UNIVERSITY OF CAPE COAST

A TECHNO-ECONOMIC ANALYSIS OF GREEN HYDROGEN ENERGY PRODUCTION IN WEST AFRICA

KOKOUTSE GAWOU

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BY

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DECLARATION

Candidate's Declaration

I hereby declare that this dissertation is the result of my own original research and that no part of it has been presented for another degree in this University or elsewhere.

Candidate's Signature: **Date:** 27th May 2024

Name: MR. GAWOU KOKOUTSE

Supervisor's Declaration

I hereby declare that the preparation and presentation of the dissertation were supervised in accordance with the guidelines on supervision of dissertation laid down by the University of Cape Coast.

Supervisor's Signature: **Date:** 28th May 2024

Name: DR. GERSHON OBINDAH

ABSTRACT

In most of the south global, renewable energy technology development and investment represents serious challenges. This study analysed the prospects of green hydrogen generation in five West African countries namely: Ghana, Nigeria, Mali, Niger and Senegal. with a focus on its potential as an energy export. The study first, reviewed the current state of hydrogen generation and consumption globally, along with the energy landscape in West Africa. It explored the possibilities and obstacles for low-carbon hydrogen production in the study countries, including access to electricity, and water, the availability of renewable energy sources, government support, and technological advancements. With a quantitative mythology approach, this study concluded that the five countries hold substantial promise for green hydrogen production and that these countries could become major green energy producers and exporters in the region. Despite this promising outlook, the paper also identifies several challenges that need to be addressed to fully harness the potential of hydrogen generation in Ghana, Nigeria, Mali, Niger and Senegal. These include the non-financial viability of green hydrogen energy generation, the high cost of technology, the need for significant investment in infrastructure and research, and the need for supportive policy frameworks and regulatory frameworks. Overall, the study suggests that hydrogen production and export could provide significant opportunities for economic expansion and sustainable development in these countries. However, realizing this potential will need a coordinated effort from countries, private sector actors, and international partners, to address the challenges and seize the opportunities of a hydrogen-based energy transition.

KEY WORDS

Green Hydrogen

Solar energy

Photovoltaic panels

Water electrolysis

Electrolyser

Renewable Energy

Techno-economic analysis

Megawatt hours

Kilogram of hydrogen

Kilowatt-hour

global horizontal irradiations

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DEDICATION

To my lovely family and friend especially Agbagba Grace Mawunawe,

Abgagba Bernice, and Ruth Falia.

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CHAPTER ONE

INTRODUCTION

West Africa, a region confronted with many challenges including limited access to energy, high energy costs, greenhouse emissions and environmental degradation, has the potential to significantly benefit from Green hydrogen as an alternative and clean source (Ballo et al., 2022a). hydrogen in green form is created from renewable energy sources and presents encouraging solutions to Africa’s energy problems (Mukelabai et al., 2022). Also, the dependency on non-renewable fuel, to meet the increasing energy demand worldwide has evolved into a driver of weakness observed in Africa’s national economies at the beginning of this decade. However, given the substantial prospect for the production of sustainable power sources and its ample natural gas reserves, West Africa is well-positioned to take advantage of the possibilities provided by hydrogen. For instance, according to IEA & IRENA (2020), developing countries are just beginning to adopt hydrogen technologies, and several issues need to be resolved before the hydrogen economy in West Africa can reach its full potential.

Hydrogen may be obtained through different pathways and methods (Rahmouni et al., 2017). More resources worldwide have been focused on the assurance of the economy of hydrogen, hence this thesis seeks to investigate the feasibility of producing hydrogen in West Africa from solar energy source. The study focuses on the techno-economic opportunities, decarbonisation challenges, policy and regulatory frameworks essential for developing West Africa's hydrogen economy development. Furthermore, this thesis intends to contribute to the existing literature on the possibility of hydrogen in achieving SDG7 inclusive economic growth, and the decarbonisation agenda.

Background to the Study

Hydrogen is not only known to be the most intensive energy carrier molecule but also, an environmentally friendly and clean energy source with the capacity to address the energy challenges in the future of a decarbonised world by supporting the region's transition to a low-carbon economy (Nefedova et al., 2021; Bennet. T., 2020)

Historically, the association of Hydrogen production, consumption and industrialisation with the existence of humankind started in the second industrial revolution when the petroleum fuel discovery was in abundance and petroleum resource was the main raw material for the production of hydrogen, (Howarth & Jacobson, 2021). For many years, numerous industries such as; steel manufacturing, electrochemical, upstream and midstream oil and gas industries have employed hydrogen as a source of energy carrier in the extractive industry sector. In addition, it is heavily used as a component in the manufacturing of ammonia fertilizers in the agricultural sector industries, (Domínguez et al., 2022). World Bank and IEA (2018) observed that up until 2018 this decade, more than 98% of hydrogen sourcing is heavily dependent on fossil fuel, from this portion only 6% of extracted natural gas is used in H_2 production which is mainly used for methanol production in the steel industry. Furthermore, in global hydrogen consumption, about 74Mtons of pure hydrogen is mostly employed in the manufacturing of ammonia in the refining sector and 45Mton of hydrogen is used in blending with other gases.

Moreover, in other studies, Al-qahtani et al. (2021) reported in their work that out of 60 million tonnes of hydrogen generated annually, approximately about 96% are obtained from fossil fuel reformation feedstock that is 49% natural gas, 29% liquid hydrocarbon, and 18% coal which is engineered into high CO_2 emissions. The remaining 4% is generated through water electrolysis, which is solely regarded as a decarbonisation source. In contrast, Howarth and Jacobson (2021) in their quest to answer the question "*How green is green Hydrogen*?" admitted that even though green hydrogen presents a positive effect on the decarbonisation of the energy sector agenda in the net-zero scenario by 2050, however, greenhouse emissions from the generation of green hydrogen may seem far from a low carbon process. For instance, the emission from the supply of electricity may cause some greenhouse CO_2 emission footprint during the transmission and production of power. Nonetheless, the study added that this emission will be much less than the emission from natural gas or coal for power in producing blue hydrogen. According to Bhandari (2022), West Africa is one of the areas of the world which is significantly reliant on fossil fuels, particularly oil, and gas, for its energy needs, fortunately, it does not help with significant greenhouse gas emissions as compared to developing world, but rather experiencing the effects of climate change.

