems [16–19].

Additionally, moving green hydrogen over long distances is not difficult. For the large-scale and hence affordable generation of green hydrogen, this renders nations possessing ideal sun and wind conditions, space, and water availability appealing [20].

Most of the countries in SSA have fossil-fuel dominated grid network and integrating EVs to such network will increase the pressure on the already stressed and overload system [16,17].

The process of green hydrogen production is endothermic reaction. The energy conversion efficiency of the process ranges from 75% to 85% capacity. It has high production speed and can cope with the intermittent nature of renewable energy sources [21].

However, other sources of hydrogen such as natural gas, coal and nuclear energy (as will be detailed in this paper), emit CO_2 [10].

Moreover, one of the most prospective effective avenue through which global carbon neutrality can be achieved is the mass production of hydrogen fuel from sunlight and water via photocatalytic water splitting technique [22–27].

The adoption of green hydrogen as the main source of energy in SSA, does have huge benefits in terms of improving the region's economy through the increment in electricity supply coverage, which will drastically reduce the percentage of lack of access to clean energy supply by the member countries [13].

Limited access to green energy supply poses a huge challenge towards achieving the SDGs in SSA and one of the major challenges is the inability to minimise the usage of fossil fuels as major sources of energy supply [28].

In addition, the 2030 agenda, (the SDGs) along with the European hydrogen strategy have presented a fundamental framework for the feasible pathway of mass production of green hydrogen [29].

Moreover, the agenda has become an obvious necessity with the emerge of the Russian-Ukraine war. Most of the European countries have already entered into partnership with many SSA member countries for production and importation of green hydrogen [29,30].

The main consideration in selecting such production base countries includes; the availability of the required resources, such as sunlight, wind and water, plus other conditions such as human right issues, social-economical and political conditions [29].

Given that green and gray hydrogen may reach cost parity as early as 2025 due mostly to the latter's continued reliance on natural gas pricing, SSA region's hydrogen product is most likely to be green [9].

Regardless of the robust energy efficiency ratio (EER) of HFCVs, sufficient power-to-weight ratio and drastic emissions reduction capability, the global acceptance remains far fetch as a result of several factors such as; production costs, low energy density of hydrogen gas, durability issues of fuel cell, logistics terms of transportation, storage complexity refueling infrastructure and safety issues [10].

However, recent works in literature focus mainly in hydrogen fuel cell technology in terms of its efficiency, cost-effectiveness and durability. And such do pose huge challenges, when it comes to the production, distribution and storage of hydrogen fuel cell [31,32]. Hence, further research with

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regards to the above-mentioned obstacles is eminent. There are several approaches towards alleviating such problems in the literature.

The reassurance, as detailed in [10], suggests that advancements in technology and some promising oncoming policy around hydrogen fuel cell technology interventions could facilitate and enhance the global acceptance of hydrogen fuel cell vehicle as the most viable means of transportation in the near future [10].

Green hydrogen as an essential commodity and viable solution towards the global efforts to decarbonize the atmosphere, has been identified by the South African government as at 2021. South Africa is the only country, among all the countries in sub-Saharan Africa to have adopted American National Standard [33], as a standard required for the installation of hydrogen production technology [13]. Hence, SSA is still a virgin platform to establishing a sustainable norms and standards on hydrogen production technology in a local context.

According to [34], none of the countries in SSA or even Africa as a whole is currently taking any safety measure in the development of hydrogen technology unlike other developed world, such as USA, Europe and Asia.

The main motivation of this research is the quest for useful information regarding the general acceptance and viable means of adopting green hydrogen in SSA with net-zero carbon emission, in line with the global Sustainability Development Goals (SDGs).

This review paper's innovation lies in illuminating the advancements achieved by each of the SSA's member nations in terms of strategy, finance, execution, and collaboration, as well as the gaps that still need to be closed in terms of localized green hydrogen production.

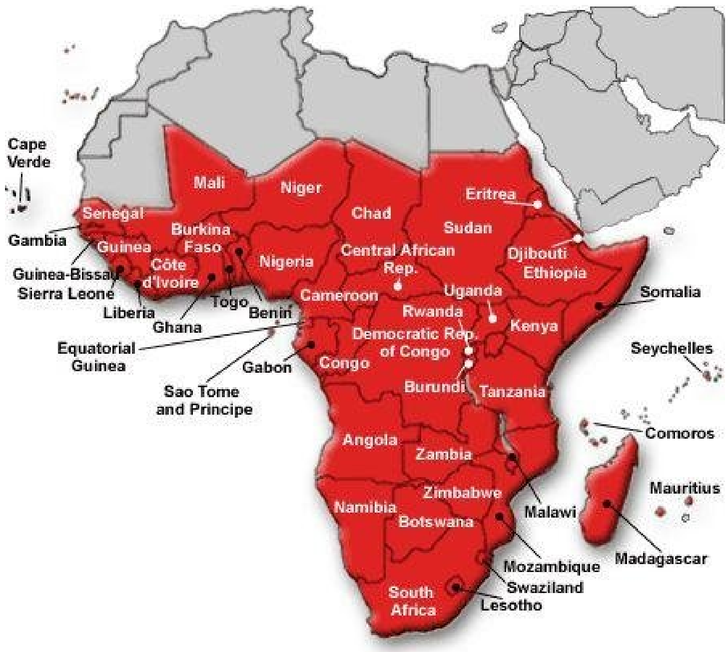

Figure 1. Map of Sub Saharan African countries [1]

2. Past Related Work in Literature

Several methods of producing hydrogen in SSA have been reviewed in [35], especially from biomass (forest residue and products, agricultural wastes, crops, grass and municipal solid wastes), which is in abundance in SSA [13,36].

However, the drawback of hydrogen production from biomass is the co-production of CO that results to the presence of CO_2 after reacting with Oxygen in air [36,37].

Zainel, B.S. et al [38], in their review paper highlights the various color codes of hydrogen, which have not been extensively covered in the literature up until this point. Color-coded systems are used to categorize hydrogen production; green hydrogen, which is generated from renewable sources like solar and wind power, is the most preferred alternative. It is anticipated that demand for green hydrogen would soar in a number of industries. The assessment in [38], thoroughly assesses the main approaches for producing hydrogen in terms of cost, environmental effect, and technological development.

In-depth review of the most recent developments, difficulties, and prospects for hydrogen production, transportation, storage, and usage (HPTSU) technologies is presented in [39]. The paper explores the potential applications of hydrogen in various sectors, discusses different ways to produce hydrogen, highlights advancements in transportation and storage solutions, and identifies important research areas for further development and widespread implementation of hydrogen technologies. Researchers, engineers, legislators, and industry stakeholders who want to learn about the most recent developments in HPTSU technologies and how they might hasten the shift to sustainable energy sources will find the article to be an invaluable resource [39].

A historical review of hydrogen storage technology in terms of safety, reliability, qualitative and quantitative analysis is presented in [40]. While a detailed survey of the physical and material based storage and transportation technologies of hydrogen is presented in [41].

The key results of the paper, [41] is the comparison of several hydrogen storage systems and transportation technologies, which provides useful recommendations for the choice of adequate infrastructure for respective hydrogen transportation and storage scenarios.

However, material-based storage technology is still at its infancy stage. More research are still needed to demonstrate its feasibility as a long-term fix energy storage system [40].

It is emphasized that the establishment of a suitable means of transporting hydrogen and its proper storage are of high importance apart from the efforts put in place in terms of reduction in production costs. The paper further showcases some viable means of transporting hydrogen, such as pipeline, overseas shipping and land transportation. Comparisons of the different technologies surrounding hydrogen storage and its means of transportation are discussed in details to pave way for useful recommendations [41].

A review of hydrogen storage technologies that focuses on transportation applications is presented in [14]. It was pointed out that compressed hydrogen offers a more functional solution and showcases a robust storage system for locomotives. It is crucial to note that hydrogen fuel cell has a potential superiority for energy supply than batteries in mobility applications despite its present state of less energy efficiency compared to batteries [14].

Underground hydrogen storage system is ranked as a technology with a relatively economic maturity for long-term storage that can be applied even in large-scale functions [40].

A review of hydrogen conversion techniques from fossil fuels is found in [32]. And other crucial information concerning the production and application of hydrogen are detailed below.

An empirical research that utilised public opinions towards the adoption of HFCVs in India is presented in [42]. While, several types of fuel cells and their applications are reviewed in [43].

An in-depth survey that explored the current/future challenges in hydrogen fuel cell mobility is presented in [10]. The technology behind HFCVs is the utilisation of hydrogen gas to energise an inbuilt electric motor, thereby emitting vapour and heat only instead of carbon.

A study that proposes a dual-nozzle ejector to overcome the shortcoming in operating the proton exchange membrane fuel cell (PEMFC) system is presented in [44]. The study forms a reference point for choice of optimisation of ejectors.

A fundamental analysis and evaluation on the associated costs of producing hydrogen fuel in large scale scenario is conducted in [45].