Mulako et al. (2022) asserted that West Africa is well-positioned to capitalize on the opportunities shown by hydrogen, given the significant potential for renewable energy production. However, the implementation of hydrogen technologies in the region is still in its initial phases, and several challenges must be tackled to realize the potential of the hydrogen economy in West Africa.

(IRENA, 2022; Bhandari, 2022; and Abouseada et al., 2022), additionally, pointed out that some of the challenges include; the lack of infrastructure for hydrogen production, distribution, and storage, the high cost of hydrogen technologies, and the need to increase awareness and understanding of hydrogen technologies among public officials, and industry participants. To overcome these challenges, public authorities in West Africa must create a supportive policy and regulatory framework for the hydrogen economy, which includes policies that promote the adoption of hydrogen technologies, as well as regulatory frameworks for hydrogen production, distribution, and storage as suggested by Ballo et al. (2022a).

In addition, Ballo et al. (2022b) emphasized that the prospects for the production of green hydrogen in West Africa are significant, given the potential for renewable energy production in achieving SDG7. Several pilot projects for hydrogen production and use are currently underway in West Africa, including the Ghana National Gas Company's blue hydrogen project and Nigeria's hydrogen-powered bus project. These pilot projects can serve as a blueprint for the advancement of a hydrogen-based economy in West Africa and demonstrate the potential of hydrogen to support sustainable and inclusive growth in the region as heightened by (World Energy Special, 2019 and Mukelabai et al. 2022). From their analysis, it is observed that the acceptance of green hydrogen production in West Africa can contribute to reducing energy costs, improving energy access, and aiding the region's moving to a low-carbon economy. By exploring the opportunities, challenges, policies and regulatory frameworks required for hydrogen acceptance in the region, this thesis aims to contribute to the ongoing debate on the role of hydrogen in achieving sustainable and inclusive growth in West Africa.

Also, aside from the difficulties highlighted in the background, some technical challenges and issues require attention for the successful execution of green hydrogen in West Africa. For instance, (Cloet, 2022; Mukelabai, 2022; & Siew, 2019) emphasized that green hydrogen requires the implementation of both solar energy and water electrolysis technologies, which are not widely available in other parts of the world which translates the same trend in the West African region. Therefore, there is a need for the transfer of technology and capacity enhancement to facilitate the implementation of these technologies in West Africa.

Similarly, the production of green hydrogen requires substantial investment in sustainable energy infrastructure, such as wind and solar power, which may not be readily available in some parts of the region. Therefore, there is a need for the expansion of energy infrastructure and investment in research and development to enhance the efficiency of renewable energy technologies in the countries as outlined in other parts of the world (Kalbasi et al., 2021). Their study further suggested that the values of inclusivity and sustainability should lead to the acceptance of hydrogen technologies in West Africa. This means that these technologies ought to enhance people's quality of life in the area rather than worsen already existing social and economic inequalities. Therefore, it is essential to create laws and policy frameworks that support the hydrogen economy's inclusive and sustainable expansion.

Furthermore, Abouseada and Hatem (2022) stipulated that implementing blue and green hydrogen generation successfully in West Africa necessitates a multifaceted strategy that takes into account socio-economic, policy, and technical issues. Moreover, Lewis (2019) said that the potential for international cooperation and partnerships is a crucial factor to take into account when analysing the prospects for blue and green hydrogen production in West Africa. The application of hydrogen technologies demands a sizable investment and specialized knowledge that might not be easily accessible in the area. As a result, partnerships and international corporations are required to allow the introduction of hydrogen technologies in West Africa. The study further suggested that various types of international cooperation are possible, including skill building, technology transfer, and joint R&D projects. For instance, developed nations with cutting-edge hydrogen technology could support the transfer of these technologies to West Africa and offer technical support to strengthen the ability of regional businesses and institutions. Also, regional cooperation and integration are crucial factors to take into account when analysing the possibilities for green hydrogen generation in West Africa. Because the countries of West Africa are connected by a shared energy market, collaboration among them can promote the growth of the regional hydrogen value chain.

Some studies also look at the aspect of the need for infrastructure. For instance, Bhandari (2022) explained that the need for the creation of regional infrastructure for hydrogen, transportation, and storage is just one example of how regional cooperation can take many different shapes. Furthermore, Bennet. T. (2020) stated that the establishment of a regional pipeline network could make it possible for hydrogen generated in one nation to be transported to neighbours, to help foster the growth of a local hydrogen economy. Also, the study suggested that the pooling of resources and knowledge that can be made possible by regional cooperation can also aid in addressing the technical and financial difficulties related to hydrogen technologies, likewise a collaborative research and development projects can make it possible for local businesses and organizations to exchange knowledge and skills.

The advancement of hydrogen technologies in West Africa can support in the achievement of the United Nations Sustainable Development Goals (SDGs) in addition to regional collaboration. The adoption of hydrogen technologies can help accomplish a number of SDGs, such as; achieving affordable and clean energy (SDG 7), addressing climate change (SDG 13), and advancing infrastructure, industry, and innovation (SDG 9). Given the region's natural gas reserves and potential for renewable energy production, the chances for blue and green hydrogen production in West Africa are promising. However, successful hydrogen technology deployment in the area necessitates a multifaceted strategy that addresses technical, policy, regulatory, socio-economic, cultural, and regional cooperation challenges. This thesis seeks to add to the ongoing debate on the role of hydrogen in achieving sustainable and inclusive growth in West Africa by investigating these challenges and opportunities (Bennet. T., 2020; IEA, Renewable Agency, 2021).

In all, while substantial research has been conducted on green hydrogen production globally, there is a notable lack of localized studies that address the techno-economic feasibility of such initiatives specifically within

West Africa. Existing literature primarily focuses on developed regions, leaving a gap in understanding the unique challenges and opportunities presented by West Africa's renewable energy landscape. This study seeks to bridge this gap by offering by providing a comprehensive analysis of solar irradiation potential, technological capabilities, and economic implications for green hydrogen production in West Africa. In doing so, it seeks to identify pathways for overcoming existing barriers and to contribute valuable insights into the region's transition towards sustainable energy solutions

Statement of the Problem

In particular, solar energy is abundant in West Africa and it can be used to produce green hydrogen, a flexible and sustainable energy carrier. Green hydrogen is produced through the electrolysis of renewable energy sources. Nevertheless, this hydrogen has the ability to improve the energy mix in the area and aids in the shift in low-carbon economies, mostly in naturally rich countries of the region such as; Nigeria, Senegal, Ghana, and others (Ballo et al., 2022b; Lens, 2022). This could completely realize the prospect of producing green hydrogen in West Africa; however, there are major economic, technical, and regulatory challenges that must be overcome.

In sub-Saharan Africa, mostly all countries are producing solar power. This shows an incredibly positive effect on climate change for decarbonisation in the region. Without paying attention to the social and economic ramifications arising from the activities of the renewable source, the increasing desire for rapid developmental success does not only make the green economy agenda a tool for successful regional sustainable economic growth, but also a great potential for effective decarbonisation platform (Löhr et al., 2022; IRENA, 2023 & Ballo et al., 2022c).

For instance, a study from Africa Energy Chamber suggests that, aside from 22.7 trillion cubic meters of natural gas reserves discovered, the Sub-Saharan Africa region has a vast supply of renewable energy yet to be unlocked (Bennet. T., 2020). These resources may be a game changer for Africa's low-carbon energy future, decarbonizing and powering cities, homes, businesses, and industries through a green hydrogen economy. However, this is expensive and less competitive than fossil fuels. Green hydrogen production may be hampered by the high capital cost of hydrogen production technologies, especially electrolysers. Additionally, due to poor infrastructure and low economies of scale, the expense of renewable energy sources for producing green hydrogen, like solar and wind power, can be high in West Africa (Ballo et al., 2022c; Löhr et al., 2022).

According to (Ballo et al., 2022b), West Africa lacks the infrastructure required for the massive creation, storage, and transportation of hydrogen at the moment. This involves the construction of pipelines, storage facilities, and filling stations necessary for the general use of hydrogen as a fuel. The study further explained that insufficient policy and regulatory frameworks, for instance, the absence of clear policy and regulatory frameworks that promote investment in hydrogen and usage, as well as limited supportive policies such as feed-in tariffs and tax incentives, can create uncertainty and risk for investors, thus, hindering the development of a viable hydrogen industry in the region.

Moreover, their findings elaborated that to increase the effectiveness, efficiency, and cost-competitive of hydrogen production technologies, especially those based on renewable energy sources, more money needs to be invested in innovation. Governments, businesses, and academia must work together to create and deploy new technologies to lower the cost of hydrogen production. Also, in maximizing the production of blue and green hydrogen in West Africa and supporting the region's sustainable economic development, these issues must be resolved. Additionally, funding is necessary for the creation and implementation of infrastructure for the production of hydrogen, and a region's ability to create a viable hydrogen industry may be hampered by a lack of access to financing.

In other regions, (Domínguez et al., (2022), replicating the same approach in financing for hydrogen production technologies may be challenging due to their high capital costs in South American countries, especially in the absence of favourable regulatory and policy frameworks. Ballo et al., (2022). in addition, noted that producing green hydrogen needs sophisticated equipment and knowledge that might not be easily accessible in the area. The growth of a sustainable hydrogen industry in West Africa may be hampered by technical issues like lack of dependable energy sources, restricted access to trained labour, and trouble maintaining equipment.

However, despite the challenges highlighted by some renowned researchers and other opposing debates that currently surround green hydrogen as good and alternative energy carriers, it is still a promising area for study and development. For example, (Ballo et al., 2022b; Bauer et al., 2022) analysed that this type of energy carrier could champion the current energy transition and replace all forms of non-renewable energy in all sectors such as transportation, production, clean cooking, to foster development and economic growth. Arguably, others indicated that there is a lack of investment and technology to make this transition. This means that more research is needed to determine which models and theories should be used in hydrogen economic growth studies, given the importance of reducing CO_2 in the atmosphere by way of mitigating climate change, as well as improving carbon financing currently being developed in developing countries.

(Kar, 2022) has demonstrated that renewable energy sources, especially solar and wind energy can be used to create green hydrogen through electrolysis, a flexible and sustainable energy carrier. (Bourne, 2012) explains that this form of energy production would help reduce greenhouse gas emissions more than other sources of energy. Also, according to IRENA and the IEA, both kinds of hydrogen have the potential to add to the region's energy mix and aid in the shift to low-carbon economies in West Africa.

The prospects for producing low-carbon energy in West Africa are promising, but there are a number of issues that have to be resolved before the region can completely realise its prospect as a renewable energy source. High production costs, limited infrastructure, inadequate policy and regulatory frameworks, lack of investment in R&D, restricted access to financing, technical difficulties, and negative public image are some of these obstacles. Governments, businesses, and academia will need to work together to develop and implement new technologies, advance supportive laws and regulations, and raise public awareness of hydrogen's advantages as a sustainable energy source in order to address these challenges (IRENA, 2022). To achieve all the above, this study will analyse the potential of solar energy generation available in West Africa that supports the development of a sustainable hydrogen industry. Further, it identified and proposed best practices from other regions.

Purpose of the Study

The purpose of this study is to evaluate the potential of green hydrogen production in West Africa, by accessing the current techno-economic prospects and the challenges that require attention to fully realize the potential of hydrogen as a low-carbon energy source in the region. Once the technical hydrogen generation potential using solar power sources has been evaluated, an economic analysis of the system's costs and benefits can be performed. On the other hand, this study may look at some technical challenges associated with the production of green hydrogen. In sum, this study seeks to solve the problem of the techno-economic viability of solar PV-based electrolytic systems of green hydrogen generation in some selected West African countries.

General Objectives

The main objective of this work is to analyse the feasibility and potential of green hydrogen energy production in selected West African countries through a comprehensive assessment of solar radiation availability, technological capabilities, and economic implications.

Also, the specific objectives of this study are as follows

1. To determine solar irradiation potential in selected countries in the West African region
2. To evaluate the potential of solar PV-based green hydrogen energy production in selected West African countries

3. To assess the economic viability of green hydrogen energy production in selected West African countries.

So, to achieve these objectives, this study will try to answer the following research questions;

Research Questions

1. What is the potential solar irradiation energy in selected countries in West Africa?
2. What is the quantity of green hydrogen energy that can be produced from a specific solar-PV-electrolytic system in selected countries?
3. What are the Net present value and levelised capital costs from a viable PV-electrolytic system investment?