An empirical experiment to investigate a correlation between the use of HFCVs and their corresponding impact on SDGs both in direct and indirect mode is proposed in [42]. About 358 valid sample responses from Pan-India survey were used in the study and analysis revealed that the majority of Indians agree to the fact that the adoption of HFCVs has a significant effect on SDGs.

The major contribution in [42], is the linking of the impact of the adoption of HFCVs to SDGs, which has always been neglected in literature.

Hydrogen as Fuel in Commercial Power Plants

There is a high sense of urgency to address climate change. Significant investments are being made globally in a very high scale and fast pace to meet the goal of decarbonization. Burning of hydrogen as fuel in all combustion engines is a promising avenue that supports decarbonization due to its near-zero or absolute zero carbon emissions, with respect to the source.

One of the major uncertainties in power sector is energy transition. However, more efforts must be put in place to lower the cost of hydrogen and its capture capture technologies. And such can be achieved by increasing global incentives to those power utilities that are adopting hydrogen as a burning fuel instead of the conventional fossil fuel [42]. Such can increase the deployment of hydrogen fuel technologies in most power plants globally, thereby accelerating the speed of decarbonization.

Several power utilities are currently exploring viable options on how to adopt hydrogen as a fuel with zero or near-zero carbon emissions. According to [46], the General Electric (GE) has more experience in hydrogen utilization as fuel that dates back to mid-1990s. about 100 gas turbines in GE system are currently using hydrogen as fuel, which has accumulated more than 8 million hours of operation.

3. Hydrogen Production Technologies

As the present need begins to progressively rise, hydrogen energy emerged as the most important energy source. One crucial way to combat the rise in global temperatures is via hydrogen energy. The hydrogen economy is a critical component in the manufacturing of hydrogen. Technologies for producing hydrogen are available on the market, while some are still in the development stage. Several methods for producing hydrogen using fossil and non-fossil fuels, including pyrolysis, steam reforming, autothermal, partial oxidation, and plasma technology are reveiwed in [47]. Technology related to water electrolysis was also reviewed. Renewable energy sources and water electrolysis can be coupled to create environmentally beneficial technology. At the moment, the methods of gasification, partial oxidation, and steam reforming with fossil fuels have the highest recorded generation of hydrogen fuel [47].

Industry, the government, and the general public have all expressed strong support for hydrogen energy, establishing it as a key fuel source for the future. However, there are other obstacles in the way of its commercial realization, such as the expensive production of clean hydrogen and the sluggish expansion of infrastructure [48].

Electrolysis method of producing hydrogen (as included in Figure 2), remains the safest and most viable method. Its installation requires much less space compared to PV and wind generation system [10,49]. Its availability represents 4% of the world's energy demand [35]. Rural or urban installation is viable due to its noiseless, ordourless and non-pollutant characteristics [13].

Electrolysers life-span can also affect the future cost of green hydrogen production. The current life-span of electrolysers is about 50,000 t0 80,000 hrs (approximately 6 to 9 years). However, such can be prolonged up to 120,000 hrs by 2050 as long as the quest for the improvement continues [16,17]. Enhancing and prolonging the life-span of electrolysers can drastically reduce the green hydrogen production cost [17,50].

The limitation of a single-nozzle ejectors can be mitigated (as proposed in [44]) by replacing such single-nozzle with a dual-nozzle ejector that enhances the flow of hydrogen fuel to meet the requirement of hydrogen supply in PEMFC system. The simulation of the optimised dual-nozzle technique was also validated experimentally, which led to the development of a three-dimensional hydrodynamic model for smooth and efficient hydrogen circulation in PEMFC system.

A study on hydrogen refuelling station (HRS) that is powered by hybrid PV-Wind system via PEM electrolyser is presented in [51]. The economic analysis and optimisation of the hybrid design

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was conducted in HOMER software. It was demonstrated that powering HRS using renewable energy is economically appropriate. While the analysis of optimal strategy of hydrogen refuelling station powered by PV and grid system via PEM electrolyser is proposed in [52]. The model is formulated as a Mixed Integer Linear Programming (MILP) model with multiple objectives such as capacity utilization of electrolysers, CO_2 emission targets and the minimisation of the operational cost of the entire system.

Hybrid hydrogen fuel cell with lithium-polymer battery to increase the endurance of Unmanned Aerial Vehicle (UAV) were investigated in [53]. The effect of the control technique on energy efficiency of hydrogen fuel cell-electric hybrid vehicles is proposed in [54]. A comparison of the two control techniques; Optimised Fuzzy Logic Control (OFLC) and Rage Extender (RE) were carried out and it was deduced that OFLC is capable of increasing the hydrogen to wheel conversion up to 48.1% efficiency, while the RE can only go up to 45.7% . Hence, the load stresses on the battery pack benefits more on the OFLC strategy than that of RE [54].

A hybrid standalone renewable energy system (using Ghana as a case study), that is based on solar power plants, biomass and wind power plants to meet the needs of up to 30 EVs and 70 connected batteries is proposed in [17]. Such proposed hybrid system contributes immensely towards achieving the global SDGs and can help to facilitate the promotion of non-grid dependent EVs in SSA.

A model known as GREET has been utilised in [12], to evaluate hydrogen fuel cell commercial vehicles' carbon emissions and the corresponding costs in China. The paper further provided a benchmark for future policies of including hydrogen energy in Chinese carbon trading system.

The effect of hydrogen fuel cell's ambient temperatures on the transportation's driving and its stack heating characteristics is presented in [55].

A study on hydrogen fuel production that offers an applicable and efficient approach to producing hydrogen from sunlight and water, (using an indium gallium nitride photo-catalyst) is presented in [22]. Such production approach does have the benefits of overcoming the bottleneck of solar-hydrogen production with reasonable percentage of energy conversion efficiency. However, such method calls for a catalyst, which is additional requirement that attracts extra cost and complexity of the production [56,57].

Production cost of hydrogen from PV solar cell system is about 1.09 Euros per cubic metre in a condition of producing only 115 litres per day. Hence, it might be a good ideal in terms of cost-effective, provided that other challenges and constraints are met/ignorable [13,45].

Carbon capture and storage (CCS) technology is a promising technology that can mitigate or eliminate the emission of CO_2 during the production of hydrogen from Coal and natural gas [13,45]. The technology has been in use by several commercial industries for more than 20 years. Moreover, many experts have predicted the large-scale deployment of CCS technology in the near future to facilitate the net-zero carbon emission goals. It is noteworthy that the net-zero carbon emission goal will not be possible without the deployment of CCS technology in blue and turquoise hydrogen productions from fossil fuel [58]. According to International Energy Agency (IEA) report as referred to in [58], the global carbon management industry must be capturing about 8 gigatons of carbon per annum to meet the target of net-zero carbon emission by the year 2050.

The Off-Grid (standalone) hybrid system (as shown in Figure 4) could possibly consists of the electrolyser, solar PV, wind, micro-hydro, battery and hydrogen storage systems, while grid connected hybrid system (as shown in Figure 5) could possibly have all the features of the standalone hybrid system plus the grid [52,59]. The purpose of the grid is to keep the system in active mode during the downtime of the renewable sources. The battery is also an additional back up supply that charges when the renewable sources are available to compensate for short-term fluctuations of renewable sources [52].

The summary of sources of different types of hydrogen is shown in Figure 3 and the summary of methods of production, possible emissions and climate change impacts is shown in Table 1.

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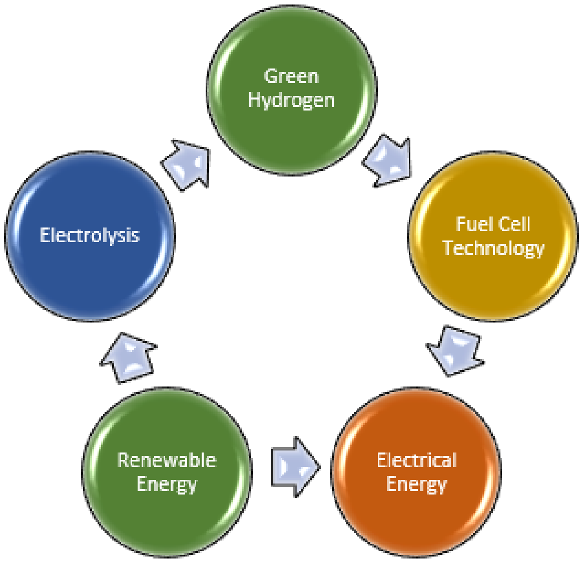

Figure 2. Hydrogen-Electricity Production Cycle.

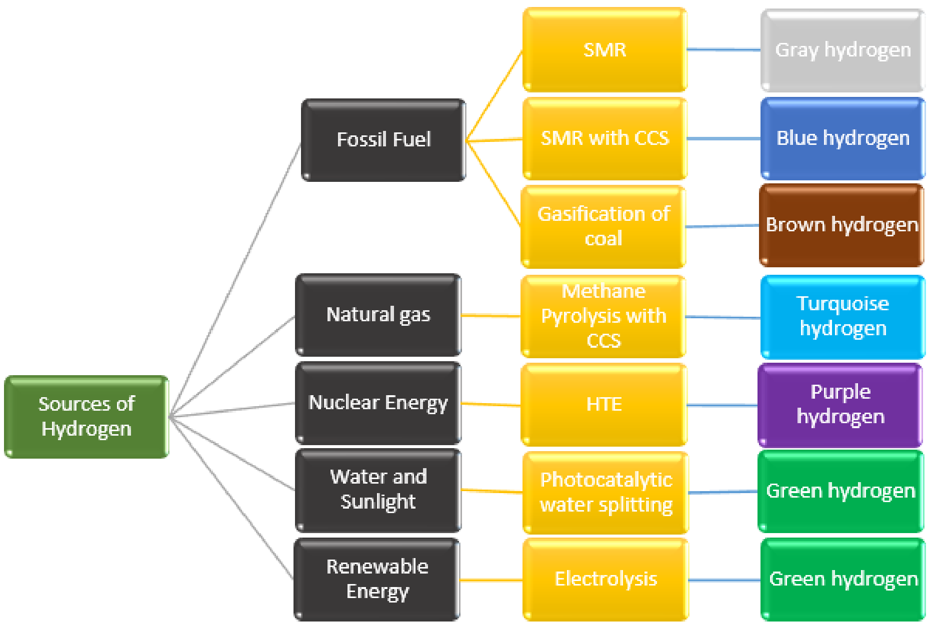

Figure 3. Types of hydrogen, sources and their production techniques.

Table 1. Hydrogen production types, emissions and their impacts to climate change

Type of Hydrogen	Source	Method of Production	Emission	Climate Change Impact
Gray hydrogen	Fossil fuel Natural gas or coal	Steam Methane Reforming (SMR)	CO_2	High
Brown hydrogen	Fossil fuel (coal)	Gassification of coal	CO_2	High
Blue hydrogen	Fossil fuel Natural gas or coal	SMR with Carbon Capture and Storage (CCS) system	Captured CO_2	Low
Turquoise hydrogen	Natural gas or coal	Methane Pyrolysis with CCS	Captured CO_2	Low
Purple hydrogen	Nuclear energy	High Temperature Electrolysis (HTE)	Radioactive wastes	Zero
Green hydrogen	Renewable energy sources	Electrolysis or photocatalytic reaction	Vapour	Zero

Hydrogen production system for hydrogen refueling station and other purposes can be of two types (as shown in Figures 4 and 5) viz:

- Off-Grid (standalone) hybrid system and
- Grid connected hybrid system

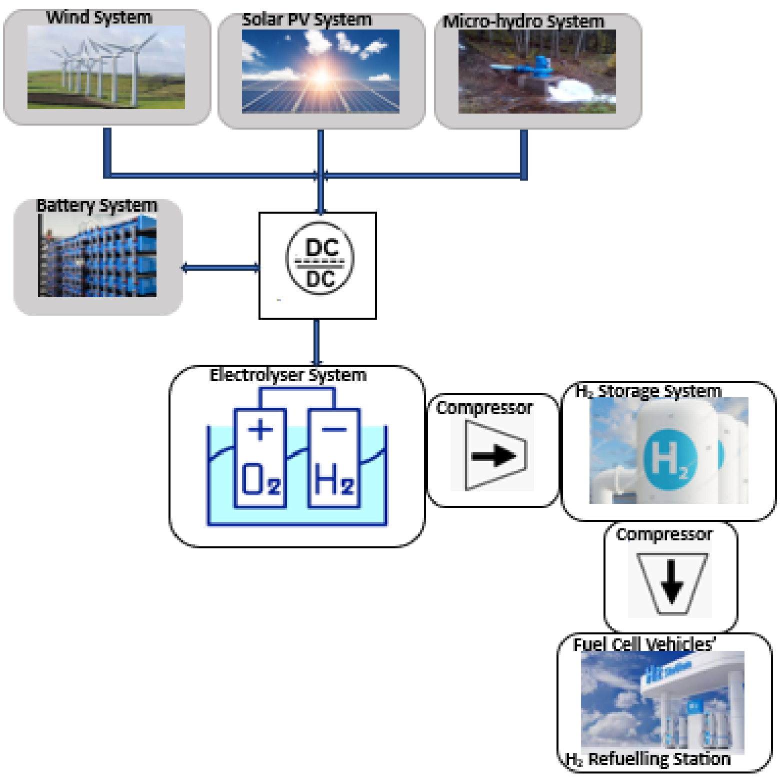

Figure 4. Standalone hybrid system for hydrogen energy production, storage and dispatch.

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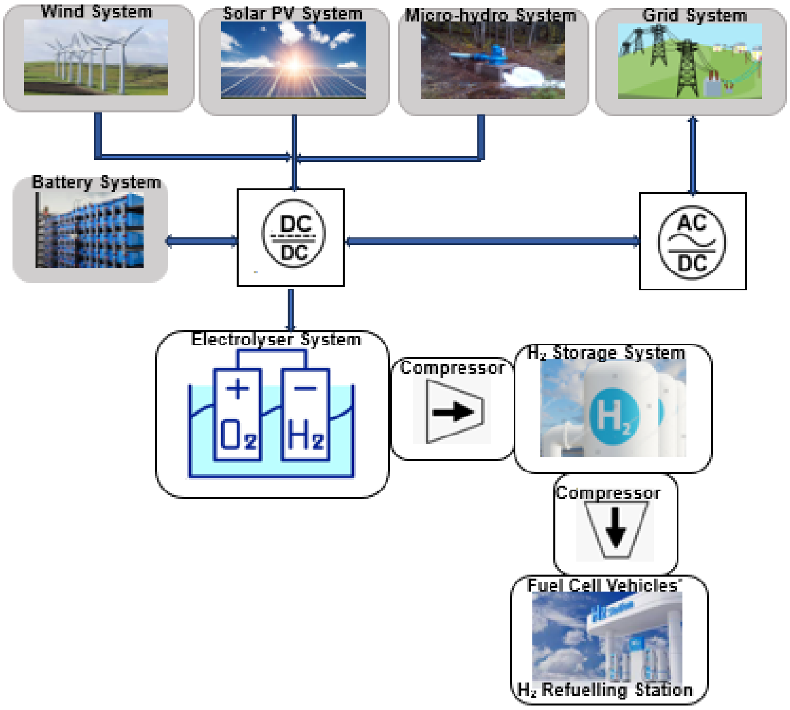

Figure 5. Grid-connected hybrid system for hydrogen energy production, storage and dispatch.

4. The Status of Hydrogen Economy in Sub-Saharan African Countries

Globally, solar energy is most abundant in Africa. Green hydrogen produced from solar energy may boost energy security, reduce emissions and pollution, and decarbonize industry and transportation, according to the European Investment Bank, which collaborates with investors to maximize Africa's hydrocarbon potential and lower production costs. Achieving a cost of US$2.17 per kilogram of hydrogen during production would be necessary for commercial feasibility. Solar technology specialists predict that by 2030, solar power will bring down energy costs and bring hydrogen production below US$2 per kilogram [60].

An alliance to facilitate collaboration on the creation of a sustainable enabling environment by the adoption of green hydrogen has been entered by six African countries, of which four out of the six countries are SSA member countries. The six countries in alliance are Kenya, Mauritania, Namibia, South Africa, Morocco and Egypt. Such alliance constitutes the development of regulatory and public policies, certification, capacity building, and financing needed for the mobilisation of green hydrogen production for commercial export and domestic use [60–63].

Implementation of such alliance has the benefit of attracting foreign investors and providing access to external incentives and price support [61].

According to the International Renewable Energy Agency (IRENA) report, (as quoted in [15]), SSA has the greatest potential for the global competitive production of green hydrogen. The region, by estimation is capable of producing up to 35 % of the global hydrogen production capacity at a price less than $ 1.5 per Kg of hydrogen.

Energy crises in SSA can possibly be curbed by the modern day growth in hydrogen fuel cell technology. Hydrogen and its associated technology are not quite popular in sub-Saharan African (SSA) countries due to the economic nature of the most of the countries SSA [13]. The major advances of the technology is still in its infancy, theoretical and conceptual state. However, SSA has the technological capacity to generate affordable green hydrogen at a high rate [9].

Major challenges and drawbacks associated with the adoption of hydrogen as a source of energy in SSA, along with possible solutions are reviewed in [13]. Other aspects of hydrogen fuel cell production,

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such as the feasibility of its availability for uninterrupted electric power supply, system hybridization ideas and possible risks intervention techniques are also covered in the review paper.

The major finding in [13], is that about 17% of the SSA countries are already engaged in hydrogen fuel cell technology activities.

Most of sub-Saharan African countries that have already engaged in hydrogen fuel cell production are mentioned in [13]. However, only few of the SSA countries stand the chance to benefit more from the early transition to hydrogen fuel cell especially for mobility and electric power supply.