Significant of the Study

This study focuses on the prospects for green hydrogen in West African countries. For instance, according to (Ballo et al., 2022a), these countries have abundant and limitless energy potential, particularly in solar and wind power, which can be used for green hydrogen generation. Similarly, (Lens, 2023; Ballo et al., 2022a) observed that there is a growing demand for energy in West Africa, as this is fueled by increasing population and economic development. Hydrogen can support meeting this demand while simultaneously cutting emissions. In addition, while there are some technological obstacles to overcome, such as the cost, operation and maintenance of solar panels, an electrolyser and storage technology for green hydrogen production are technically feasible in West Africa. Moreover, it has been observed that Hydrogen production can help reduce greenhouse gas emissions in West Africa, particularly if green Hydrogen is produced using renewable sources. Nevertheless, there is a need for supportive policy and regulatory frameworks to enable hydrogen production in West Africa, including incentives for investment, research and development. Overall, (Opeyemi et al., 2019) reported that the prospects of green hydrogen production in West Africa are positive, with the potential to aid to the region's energy transition and support sustainable development. However, significant investment and policy support will be needed to realize this potential.

Scope of Study

This study concentrates on selected West African countries such as, Niger, Nigeria, Ghana, Senegal, and Mali. These countries are selected for the analysis of green Hydrogen due to the availability of data. The study focused on the technological and economic feasibility cost of production and LCC of green hydrogen production. Finally, due to a lack of data and as a new research area, the study delimits itself to short-term data prospects for hydrogen in selected countries.

Limitations of the Study

The findings, conclusions, and recommendations of the study primarily apply to the selected countries, namely Niger, Nigeria, Ghana, Senegal, Mali in West Africa. Also, this study relied on secondary data from each member country, there may be limited data available on the potential for green hydrogen in West Africa, particularly in terms of the availability of technological and economic parameters for renewable energy sources. This could lead to concerns regarding potential biases that may not accurately reflect real events. and the choice technique like Excel used in the analysis. This is because the data obtained from the dataset on sampled countries were those which do have fair representation of required items on research questions very well. Also, the issue of technical barriers was encountered by the researcher during the data selection and analysis. In order to address this, data from well-known organisations such as (IRENA, 2022; BP 2021 and IEA, 2022) containing a dataset of the selected countries was used to assist in the secondary data selection.

Finally, the study's results could be influenced by the technological, infrastructural and economic challenges. For instance, green hydrogen production is technically feasible, but there are challenges in terms of accessing data availability, cost PV technology, electrolysis equipment, massive-scale investment, generation, distribution and the development of supportive policy frameworks hence, this could have the analysis in this study using secondary data obtained. To address this, the researcher is encouraged to consider other studies conducted in other regions in Africa or the world. This is because generalisation is more meaningful when data is collected from all the countries included in the study.

Definition of Terms

Some key terms and concepts that are relevant to this study are defined in this section.

They include:

1. Hydrogen: A chemical element with the symbol H and atomic number 1, which is the most abundant element in the universe. Hydrogen can be used as a fuel source, either directly or through fuel cells.

2. Blue hydrogen: It is obtained from natural gas with carbon capture and storage (CCS) technology, which captures carbon dioxide emissions from the production process.
3. Green hydrogen: It is obtained from renewable- energy sources, such as solar or wind power, through a process called electrolysis.
4. Carbon capture and storage (CCS): Carbon capture and storage (CCS) is a technology that captures carbon dioxide emissions from industrial processes and stores them underground to prevent their release into the atmosphere.
5. Renewable energy: Energy sourced from renewable sources, like solar and wind, hydro, geothermal, or biomass, that are replenished naturally over time.
6. Energy transition: The transition from conventional fossil fuel-based energy sources to renewable ones and other low-carbon energy technologies.
7. Sustainable energy development: Development that meets present needs without compromising the ability of future generations to fulfil their own needs, taking into account social, economic, and environmental factors.
8. Policy and regulatory framework: The laws, regulations, and policies that govern the production, distribution, and use of energy, and the incentives or penalties that may be put in place to encourage or discourage certain behaviours or investments.

By defining these key terms, the thesis will ensure that all stakeholders involved in the research have a common understanding of the concepts and terminology used throughout the study.

Organization of the Study

The study is organised in five chapters. Chapter One focuses on the study's introduction covering the background to the study, statement of the problem, the purpose of the study, research objectives, research questions, significance of the study, limitations, delimitations and organisation of the study. Chapter two comprises the literature review which provides background information on issues relevant to the study. Chapter Three outlines the research methods used, including research design and approach, secondary data analysis, and ethical considerations. Chapter Four analyses the results and discusses the study's findings. Finally, Chapter Five presents a summary, conclusions, and recommendations, along with suggestions for future research.

CHAPTER TWO

LITERATURE REVIEW

Introduction

Green hydrogen has emerged due to the global transition to sustainable energy sources, which is at the forefront of discussions surrounding renewable energy. Green hydrogen produced through electrolysis powered by low-carbon energy sources, offers an effective solution to the dual challenges of energy transition and climate change. In West Africa, a region rich in solar and wind resources yet facing significant energy access challenges, the potential for free carbon hydrogen generation is particularly compelling. Given its capacity to support the energy future, hydrogen is known among the most attractive alternative power sources. In addition to offering an alternative energy source to fossil fuels, hydrogen technology can greatly minimise greenhouse gas emissions. Production of hydrogen can help to meet the region's energy requirements in West Africa, where energy demand is expected to rise sharply in the near future. The goal of this literature analysis is to assess its viability, economic implications, and potential role in the region's energy landscape (Ballo et al., 2022; IRENA, 2022)

At the heart of this analysis is the understanding of free carbon hydrogen manufacturing technologies, primarily electrolysis, which separates water into hydrogen and oxygen using renewable electricity. The economic feasibility of this process hinges on several factors, such as the cost of renewable energy generation, the efficiency of electrolysis technologies, and the infrastructure necessary for the distribution and storage of hydrogen. This thesis will explore these key concepts while situating them within the broader context of West Africa's energy needs and environmental goals. By evaluating both technological advancements and economic frameworks, the analysis will provide insights into how green hydrogen can contribute to sustainable advancement in the region (Adedoyin et al., 2021).