Germany has started a revolutionary path with Africa that redefines international collaboration and sustainable development. Chancellor Olaf Scholz announced this proposal during the Compact with Africa meeting, promising to invest a considerable €4 billion in renewable energy projects around the continent by 2030 [64]. This is more than just a financial commitment. It signifies a significant turn in the direction of a more environmentally friendly future and a closer, more advantageous partnership between Germany and Africa. This audacious move promises to enhance Africa's economic development, technical advancement, and energy independence in addition to aligning with Germany's ambitious environmental aims. It also heralds a new era of international environmental and economic cooperation [65].

The investment's emphasis on green hydrogen manufacturing in Africa is one of its main features. In addition to assuring African nations of Germany's position as a dependable consumer of this clean energy source, Chancellor Scholz has emphasized green hydrogen as a critical component in Europe's transition to renewable energy sources. In addition to helping Germany reach its target of net-zero carbon emissions by 2045, this strategy is expected to have a major positive economic impact on Africa by boosting employment and advancing technology [64,65].

Regardless of the firm stance by Germany in promoting anti-green house effect, her diplomatic efforts in quest for hydrogen have also accommodated the importation of blue hydrogen and its associated derivatives from United Arab Emirate and Norway [66,67].

The member countries in SSA, that are currently using or planning to use hydrogen as fuel are discussed below. In fact, the SSA member countries, whose regions are surrounded with favourable renewable energy conditions are most likely going to be the future green hydrogen exporters, while the rest of the member countries with less renewable energy favourable conditions will form the net importers [68].

Angola stands out as one of the high potential hydrogen production countries in SSA due to its abundance water availability, hypsometric and favourable geographic characteristics. Sonangol, which is Angolan state-owned oil and gas company, has developed a plan to be producing green hydrogen in Angola as part of its energy diversification policy [30]. However, renewable energy sources will not spontaneously replace Angolan's fossil fuel energy sources. There is still need to be a balance between the utilization of the two for energy supply, where the share for fossil fuel will gradually drop in the long run to pave way for renewable energy dominated system.

Angola further signed a preliminary agreement with two German companies (Conjuncta GmbH and Gauff GmbH & Co Engineering Kg) in 2021 to explore the feasibility of green hydrogen prodcution in Angola and Central African countries at large. Sonangol, through its Research and Development Centre is currently exploring the appropriate locations for the installation of the green hydrogen production sites [30,69] .

Odilon J. et al [8], tested fuel cell technology as a more reliable solar power storage system in Benin Republic. The outcome of the experiment proves that improving the devices for chemical to electrical energy conversions calls for deep exploration in Best and West Africa in general.

Botswana, through its energy department, "Tlou Energy Limited", aims to producing hydrogen via electrolysis and Pyrolysis. The initial stages of the project is to be funded by Tlou's existing cash reserves. Tlou, the elephant company of Botswana is currently developing an addition energy projects in Botswana for gas fired power, solar power, hydrogen and solid carbon productions [70,71].

A prototype gas-to-hydrogen and solid carbon converter has been built in Brisbane. such prototype uses plasma torch technology to convert natural gas to hydrogen and solid carbon. The current goal of the production hydrogen is to use it as fuel for power generation in Lesedi power station and other industrial applications. While the Graphite or solid Carbon is expected to create additional revenue stream to Botswana economy [70,71].

Burkina Faso in quest for more energy supply, has established a solar PV plant for green hydrogen production experiment in Zaghtouli, a local area that is about 25 km away from the western exit of Ouagadougou in Burkina [72]. The authorities forsee green hydrogen as a means of filling the energy supply gap in Burkina. The implementation of the scheme is spearheaded by the West African Science Service Centre on Climate Change and Adapted Land-use (WASCAL)-Burkina; funded by the German Ministry of Education and Research (GMER) [15,72].

Moreover, the assessment of the possibility of production of more hydrogen from biomass is currently under consideration. The additional hydrogen production plan via biomass is sponsored by the Ministry of Agriculture, Animal and Fisheries Resources (MAAFR) Burkina Faso [72].

The Secrtary general of the ministry classified biomass as the main source of energy in Burkina Faso, and about 17,000 biodigesters have been installed in different locations. The primary objectives as lifted by the SG of the MAAFR Burkina Faso includes; provisions for unique solutions to poor access to electricity, extreme poverty alleviation and a powerful means of tackling climate change [72].

The investigation of feasibility of hydrogen production in Cameroon is first reviewed in [35]. Energy analysis on different methods of producing hydrogen were performed and the outcome of the review provided a recommendation, which proposes hybrid energy system as a suitable production method.

Syntech Fuels GmbH German intends to produce green hydrogen and other synthetic fuels in Cape Verde. The agreement, which was signed in 2022, allows for construction of two scale-able green hydrogen plants in the islands of Santiago and Boa Vista [73].

A first attempt to model and quantify the actual yield-able renewable energy and its associated hydrogen based storage system for several areas in Chad was presented in [74]. A 20-year-average solar-wind energy date from NASA was used in the analysis. It was stated that the implementation of such hybrid system is currently infeasible in grid-connected mode in Chad's grid system. Hence, the study acts as an experiment and initial estimation to assist the energy sector of Chad in preparation for the acquisition of the required infrastructure [74].

The biggest challenge facing Comoros as a nation in the years to come will be devising strategies to strike a balance between producing high-quality power and emitting minimal greenhouse gasses. Green energy sources have enormous promise, but their development is still hampered by managerial, financial, and governance problems that Comoros' electrical industry needs to address, particularly in rural areas [75].

Said-Mohamed [76] has suggested a microgrid system based on a renewable energy source with hydrogen storage to address the ongoing load shedding issue in Comoros, a rural village on the island of Ngazidja. Using HOMER, the authors planned and examined the Comoros microgrid with hydrogen storage. The best architecture for the village, according to the authors, is a 500 kW converter, a 1000 kW electrolyser, a 1000 kW fuel cell, three 250 kW wind turbines, a 2250 kW photovoltaic farm, and a 10,000 kg hydrogen storage unit. It was found that the cost of electricity per kWh was 1.724 [77].

The Republic of Congo (Brazzaville) and Eni have agreed to outline plans for decarbonization and a green energy transition in the nation, with a focus on generating electricity from renewable sources, building an agricultural supply chain to produce feed-stock for bio-refining without interfering with the food chain, protecting and managing forests sustainably, implementing clean cooking technologies, and capturing, using, and storing CO_2. As of right now, Eni is the sole business dedicated to exploiting the vast gas reserves found in the Republic of Congo. It provides gas to the Congo Power Plant (CEC), which generates 70 % of the nation's power. Eni has been in the Congo for more than fifty years [78].

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Democratic Republic of Congo (DRC) signed a partnership agreement with Hydrogene de France (HDF) energy in January 2023 to be producing green hydrogen through PV solar power plant. Such establishment should be the first commercial solar/hydrogen project in Central Africa, similar to that of Namibia in Southern Africa [79]. A feasibility study is ongoing for the possible location of the production cite in the southern part of Kinshasa. The regional authorities have welcomed the solar/hydrogen project as part of the long-lasting solution to inadequate power supply in many surrounding areas and a source of more economic opportunities in DRC.

Moreover, HDF has several large-scale PV solar power plant projects in different countries and about 22 green hydrogen energy projects that worth up to $ 1.5 billion are currently installed in Indonesia by HDF Energy [79].

In terms of electricity mix, Côte d'Ivoire anticipates renewables to account for 45% by 2030, and the installed capacity of the nation is anticipated to reach 5.4 GW, consisting of 3.2 GW of thermal power (59%), 1.5 GW of hydropower (28%), 0.37 GW of solar power (7%), and 0.31 GW of biomass (6%) by the year 2030 [80].

The government of the Republic of Djibouti and the Continental Wind Partners (CWP), at the UN Climate Change Conference in Dubai's sidelines for COP28, signed an agreement to expedite CWP's Green Star Hydrogen Hub, a 5–10 GW green hydrogen project that seeks to transform the Horn of Africa's energy landscape. The statement outlines the top priorities for the creation of the Green Star Hydrogen Hub, including resource measurement, assessments of the socioeconomic and environmental impacts, planning for infrastructure, and negotiating key economic parameters to guarantee project viability and bank-ability. The project will provide high-skilled jobs, infrastructure investments, and reasonably priced power and water, all of which will greatly help to Djibouti's economic diversification, as acknowledged by the Dubai Joint Declaration. A evaluation of the work will be conducted by both parties by April 30, 2024. The partners hope to establish Djibouti as a center for this fuel of the future and provide green hydrogen to the thousands of ships that pass through the Bab El Mandeb Strait by putting this massive 5 to 10 gigawatt green hydrogen development project into action [81].