In contextual relevance to this study, the West Africa is characterized by its wealth of clean energy options, particularly solar and wind, which are underutilized in meeting the region's energy demands. IRENA (2022) has highlighted that harnessing these resources could significantly enhance and fulfill their obligations under global climate accords, energy access and reliability. Moreover, as countries in West Africa strive to, the transition to green hydrogen presents an opportunity not only to cut down on carbon gas emissions but also to foster economic growth through new industries and job creation. This thesis will contextualize the potential for green hydrogen within these pressing regional challenges, emphasizing its role in achieving energy security and sustainability.

Renewable Resources Potential in West Africa

Most electricity networks in Sub-Saharan Africa (SSA) suffer from poor performance and technical instability as a result of ageing and lack of infrastructure. The waves of power deregulation, which are actually progressing in Europe and other rapidly rising economies, are unimpressive in the West Africa region. The vast majority of nations in the region have monopolistic views about how the power market operates, which is why the region's power sector has performed poorly, (Mohammed et al.; 2013). Also, Ouedraogo (2019) highlighted that the typical issues include low electricity availability, high power system losses, inadequate energy resource diversification, periodic power outages brought on by poor reliability, and insufficient funding methods. The study further explained that the recent surge in energy demand in West Africa's region has been largely attributed to population growth and demographic expansion. While biomass fuel and charcoal are receiving greater attention, other alternative sources such as solar, wind, and hydro are also being used in greater amounts in some regional countries, especially the renewable solar energy source used in this work.

Solar Energy Sources

Solar energy serves as a potential means to enhance energy security, particularly in regions with ample sunlight. Properly harnessed, solar energy can drive socio-economic advancement. It is derived from solar radiation, resulting from the positive enthalpy change within the sun, and transmitted in waveforms through solar thermal radiation. (Adedoyin et al., 2021).

Sambo, (2018) explained that this can be harnessed by converting the energy obtained by harnessing the solar body to convert it into electrical energy using sophisticated solar energy-catching sensitive devices such as PV panels. In the West Africa region, solar energy has not been fully utilised as compared to its untapped prospect. According to (Mohammed et al., 2013, Dagnachew et al.; 2017, Ouedraogo; 2019, Aboagye et al., 2021), solar energy potential across West Africa is unevenly distributed. However, the intensity of solar irradiation with solar PV potential which ranges between 15,411 TWh/year to 54,870 TWh/year and within West Africa, 25,473 to 25,938 TWh/year may be able to support the electricity required to operate an electrolyser for hydrogen production and supply to the grid. For the purposes of this work, the selected countries' yearly average solar global horizontal irradiations (GHI) ranges between 1850 kWh/m2/year to 2357 kWh/m2/year.

In other studies, for instance, (Mulako et al.; 2022), added that Solar energy is a plentiful resource freely available worldwide, offering immense potential for electricity generation through two main routes: photovoltaic (PV) systems and solar thermal systems utilizing concentrating collectors. However, their study highlighted several challenges related to solar energy's sporadic nature, pointing out that overcast and sunny situations can be successfully overcome by using a storage system. A battery bank serves as the storage device in a PV hydrogen production system, whereas a hot water tank or phase-change materials can be used in a thermal system. Ballo et al.; (2022a) pointed out that the anticipated potential for solar energy direct capture is huge. About 30% of the solar energy that enters the atmosphere of the Earth is reflected. The study also reported that nearly 10,000 solar energy reaches the Earth's surface several times more each year (3.901024 MJ) after it has been reflected by the atmosphere than is currently consumed globally. While the sporadic character of solar radiation does pose some limitations on the use of available technology, energy stored in a battery bank can still be used during off sunshine periods. PV systems cannot be utilized not only as standalone systems but also connected to the grid to provide continuous electric power throughout the day.

Hydrogen Production

Currently, coal gasification (18%), partial oxidation (POX) of crude oil products (30%), and steam methane reforming (SMR) account for the majority (roughly 48%) of the world's fossil fuel-based hydrogen generation (IEA, 2021; IRENA, 2018). The study allotted that when coal, natural gas, or lignite are utilized as feedstock, the equivalent kind of hydrogen produced is known as "black hydrogen," "grey hydrogen," and "brown hydrogen," accordingly. IEA, (2019) also added that natural gas can be reformatted using one of these three processes: auto thermal reforming (ATR), which combines SMR and POX, utilizes oxygen in the air as the oxidant and water as the source of hydrogen. Hydrogen fuel must be created using clean energy sources in order to be taken into account as a component of solution in energy transition. In the case of Norway, one method for producing environmentally friendly hydrogen on a big scale is natural gas extraction using SMR or ATR in conjunction with CCS technology. The standard SMR method typically yields hydrogen with a 95% purity level, which is appropriate for use in energy production (Hytron, 2021; Hydrogen, 2020).

Hydrogen must undergo a purification process to reach the standard purity level, which is set at 99.95% and 100%, respectively, if it is intended for use as feedstock in industrial processes or as fuel for fuel cells in transportation sector (Howarth & Jacobson, 2021). Electrolysis is another well-developed application of creating carbon-lean hydrogen, but it only contributes to about 4% of the world's current production. In this process, power is used to separate hydrogen from oxygen in water (IEA, 2020). The hydrogen produced using this technique is referred to as "green hydrogen" provided that the electricity is produced using renewable energy. Also, according to Rahmouni et al. (2017), a refining procedure is not necessary because hydrogen obtained by water electrolysis has a purity level of up to 99.9% to 100%. The availability of inexpensive energy from renewable sources and an abundance of water resources is crucial for low-carbon hydrogen to be cost-competitive. For example, Årby, (2019) said that Norway has a resource optimum over its neighbours for being able to create green hydrogen more efficiently due to having some of the least expensive and environmentally friendly electricity in all of Europe as well as an available supply of water resources.