The Atlantic Methanol Production Company (AMPCO), a consortium made up of the businesses Marathon Oil, Samedan (Noble Energy), and SONAGAS, produces methanol in Equatorial Guinea through the Methanol Plant in Punta Europa, which was constructed in 2001. About 125 mmcfd of gas with a grade of 1000 BTU is used by the plant to generate 19,000 barrels of capacity, and two ships carrying 300,000 tons of methanol are sent to international markets. Almost all methanol produced globally is produced by steam reforming natural gas. "Synthesis gas" is created by the displacement reaction and steam reforming and is made up of hydrogen (H_2), carbon monoxide (CO), and CO_2. The procedure that turns natural gas, CO_2, CO, and H_2 into methanol [82].

Atlas Copso Gas and Process Eritrea has identified hydrogen as a crucial aspect of its 2050 vision statement in greenhouse gas reduction and net zero carbon emission goals. Provisions of several solutions to power your energy transition by Atlas Copco Gas and Process is feasible due their previously acquired extensive experience in cryogenic process applications [83].

A license to generate hydrogen power was granted by Ethiopia to Fortescue Future Industries (FFI), an Australian business. The Grand Ethiopian Renaissance Dam (GERD) represents only half of the company's 25 GW power producing capability. It was underlined that trucks, trains, airplanes, and high-capacity fuel-consuming businesses will all profit from hydrogen power. The company plans to begin generating electricity in Ethiopia utilizing geothermal and hydropower in 2026. Prior to now, the FFI has developed $8.4 billion worth of green energy projects in nations like Argentina [84].

Moreover, the Ethiopian Ministry of Water and Energy (MoWE) claims that the nation's topography, geographic location, and agriculture-led economic plan give it an advantage over other countries in the generation of green hydrogen. According to the Minister of State, Ethiopia has an ample supply of renewable energy to meet its needs for green hydrogen, including wind power (100 GW), solar power, hydro-power (45,000 MW), and geothermal power (10, 000 MW). Ethiopia's geography, geographic location, alternative ports in neighboring countries, and agriculturally oriented economic strategy all contributed to the country's ability to produce and export green hydrogen. In order to address the world's growing energy needs, the Ministry declared that research is being conducted into a number of renewable energy alternatives, including the production of green hydrogen [85].

Furthermore, the Chinese manufacturer of solar panels, GCL Group, intends to build a factory in Ethiopia that will use natural gas generated from fields it has been developing under a contract with the local government to produce ammonia. According to its creator, GCL, which is expanding its business by looking into alternative energy sources, will also build facilities that can convert ammonia into about 2.5 million tons of liquid hydrogen [86].

Africa's potential for hydropower is among the highest in Gabon. To build a single, integrated national grid utilizing hydropower, the Gabonese government (GoG) is implementing measures to shift to sustainable energy sources. With regard to utilizing its mainly unexplored hydro potential, GoG plans to depend on independent power providers (IPP) [87].

The national strategy of the Gambia envisions complete access to electricity by 2030 for all households in urban areas and all communities in rural regions. As of now, only 69% of the country's population has access to power. Due to the costly use of fossil fuel and power plants, the Gambians also face the issue of paying one of the highest electricity prices in the world, with an average of more than $0.23 per kWh in 2023 [88].

The Gambia is presently setting out on a path to embrace renewable energy, specifically solar and wind power, and is investigating opportunities for producing green hydrogen. In line with its National Development Plan (NDP), the nation wants to raise the proportion of renewable energy in its mix from 2% to 40% by 2025. In line with the common objective of the Mauritania, Senegal, Gambia, Guinea-Bissau, and Guinea-Conakry (MSGBC) region to end energy poverty, its all-encompassing approach offers the prospect of a more sustainable and clean energy future [89].

The Gambia's government and Swiss renewable energy company NEK have inked a Memorandum of Understanding (MoU) to discuss attaining universal, clean energy access. The purpose of the MoU is to explore green hydrogen, which is viewed as the "fuel" of the future by using the clean energy supplied by the wind farms [88].

The potential for creating green hydrogen in Ghana by solar and wind power is investigated in [90], where the generating capacity at the national and regional levels of the nation are estimated. Even though the nation does not currently have a hydrogen energy policy or initiative as of the end of 2022, there are opportunities to use green hydrogen to support the nation's decarbonization efforts and even to produce it commercially for export. Ghana has a good potential for producing green hydrogen, according to the assessment's findings. By removing any protected areas or conservation sites from the evaluation, a geographical and technological potential assessment was conducted for the two green hydrogen sources [90].

The amount of land available for the green hydrogen project in the region was then calculated using the remaining land areas. The analysis's findings indicate that 85% of the nation's total geographical area—or ~239,428.99 km^2—is suitable for the chosen green hydrogen sources. The nation has the technical capacity to produce approximately 14,196.21 Mt of green hydrogen annually through solar power and 10,123.36 Mt annually through wind power [90].

Ghana is one of the member countries in SSA responsible for up to 70% transport emissions in the whole Africa [17,91]. Ghana is currently channelling the development of hydrogen fuel cell technology to household uses only to ease the household energy demand from the national grid system. This is due to the fact that energy for cooking alone in Ghana amounts up to 95% of the total household energy consumption [92–94].

At the ECOWAS Energy Ministers' Meeting in Bissau, Guinea Bissau, the updated ECOWAS Energy Policy, the ECOWAS Green Hydrogen Policy, and the ECOWAS Regional Electricity Code were

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discussed and approved. This was based on the suggestions made by the ECOWAS Energy Experts Meeting, which took place in Bissau, Guinea, on March 22–23, 2023 [95].

The goal of the ECOWAS Green Hydrogen Policy is to address the socioeconomic development and sustainable growth of all ECOWAS member states while positioning the region as one of the most competitive producers and suppliers of green hydrogen and its derivatives [95].

In order to support the implementation of the Programme for the Enhancement of Energy Performance in West Africa (AGoSE-AO), the European Union has provided thirty-two million euros (€32,000,000) to ECOWAS, according to Madeleine Onclin, Head of Cooperation of the European Delegation in the Republic of Guinea-Bissau [95,96].

"The EU will continue to support West African states in accessing clean and sustainable energy," he stated in [96].

Kenya has the remarkable renewable energy potential due to its vast coastal breezes, regular sunshine and other desirable weather conditions. About 90 % of Kenya's source of electricity is from renewable energy, which ranks Kenya as the top leading country in renewable energy sector in Africa and seventh globally, with its geothermal capacity up to 863 MW [97].

Kenya, which plays a key role in renewable energy sector in Africa [97,98], signed an agreement with FFI; an Australian firm to establish green hydrogen and ammonia plant in Kenya to allow for the kickstart of the country's ambition towards utilising green energy across the continent and export up to 1.7 million tonnes of green hydrogen per annum. The proposed industrial-scale production of green hydrogen and ammonia targets the benefits of providing clean and affordable energy along with fertiliser production for the continent. The implementation of the deal will also assist Kenya to increase its footprint in the renewable energy market [97,99].

The initial capacity of 300 MW green hydrogen and ammonia plant is estimated to be in operation in the next three years with a plan to further expand the project for additional capacity up to 25 MW in the long run [97].

In a conference on water, hydrogen, and the digital future [100], the minister of natural resources for Lesotho hopes to explore the possibilities of the country's water resources and how to use them to boost regional development, create jobs, and revolutionize the economy. Lesotho will be able to produce more hydropower for both internal use and export. The goal is to make sure Lesotho turns into a net exporter of clean, renewable energy to South Africa and the surrounding area. By ensuring that there is less reliance on fossil fuels to power the economies in the Southern African region, forms the potential contribution of Lesotho to the fight against climate change and global warming, he stated [100].

The German Cooperation, GIZ, and the European Union are the project's funders. Its goal is to stop the country's water catchment area shrinkage and soil deterioration. He outlined the benefits of switching from water to hydrogen as well as the possible advantages for the nation, noting that green hydrogen is sometimes referred to as the fuel of the future. Green hydrogen, he explained, is produced by electrolyzing water, a process with zero carbon emissions that is driven by renewable energy sources like solar or wind. "We now have a tremendous chance to reduce transportation-related emissions and decarbonize the industrial sector. He stated that "green hydrogen might be the solution [100]."

Liberia has no active plan in adopting green hydrogen as a source of clean energy. The construction of a 15 MWh solar power plant that will be connected to a 10 MWh battery storage system is being overseen by experts hired by the Liberian government and its national utility, LEC. The objective is to offer the nation a low-cost, clean, and trustworthy arrangement with a five-year initial term, as well as a fast and flexible option for building a PV and battery storage power plant. Once constructed, the solar facility will be Liberia's first sizable photovoltaic plant. Still, the country's solar industry has advanced quite slowly thus far [101].

The most recent addition to the group of three plants in the SAVA region of Madagascar is a solar PV power plant [102].

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According to Armand F. [13], Mali is the first country in SSA to have exploited hydrogen for electrification, and about 98% pure hydrogen at $28x10^6 m^3 H_2$ was discovered in the northern part of the country "Bourakebougou" [103]. There is currently an ongoing plan by the Petrochemical Company of Mali (Firm Petroma) to electrify the entire country using hydrogen technology in the near future [13].