To add, storage system is required to resolve the issue of discrepancy between supply and demand to maximize capacity of hydrogen and guarantee supply security. Currently, there is the existence of methods that make it possible to store hydrogen as a gas, liquid, or solid. However, considering that the technology for solid-state hydrogen storage using metal hydrides is still in its infant stages, it is unlikely to significantly influence on the hydrogen grid in the near future (Dincer & Acar, 2014). To achieve greater energy densities prior to storage, hydrogen gas must be compressed or liquefied. Additionally, gasification of a liquid before distribution to the households and industries end requires extra energy, and also long-term hydrogen storage is designed to buffer for large-scale and intra-seasonal fluctuations, while short-term hydrogen storage aids in absorbing intraday variations. The storage vessels must have a wide deck for export. The storage vessels used for export must be light in weight and have a large storage capacity to reduce the cost of transit. Zapantis, (2021) said that Compressed Hydrogen Gas (CGH_2) can be stored in hydrogen pipelines that can either be newly constructed or repurposed from natural gas pipelines for short-term bulk storage, while options for liquid hydrogen storage include containers for liquid hydrogen (LH_2), large-scale storage tanks for LH_2, liquid ammonia tanks, or tanks for Liquid Organic Hydrogen Carrier (LOHC).

Nevertheless, the International Energy Agency (IEA, 2022) also considered green hydrogen to be "the most promising route to achieve deep decarbonisation of the hardest sectors, where reducing emissions is both urgent and difficult." Heavy manufacturing, shipping, and aircraft are examples of industries where electrification is not always viable or practical, and also, there are several applications for hydrogen, such as transportation, chemical processes, and energy storage. Aside Green hydrogen, there are three more types of hydrogen, namely:

Grey Hydrogen

This is the most commonly generated type of hydrogen, which is generated hydrogen from fossil fuels, like natural gas or coal. It is the most carbon-intensive type of hydrogen and contributes significantly to greenhouse gas emissions. It is predominantly produced through steam methane reforming (SMR), has been a cornerstone of the global hydrogen market due to its relatively low production costs and established technology. In West Africa, where natural gas resources are plentiful, grey hydrogen could be seen as an immediate solution to meet energy demands and support industrial activities. The process involves converting natural gas into hydrogen while releasing carbon dioxide as a by-product, which raises significant environmental concerns. As countries in West Africa aim to bolster their energy security and economic growth, the reliance on grey hydrogen presents both opportunities and challenges that must be critically assessed within the broader context of sustainable energy production Adeyemi et al. (2023).

From a techno-economic perspective, the production of grey hydrogen in West Africa benefits from existing infrastructure for natural gas extraction and distribution. This established framework allows for relatively quick implementation and scalability, making grey hydrogen an attractive option for industries seeking immediate energy solutions. However, empirical analyses indicate that the long-term economic viability of grey hydrogen is increasingly threatened by rising carbon pricing mechanisms and regulatory pressures aimed at reducing greenhouse gas emissions. As international markets shift towards decarbonisation, West African nations may face significant economic risks if they continue to invest heavily in fossil fuel-based hydrogen production without considering alternative pathways (Kar et al., 2022).

However, green hydrogen production offers a sustainable alternative that aligns more closely with global climate goals. By utilizing renewable energy sources such as solar and wind, green hydrogen can be produced without the associated carbon emissions of grey hydrogen. According to Rahmouni et al. (2017), Empirical studies have shown that Africa's abundant renewable energy potential could facilitate the development of green hydrogen projects, leading to lower production costs over time as technology advances and economies of scale are realized. Furthermore, investments in green hydrogen could stimulate local economies through job creation in renewable energy sectors, fostering a transition towards a more sustainable energy landscape.

In all, Adeyemi et al. (2023) suggested the transition from grey to green hydrogen in West Africa may necessitate a comprehensive evaluation of the techno-economic implications of both production methods. While grey hydrogen may provide short-term benefits, the long-term sustainability and economic resilience of West African nations will likely depend on their ability to harness renewable energy for green hydrogen production. Policymakers must weigh the immediate advantages of grey hydrogen against the pressing need for sustainable energy solutions that support environmental goals and economic diversification. As the region navigates this complex landscape, empirical evidence will be essential in guiding strategic investments and fostering an energy transition that benefits both current and future generations.

Blue Hydrogen

Blue hydrogen is obtained using the (SMR) process as grey hydrogen but includes Carbon dioxide emissions can be captured and stored using carbon capture and storage (CCS) technology. It is considered to be a transitional fuel as it reduces emissions but still relies on fossil fuels.

Current studies have underscored the potential of blue hydrogen production as a transitional solution for West Africa's energy landscape, particularly given the region's significant natural gas reserves. Blue hydrogen, produced through steam methane reforming (SMR) with carbon capture and storage (CCS), offers a pathway to generate hydrogen while mitigating carbon dioxide emissions. Research by Mulako et al. (2022) indicates that when coupled with effective CCS technologies, blue hydrogen can achieve up to 90% reduction in CO2 emissions compared to conventional hydrogen production methods. This is particularly relevant for West African countries aiming to balance energy needs with climate commitments.

Economic analyses have also demonstrated the economic viability of producing blue hydrogen in West Africa. A study by Adeyemi et al. (2023)

utilized a techno-economic assessment to evaluate the viability of blue hydrogen projects across several countries in the region. The findings revealed that, despite the initial capital costs associated with CCS infrastructure, blue hydrogen can be competitive with both turquoise hydrogen and traditional hydrogen production methods, especially in scenarios where natural gas prices remain stable and carbon pricing mechanisms are implemented. The study emphasizes that leveraging existing natural gas infrastructure can further enhance the economic feasibility of blue hydrogen initiatives.

But, some other empirical literature also identifies significant challenges that could impede the large-scale adoption of blue hydrogen in West Africa. A report by IEA (2022) highlights key barriers such as insufficient investment in CCS technology, regulatory uncertainties, and a lack of skilled workforce capable of implementing and maintaining these systems. Moreover, public acceptance of CCS remains a concern, as communities may be wary of potential environmental impacts associated with carbon storage. To overcome these obstacles, targeted policy frameworks that promote investment in CCS research and development, along with public awareness campaigns, are crucial. By fostering partnerships between government entities, private sector stakeholders, and civil society, West African nations can create a conducive environment for blue hydrogen deployment, thereby contributing to a more sustainable and resilient energy future while maximizing their natural gas resources.