An initial deal to create a green hydrogen project in Mauritania was signed in March 2023 by German project developer Conjuncta GmbH and Egypt's Infinity Power Holding, a partnership between Infinity and Abu Dhabi's renewable energy organization Masdar. Upon completion, the four-phase project is anticipated to yield up to eight million tons of green hydrogen or other renewable fuels derived from non-biological sources. With operations in over 40 nations, Masdar has committed to or made investments in projects valued at over $30 billion. The company has an ambitious goal to increase its capacity to at least 100 gigawatts of renewable energy globally by 2030. It is currently expanding its clean energy portfolio. The majority of this capacity will originate from solar and wind technology [104].

In [105], a heuristic size optimization approach that minimizes the levelized cost of hydrogen generation is proposed for water electrolyser sizing. The possibility for producing hydrogen from the surplus electricity of a PV battery system intended for the Island of Mauritius is examined using the algorithm.

Initially, in the first quarter of 2024, Jearrard Energy Resources (JER), United Kingdom's energy company, plan to collaborate with other industrial partners to develop solar-to-hydrogen plants in Southern Africa. The company has secured enough land in Mozambique to build a 12 GW peak solar-to-hydrogen facility, which will generate more than 4000 tonnes of hydrogen daily. JER's innovative hybrid model aims to meet the world's growing demand for green energy and expedite the delivery of much-needed green hydrogen. Next, starting in the third quarter of 2024, are fresh prospects in Southern Africa, including South Africa, and additional facilities in Mozambique [106,107].

Namibia has been listed in [108], as one of the countries in partnership with Germany for production and exportation green hydrogen. Namibia has a large flat-land with low population density along with estimated sunshine of about 3500 hours per annum, which is more than two times of availability of sunshine in Germany. Such conditions provide huge potentials for abundance production of green hydrogen in Namibia [98].

Germany has provided up to 40 million Euros as an economic stimulus package for the facilitation of the identification of the green hydrogen production hubs in Namibia [30,66]. Namibia has the greatest potentials of producing green hydrogen in abundance than other member countries in SSA due its vast unused space, high wind speed and high availability of sunshine [30,108].

It is estimated by the Federal Ministry of Education and Research (BMBF) Germany [108], that hydrogen produced in Namibia will probably have the most competitive (world standard) hydrogen price up to 2.00 Euro per kilogramme. Such could form a huge locational benefit for hydrogen produced in Namibia.

The estimated amount of green hydrogen demand by German industries alone from Namibia scales up to 1.7 billion tonnes per annum and such is expected to grow further in the near future [30,66].

However, it might be over-ambitious for Namibia to plan exportation of green hydrogen as early as 2025 [30].

Niger Republic and German Based Emerging Energy Corporation Sign Agreement in February 2020, to produce and export green hydrogen from the Republic to other parts of the world. Niger Republic has solar energy in abundance that ranges from 5 to 7 $kWh/m^2/day$, with average sunshine of 8.5 h/day [65,109–111]. Hence, harnessing the abundance energy for the purpose of producing green hydrogen is highly feasible. In that instance, the country has the aim of increasing its renewable energy mix to 30% by the year 2030 (excluding biomass energy) [65,112].

Nigeria has seen an upsurge in talks, workshops, and conversations around green hydrogen since the beginning of 2023. Nigeria's potential and readiness for green hydrogen production and regional leadership are suggested by the nation's gas distribution infrastructure, the existence of several potential offtaker industries, port infrastructure, and experience with the renewable energy sector. These factors could pave the way for an accelerated transition towards utility-scale infrastructure. After entering the blue hydrogen market, Nigeria's oil and gas sector—which is one of the biggest in Africa—may potentially venture into the green hydrogen market [113].

The development of Nigeria's utility-scale renewable energy sector is one intriguing prospect that Nigerian green hydrogen production may have. It has proven challenging to build and link to the national grid large-scale solar power plants in Nigeria, such as those with 50 megawatts or more. In addition to ongoing trade disputes, the government's financial constraints make it difficult to provide "risk guarantees." Large-scale renewable energy investments have a great chance with green hydrogen generation, which may also spur project development and investment in related areas. Investing in green hydrogen can help the country's reserves and GDP, especially in view of its declining foreign exchange profits [113].

Germany has also established hydrogen offices in Angola and Nigeria to speed up the plan for hydrogen production. However, these two countries with Algeria have the largest natural gas reserves globally. Therefore, the production of blue hydrogen might be one of their best option to diversify their fossil fuel dependent economies [3,114].

Reunion Island, a French overseas territory, wants to generate all of its energy from renewable sources by the end of 2028. Activists differ on the approaches even though they agree on the aim [115].

Rwanda has had an energy crisis for the past 20 years, primarily as a result of low investment in the energy industry. Rwanda is endowed with a wealth of renewable energy resources, including geothermal, solar, biomass, and methane gas found in Lake Kivu. Wind energy is also presently being investigated. The government has recently prioritized developing alternative energy projects for rural areas where access to the national grid is still challenging as well as expanding its national electrical infrastructure through the development of hydro power generation projects [116,117].

Sao Tome and Principe, Senegal, Sierra Leone Sudan and South Sudan are listed among the 55% of African nations that have highlighted green hydrogen as a crucial climate technological solution in their National Determined Contributions (NDCs) [118].

Senegal can reap various advantages from augmenting its renewable energy portfolio, such as decreased trade balance expenses due to diminished reliance on imported fossil fuels, the possibility of generating employment opportunities, heightened energy accessibility, and a decrease in greenhouse gas emissions. Senegal now relies on imported fossil fuels, unlike many strongly coal-dependent nations, and its current fossil fuel fleet does not employ a big number of people. In the medium to long run, Senegal might be able to take advantage of chances to export hydrogen and other fuels derived from renewable sources [119].

In the medium to long term, Senegal's abundant renewable resources might also manufacture hydrogen for domestic use and possibly export, despite substantial obstacles. One of the biggest obstacles to hydrogen production is probably going to be finding fresh water for electrolysis, which will get harder as the climate changes. The generation of desalinated water, which is eventually needed for larger-scale hydrogen production, must be carefully controlled to preserve nearby marine habitats and fish stocks, which are vital to the local fishing economy [119].

The Public Utilities Corporation (PUC) Seychelles has acknowledged the necessity of switching to a cleaner fuel in the near to medium term. As a result, conversations about future conventional generation projects, including switching to hydrogen, have been discussed with the Masdar team. The direction for implementing a comprehensive Seychelles Electricity Generation Plan was the main topic of discussion during the meeting with senior manager of project management services Simon Bräunigerr and Masdar chief green hydrogen officer Mohammed Abdelqader El Ramahi [120].

Given its position, Somalia offers a great deal of potential for producing solar energy on a huge scale. Nevertheless, there is currently no plan in place to use the energy for the manufacture of green hydrogen [121].

South Africa has a potential competitive merit towards production and exportation of green hydrogen fuel and aspires to replace the existing natural gas method of hydrogen production with the renewable energy method that yields green hydrogen. The South African Department of Science and Innovation along with its partners in their Hydrogen Valley Feasibility Study Report (HVFSR), have identified four major green hydrogen hubs, namely: Durban, Johannesburg, Limpopo and Mogalakwena hubs. German development bank kfw, (as at May 2021) has offered to support South Africa with 200 million Euros scheme to assist in establishing green hydrogen projects across the country [122].

The goal is to be producing about 500,000 tonnes of green hydrogen per year by 2030, and to be deploying up to 10GW and 15GW of electrolysis by 2030 and 2040 respectively.

Some of the listed objectives in terms of green hydrogen production are

- to create an export avenue for green hydrogen in South Africa
- to transform the power sector from fossil fuel to green energy system.
- to decarbonize all transport and heavy industrial systems.
- to locally produce green hydrogen network modules.

Moreover, South Africa has up to 70 identified and classified key actions [123], by the Department of Science and Innovation in their Hydrogen Soceity Roadmap (HSRM). The implementation of such plans is assumed to set the pace for obtaining a sustainable workforce that will be green-growth oriented and inclusive.

However, South Africa is the 13th highest contributors towards climate pollution in the whole world and the 1st in Africa [124,125]. The energy sector of South Africa ranks number 1 source of climate pollution among G20 countries, due to her major dependent on coal as a primary source of energy. Sasol (apart from ESKOM) in its energy processing such as its Secunda coal-to-liquid fuel plant forms the major contributor of climate pollution in South Africa [125].

An investigation of the possibility of producing hydrogen from biomass, solar energy, and wind has been carried out for the first time in West Africa, specifically in Togo. In Togo, solar power and biomass can be used to produce hydrogen. According to the report, biomass is the most valuable resource. A maximum of 100,000 megatons of hydrogen can be produced in Togo by solar and biomass energy. Presently, the nation uses biomass, but it's for different purposes that exacerbate climate change. The switch to green hydrogen would be beneficial for reforestation in areas where biomass is declining, climate change adaptation, and satisfying the population's increasing energy needs. It would also strengthen the decentralisation process [4].

In addition, Hydrogen Africa (HyAfrica) seeks to evaluate the socioeconomic effects of natural hydrogen resources in potential areas of Morocco, Mozambique, South Africa, and Togo. Co-funded by the European Union under the Euro-African Renewable Energy Research and Innovation Partnership (LEAP-RE) [126].

In November 2022, the French-based independent power producer HDF Energy and the Ugandan Ministry of Energy and Mineral Development signed a memorandum of understanding (MoU). The parties will create the nation's first green hydrogen power plant under the terms of the MoU [127–129].

Uganda, which presently relies on thermal and hydroelectric power plants but is keen to increase its generating capacity, particularly in renewable energy, will have its first hydrogen power plant if the plan is implemented [128].

By eliminating the intermittent nature of renewable energy sources through hydrogen long-term energy storage, the proposed first non-intermittent renewable energy power plant in Uganda is expected to provide a supply for the equivalent of 24 hours a day throughout the year. This plant foreshadows the future of renewable energy sources in Uganda [129].

A French developer of green hydrogen, HDF Energy stated on November 15, 2023, that it has partnered with Falcon Capital Dakhla, a Moroccan business, to build an 8 GW green hydrogen production project "in the Dakhla region of Morocco. However, Dakhla is not in Morocco; rather, it is in the region of the Western Sahara that Morocco has militarily and illegally annexed since 1975. The territory is confirmed by HDF Energy's press release, which also states that preliminary environmental and social impact assessments, phased planning, feasibility studies, and project designs have already been completed during the previous two years [130].

There are several projects that demonstrate Zambia's dedication to utilizing the advantages of this clean energy source, even though the nation is still in the early phases of creating its green hydrogen sector. A collaborative effort involving the government of Zambia and foreign partners, the Zambia Green Hydrogen Initiative is one example. Its goal is to investigate and promote the use of green hydrogen for a range of uses, such as energy storage and transportation. Zambia's future use of sustainable energy has enormous potential because to green hydrogen. A solid basis for the electrolysis-based synthesis of green hydrogen is provided by the nation's copious renewable energy resources, including wind and solar energy. Zambia may take advantage of several opportunities and overcome significant obstacles by adopting this clean energy source [131].

Zimbabwe Electricity Transmission and Distribution Co. (ZETDC) and HDF Energy have reached an agreement in March 2023, to build Zimbabwe's first utility-scale green hydrogen power plant. The project is being developed by HDF Energy in the southeast Zimbabwean province of Manicaland, although the majority of the nation's generation resources are located in the northwest. A substation 4 km from the project site would supply the grid with continuous green power from the plant, according to HDF Energy, whose yearly electric production is expected to exceed 178 GWh [132].

The $300 million Middle Sabi Renewstable® project will be situated in Zimbabwe's Manicaland Province, which borders Mozambique, within the multi-technology Chipangayi Renewable Energy Technology Park (RETPark). Approximately 178 GWh will be produced annually, which is sufficient to supply 220,000 Zimbabwean households with power. A specific Power Purchase Agreement (PPA) has been used to commercialize the electricity, and the agreement has established a framework for both businesses to carry out collaborative technical and administrative work [133].

Based on IEA data, hydropower accounts for 57% of Zimbabwe's electricity mix, while coal accounts for 41%. The nation's hydroelectric dams haven't operated as well as they could in recent years due to droughts, which has made the nation utilize more coal. Zimbabwe expanded capacity at its flagship Hwange power plant and reduced power outages by commissioning a new 300 MW coal-fired unit early in 2023. Zimbabwe aims to cut its greenhouse gas emissions by 40% by 2030, but this action could completely undermine that goal. With its National Renewable Energy Policy, Zimbabwe intends to commission 1,100 MW of renewable energy capacity by 2025 and 2,100 MW by 2030 in order to accomplish its emissions reduction targets while expanding electricity availability [133].

By adding a hydrogen plant, Zimbabwe would be able to diversify its energy sources even further and establish itself as a leader in the growth of the hydrogen industry throughout Africa [131,133].

5. Discussion

The SSA region is projected to be the main hub of green hydrogen production by the year 2050 [30,134]. However, a significant expansion of renewable energy generations and water availability management are still needed for the successful realisation of the green hydrogen production targets in SSA [30].

Africa in general, now has 114 GW of stated electrolyzer pipeline capacity, with Sub-Saharan countries accounting for 61 GW of that amount, according to Rystad Energy [132]. According to the report [132], SSA region has an announced electrolyzer pipeline with a capacity of roughly 70 GW, of which 50% is expected to come from Mauritania and the remaining 50% from South Africa and Namibia. South Africa is home to about 90% of the world's reserves of platinum group metals, which are essential for the manufacturing of polymer electrolyte membrane (PEM) electrolyzers. Hence, SSA is in a highly advantageous position for the creation of a sustainable green hydrogen economy.

Key indicators of the readiness of each member country of SSA in hydrogen production in both small-scale and commercial aspects are summarised in Table 2. Such reveals potential SSA member countries in which foreign or local investors can still approach for hydrogen production purposes.

The race to generate green hydrogen is just getting underway for African nations [118].

As a critical climate technological option, 35 out of 48 SSA nations—or more than 72%—have included green hydrogen in their NDCs, and out of the 35, only 4 or 8% SSA member countries have implemented the actual production of hydrogen but not in a large scale yet as shown in Figure 6. Moreover, 27 out of the 35 SSA member countries are in partnership plan with the western world; while 8 SSA member countries are not yet into any partnership plan but they have the local hydrogen production plan. However, there is no existing plan for hydrogen production in 13 member countries as shown in Figure 7 and Table 2. The development of green hydrogen production infrastructure, which enables the conversion of renewable energy sources into transportable and valuable products, is a major priority for NDCs in their efforts to seize the first economic possibilities with zero carbon emissions in history [118].

Recently approved large-scale green hydrogen projects require both governmental and private sector participation, in addition to the use of solar and wind energy resources. Through the identification of partners and the mobilization of internal and external resources at the national level, private-public partnerships have the potential to fortify the green hydrogen business ecosystem [118].

Africa in general is at the forefront of the global competition to produce green hydrogen. Green hydrogen is a critical climate technology solution that has been included in the NDCs of over 55% of African nations (30 out of 53). And 90% (27 out of 30) of the 30 member countries are from SSA region. The NDCs are primarily focused on developing green hydrogen production infrastructure, which enables renewable energy sources to be transformed into transportable and value-added products, in order to unlock the world's first zero-carbon industrial potential. The UN Climate Technology and Network (CTCN), in collaboration with the West African Development Bank (BOAD), hosted an event in Benin on October 4-5 2023. It is intended for 16 National Designated Entities (NDEs) in the African region who are interested in developing national hydrogen strategies for the energy, business, and industry sectors [118].

Regionally, there is a concerted attempt to turn the continent into a hub for the production of hydrogen. The African Hydrogen Partnership (AHP) has been established to identify possible landing zones and bridgeheads for the first steps in the development of green hydrogen in Africa. The particular markets mentioned are Egypt, Djibouti, and Kenya. Nigeria, Tanzania, Ghana, Morocco, Ethiopia, and South Africa [135].

The Democratic Republic of the Congo, Rwanda, Burundi, Uganda, Kenya, Tanzania, South Sudan, and Uganda make up the East African Community (EAC), which is endowed with an abundance of lakes and rivers. Several famous bodies of water can be found in the area, such as the powerful Nile and Congo rivers, Lake Victoria, Lake Tanganyika, and Lake Malawi. The development of hydrogen infrastructure and technologies through cooperative efforts amongst EAC members will spur the transition to a more affluent and cleaner energy landscape. The East African Community can ensure a better future for its people and the region's distinctive lakes and rivers by embracing hydrogen and realizing its full potential in the areas of energy, economy, and the environment [136].

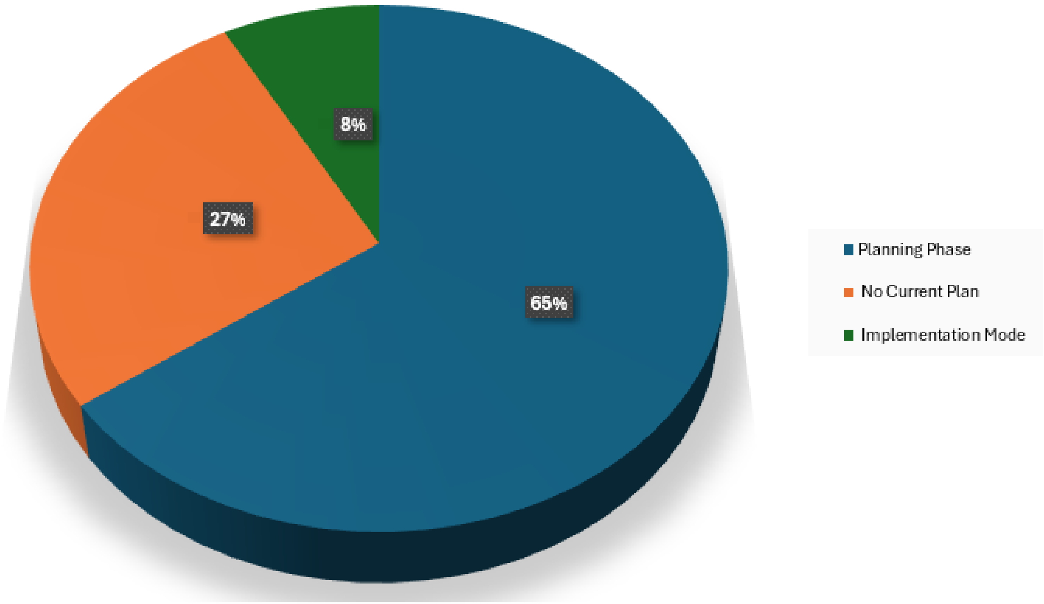

Figure 6. Current Status of Hydrogen Production Activities in Sub-Saharan African Countries.