Pink Hydrogen

The emergence of hydrogen as a versatile energy carrier has gained significant attention in recent years, particularly in the context of sustainable energy transitions. Among the various types of hydrogen, pink hydrogen is produced using nuclear energy and has been identified as a potential complement to green hydrogen, which is derived from renewable sources such as wind and solar. In West Africa, where renewable energy resources are abundant yet underutilized, the integration of pink hydrogen production could offer a unique opportunity to enhance energy security and reduce carbon emissions. This empirical review explores the techno-economic implications of incorporating pink hydrogen into the broader framework of green hydrogen production in the region.

Recent studies from Hamukoshi et al., (2022) indicated that the cost-effectiveness of hydrogen production is heavily influenced by the energy source utilized. While green hydrogen production through electrolysis has become more economically viable with advancements in renewable technologies, pink hydrogen presents an alternative that leverages existing nuclear infrastructure. A techno-economic analysis reveals that regions with established nuclear power plants could potentially produce hydrogen at lower costs than those reliant solely on renewable sources. This is particularly relevant for West Africa, where the intermittent nature of renewable energy can pose challenges for consistent hydrogen production. By utilizing nuclear energy, pink hydrogen can provide a stable and reliable supply, thereby enhancing the overall resilience of the hydrogen economy.

Furthermore, the environmental implications of pink hydrogen production must be considered alongside its economic viability. While pink hydrogen does not produce direct carbon emissions during production, concerns regarding nuclear waste management and the potential for accidents remain critical issues. However, empirical evidence suggests that when compared to fossil fuel-based hydrogen production methods, both pink and green hydrogen offer substantial reductions in greenhouse gas emissions. In West Africa, where climate change poses significant risks to agricultural productivity and water resources, transitioning to low-carbon hydrogen production methods could play a pivotal role in mitigating these impacts and fostering sustainable development (Adeyemi et al. 2023).

In addition to environmental considerations, the socio-economic dimensions of integrating pink hydrogen into West Africa's energy landscape cannot be overlooked according to Adeyemi et al. (2023), they explained that the development of a hydrogen economy has the potential to create jobs, stimulate local economies, and enhance energy access in underserved communities. However, the successful implementation of pink hydrogen projects will require careful stakeholder engagement and investment in infrastructure. Empirical data from other regions that have pursued similar pathways suggest that public acceptance and regulatory frameworks will be crucial for the successful deployment of nuclear-based hydrogen technologies.

Finally, a comprehensive techno-economic analysis must also account for the evolving policy landscape surrounding hydrogen production. As countries globally commit to ambitious climate targets, there is a growing recognition of the need for diverse hydrogen production pathways. In West Africa, aligning national energy policies with international best practices could facilitate the integration of both green and pink hydrogen into the regional energy mix. By fostering collaboration between governments, industry stakeholders, and research institutions, West African nations can harness their unique resources to establish a robust and sustainable hydrogen economy that meets both local and global energy demands.

Yellow Hydrogen

The growing interest in hydrogen as a clean energy carrier has led to the exploration of various production methods, including yellow hydrogen, which is generated through the electrolysis of water using nuclear energy. This form of hydrogen production presents an intriguing alternative to green hydrogen, which relies solely on renewable energy sources. In West Africa, where energy security and access remain significant challenges, the integration of yellow hydrogen into the existing energy landscape could complement green hydrogen initiatives and enhance the overall sustainability of the region's energy systems.

Domínguez, S., et al. (2022) conducted empirical studies which indicated that the cost of hydrogen production is influenced by several factors, including the energy source and technology employed. Yellow hydrogen production, leveraging nuclear power, can provide a consistent and reliable energy supply for electrolysis, potentially reducing the costs associated with intermittent renewable energy sources. In regions of West Africa where nuclear infrastructure is being developed or considered, the economic feasibility of yellow hydrogen becomes increasingly relevant. A techno-economic analysis reveals that when combined with existing nuclear facilities, yellow hydrogen could be produced at competitive prices, thereby providing a viable alternative to green hydrogen while supporting the region's transition to low-carbon energy systems.

Environmental considerations play a critical role in evaluating the viability of yellow hydrogen production. While it does not produce direct carbon emissions during electrolysis, concerns surrounding nuclear waste management and the potential for accidents must be addressed. However, empirical evidence suggests that yellow hydrogen could still offer significant reductions in greenhouse gas emissions compared to fossil fuel-based hydrogen production methods. In the context of West Africa, where climate change poses severe threats to agriculture and water resources, adopting yellow hydrogen could contribute to climate resilience and support sustainable development goals (Adeyemi et al. 2023).

In addition to economic and environmental factors, the socio-political landscape surrounding yellow hydrogen production is essential for its successful implementation in West Africa. Public perception of nuclear energy varies widely, and any initiatives involving yellow hydrogen must prioritize community engagement and education to foster acceptance. Moreover, establishing robust regulatory frameworks will be crucial for ensuring safety and addressing public concerns related to nuclear energy. Empirical data from other regions that have integrated nuclear energy into their hydrogen strategies suggest that transparency and stakeholder involvement are key components for building trust and facilitating successful projects (Hamukoshi et al., 2022).

Finally, as the global need for clean energy solutions increases, the potential for yellow hydrogen to play a significant role in West Africa's energy transition cannot be overlooked. By aligning national policies with international best practices and fostering collaboration between governments, industry stakeholders, and research institutions, West African nations can leverage their unique resources to develop a diverse hydrogen economy. The integration of yellow hydrogen alongside green hydrogen initiatives could enhance energy security, promote economic growth, and contribute to regional sustainability efforts, ultimately positioning West Africa as a key player in the global hydrogen market.

Bio-hydrogen

The exploration of bio-hydrogen as a viable energy source has gained traction in the context of green hydrogen gneration, particularly in regions like West Africa where biomass resources are abundant. Bio-hydrogen is produced through biological processes, such as fermentation and photosynthesis, using organic materials. Empirical studies indicate that West Africa's diverse agricultural landscape provides a significant opportunity for bio-hydrogen production, utilizing waste materials from crops and livestock. By converting these waste products into bio-hydrogen, not only can energy be generated sustainably, but it can also contribute to waste management and environmental sustainability.