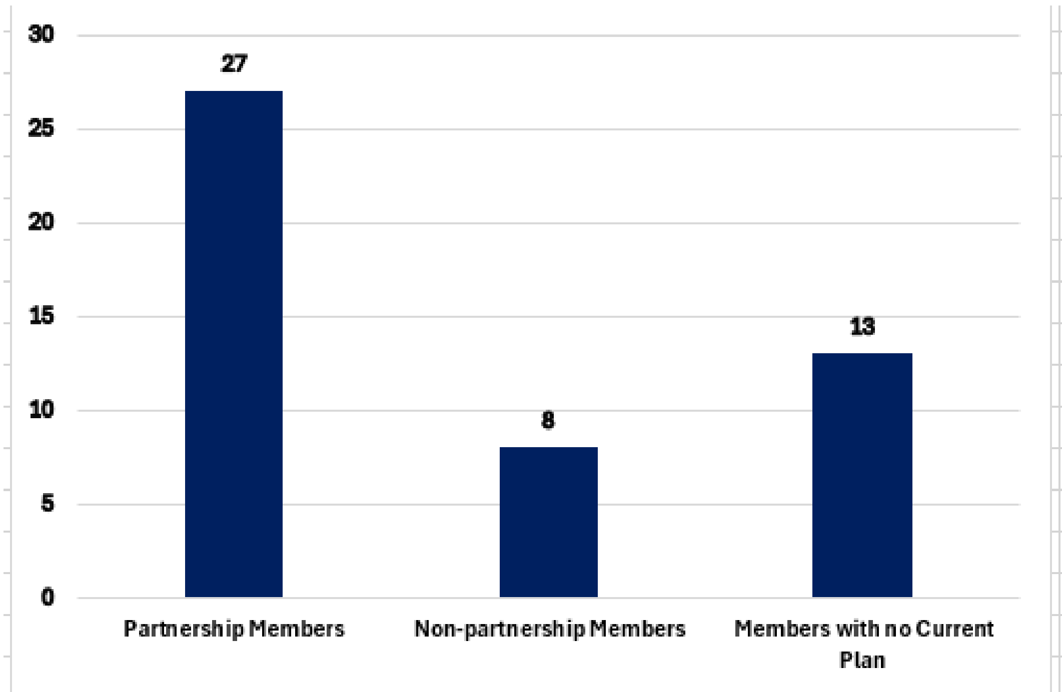

Figure 7. Current Status of Sub-Saharan African Countries in Partnership for Hydrogen Production.

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Table 2. Hydrogen production status indicators in sub-Saharan African countries

SSA Countries	Production Plan	Implementation	Internal Funding	Partnership Funding
Angola [30,69]	✓	×	×	✓
Benin[8]	×	×	×	×
Botswana [70,71]	✓	✓	✓	×
Burkina Faso [15,72]	✓	✓	✓	✓
Burundi [136]	×	×	×	×
Cameroon [35]	✓	×	×	×
Cape Verde [73]	✓	×	×	✓
Central African Republic [79]	×	×	×	×
Chad [74]	×	×	×	×
Comoros [77]	✓	×	×	×
Congo (Brazzaville) [78]	✓	×	✓	×
Congo (Democratic Republic) [79]	✓	×	×	✓
Côte d'Ivoire [80]	×	×	×	×
Djibouti [135]	✓	×	×	✓
Equatorial Guinea [82]	×	×	×	×
Eritrea [83]	✓	×	×	×
Ethiopia [85,86]	✓	×	×	✓
Gabon [87]	✓	×	×	×
Gambia [88,89]	✓	×	×	✓
Ghana [90,92–94]	✓	✓	✓	×
Guinea [95]	×	×	×	×
Guinea-Bissau [95,96]	✓	×	×	✓
Kenya [97–99]	✓	×	✓	✓
Lesotho [100]	✓	×	×	✓
Liberia [101]	×	×	×	×
Madagascar [102]	×	×	×	×
Malawi [136]	×	×	×	×
Mali [13,103]	✓	✓	✓	×
Mauritania [104]	✓	×	×	✓
Mauritius [105]	✓	×	×	×
Mozambique [106,107]	✓	×	✓	✓
Namibia [30,66,98,108]	✓	×	×	✓
Niger [65,109–111]	✓	×	×	✓
Nigeria [9,113]	✓	×	×	✓
Réunion [115]	✓	×	×	✓
Rwanda[116,117]	×	×	×	×
Sao Tome and Principe [118]	✓	×	×	✓
Senegal [118,119]	✓	×	×	✓
Seychelles [120]	✓	×	×	✓
Sierra Leone[118]	✓	×	×	✓
Somalia[121]	×	×	×	×
South Africa	✓	×	✓	✓
Sudan[118]	✓	×	×	✓
Swaziland	×	×	×	×
Tanzania[135]	✓	×	×	×
Togo [4,126]	✓	×	×	✓
Uganda[127–129]	✓	×	✓	✓
Western Sahara[130]	✓	×	✓	✓
Zambia [131]	✓	×	✓	✓
Zimbabwe [131,133]	✓	×	✓	✓

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6. Conclusions

This study has reviewed the current level of Sub-Saharan African nations' preparedness to adopt green hydrogen as a way to mitigate climate change impacts, alleviate local energy supply issues and strengthen their individual economies.

Green hydrogen's promise in sub-Saharan African countries like South Africa, Namibia, and Kenya runs the risk of being disregarded as a driver of necessary sustainable energy and economic development while Europe leads investment into the MENA area. The number of people in sub-Saharan Africa without access to electricity increased in 2020 for the first time since 2013, partly as a result of the effects of COVID-19. Up from 74% before the pandemic, the region now houses 77% of the world's population without access to power. With the region's current population of 1.18 billion predicted to double to over 2.2 billion by 2050, energy demand is expected to climb considerably over the next 30 years.

However, promoting sustainable energy development in sub-Saharan Africa is not only a crucial aspect of a fair global energy shift, but it would also be a wise financial move for both parties. In comparison to Europe, where the average yield is 3.44 kWh/kWp/day, the average long-term practical yield for a photovoltaic solar energy plant in the region is 4.34 kWh/kWp/day. The region has over 30% of its area capable of generating more than five kWh/kWp/day of photovoltaic output; Namibia, South Africa, Botswana, and Ethiopia have some of the highest concentrations of solar intensity. The potential for wind energy in Sub-Saharan Africa is likewise substantial, especially around the shores of Namibia, South Africa, and Kenya. By 2030, if renewable energy capacity is successfully developed, green hydrogen produced in Africa might be produced at a cost of less than € 2 per kilogram.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	African Hydrogen Partnership
AMPCO	Atlantic Methanol Production Company
CCS	Carbon Capture Storage
CTCN	Climate Technology and Network
CWP	Continental Wind Partners
DRC	Democratic Republic of Congo
EAC	East African Community
ECOWAS	Economic Community of West African States
EER	Energy Efficiency Ratio
FFI	Fortescue Future Industries
GE	General Electric
GERD	Grand Ethiopian Renaissance Dam
GMER	German Ministry of Education and Research
GoG	Gabonese Government
HDF	Hydrogène de France
HFCVs	Hydrogen Fuel Cell Vehicles
HPTSU	Hydrogen Production, Transportation, Storage, and Usage
HRS	Hydrogen Refuelling Station
HTE	High Temperature Electrolysis
IRENA	International Renewable Energy Agency
JER	Jearrard Energy Resources
MAAFR	Ministry of Agriculture, Animal and Fishery Resources
MILP	Mixed Integer Linear Programming
MoWE	Ministry of Water and Energy

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MoU	Memorandum of Understanding
NDCS	National Determined Contributions
NDP	National Development Plan
OFLC	Optimised Fuzzy Logic Control
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PUC	Public Utility Corporation
SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
SMR	Steam Methane Reforming
UAV	Unmanned Aerial Vehicle
WASCAL	West African Science Service Centre on Climate Change and Adapted Land-use
ZETDC	Zimbabwe Electricity Transmission and Distribution Co.

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