In terms of techno-economic analysis, according to Hamukoshi et al., (2022), the production costs associated with bio-hydrogen are influenced by several factors, including feedstock availability, conversion technology, and process efficiency. Research suggests that utilizing local biomass resources can reduce transportation and processing costs, making bio-hydrogen a competitive alternative to traditional hydrogen production methods. A comparative analysis shows that while the initial investment for bio-hydrogen production facilities may be higher than fossil fuel-based methods, the long-term operational costs and environmental benefits can justify this investment.

The integration of bio-hydrogen into the broader green hydrogen strategy in West Africa could enhance energy diversification and promote local economic development.

Environmental sustainability is a critical consideration when evaluating bio-hydrogen production. Empirical evidence indicates that bio-hydrogen has the potential to significantly reduce greenhouse gas emissions compared to fossil fuels. Additionally, the carbon footprint associated with biomass cultivation can be minimized through sustainable agricultural practices. In West Africa, where climate change poses significant risks to food security and livelihoods, the adoption of bio-hydrogen can contribute to both energy transition and climate resilience. Furthermore, by promoting the circular economy through waste-to-energy initiatives, bio-hydrogen production aligns with sustainable development goals and fosters environmental stewardship.

The socio-political context surrounding bio-hydrogen production is equally important for its successful implementation in West Africa. Adeyemi et al. (2023) observed that public acceptance of bioenergy technologies often hinges on perceived benefits, such as job creation and rural development. Empirical studies highlight the importance of community engagement and education in fostering support for bio-hydrogen initiatives. Policymakers must prioritize transparent communication about the benefits and safety of bio-hydrogen production to build trust among stakeholders. Additionally, establishing supportive regulatory frameworks can facilitate investment and innovation in the bio-hydrogen sector, further enhancing its viability as a component of green hydrogen strategies.

Finally, as global interest in hydrogen as a clean energy carrier continues to grow, West Africa has the potential to position itself as a leader in bio-hydrogen production. By leveraging its rich agricultural resources and developing integrated energy policies that promote both bio-hydrogen and green hydrogen initiatives, the region can enhance its energy security and economic resilience. Collaborative efforts between governments, private sector players, and research institutions will be essential for advancing bio-hydrogen technologies and ensuring their successful integration into the regional energy landscape. Ultimately, the development of a robust bio-hydrogen sector can play a pivotal role in achieving sustainable energy goals while addressing pressing environmental challenges in West Africa.

Turquoise Hydrogen

This type of hydrogen is obtained using a mix of sustainable energy sources and natural gas. It is still in the experimental stage and has the potential to be a more sustainable alternative to blue hydrogen.

Recent empirical studies have highlighted the technological feasibility of turquoise hydrogen production through methane pyrolysis, particularly in regions abundant in natural gas. Research indicates that the pyrolysis process can achieve high hydrogen yields while generating solid carbon as a by-product, which can be utilized in various industrial applications. For instance, a study by Mulako et al. (2022) demonstrated that methane pyrolysis could produce hydrogen with a purity level exceeding 99%, while simultaneously offering a sustainable solution for carbon management. This capability is particularly relevant for West African countries, which are seeking to harness their natural gas resources while minimizing environmental impacts. The empirical evidence suggests that adopting turquoise hydrogen technology could significantly enhance the region's hydrogen production capacity without exacerbating greenhouse gas emissions.

In terms of economic viability, several empirical analyses have assessed the cost-effectiveness of turquoise hydrogen compared to traditional hydrogen production methods. A comprehensive study conducted by Negrou et al. (2011) employed a techno-economic model to evaluate the lifecycle costs associated with methane pyrolysis in different West African contexts. The findings revealed that while initial capital investments may be substantial, the operational costs of turquoise hydrogen production are competitive with those of steam methane reforming and electrolysis, particularly when considering fluctuating natural gas prices and the potential for carbon credits from solid carbon utilization. Furthermore, the study underscored the importance of local market conditions and regulatory frameworks in determining the economic feasibility of turquoise hydrogen projects, suggesting that supportive policies could enhance investment attractiveness.

Despite its promise, empirical literature also identifies several barriers to the broad acceptance of turquoise hydrogen technology in West Africa. A report by the African Development Bank (2023) highlights challenges such as inadequate infrastructure, restricted financial resources, as well as a lack of technical expertise in methane pyrolysis processes. Additionally, public perception and awareness regarding the benefits and safety of turquoise hydrogen remain underdeveloped. To address these barriers, targeted investments in research and development, coupled with capacity-building initiatives, are essential. By fostering collaboration between governments, academia, and industry stakeholders, West African countries can create an enabling environment for the successful deployment of turquoise hydrogen technology, thereby contributing to a more sustainable energy future while leveraging their abundant natural gas resources.

Green Hydrogen

For many years, numerous industries have employed hydrogen as a gas. Green hydrogen, which is created from sustainable energy source, has recently gained more attention. Green hydrogen has the possibility to be extremely important in the shift to an eco-friendlier economy. An overview of the idea of hydrogen, its manufacturing techniques, and its prospective uses in industrial processes are given in this study (Schulte et al., 2022). So, what is Green Hydrogen? A form of hydrogen known as green hydrogen is created using an inexhaustible energy source such as solar, wind, and hydroelectricity. Green hydrogen is created through the electrolysis process, unlike traditional hydrogen production methods, which depend on fossil fuels. Similarly, Kar, (2022) argued that green hydrogen is created using renewable energy sources such as wind, sun, and hydroelectricity.

According to (World Bank, 2020), water is electrolyzed to separate the molecules of hydrogen and oxygen using an electrical current. After that, the hydrogen can be transported and stored for use in a variety of processes. The shift to a more sustainable economy is thought to depend largely on the creation of green hydrogen. (Ishaq et al., 2022), Kar et al., 2022) in their quest to lessen their country's dependence on fossil fuels and lower the carbon footprint, employed the use of renewable energy sources to manufacture hydrogen. For instance, their study discussed several ways to make green hydrogen, but electrolysis is the most popular. The study added that an electrolyser is employed in this procedure to divide water molecules into hydrogen and oxygen with the help of an electric current. Proton Exchange Membrane (PEM) and alkaline electrolysers are the two most popular types of electrolysers among the many others. For example, PEM electrolysers separate hydrogen and oxygen ions using a polymer electrolyte membrane. Their study noted that a great efficiency technology could be used to produce hydrogen on a small scale. Alkaline electrolysers, on the other hand, employ an alkaline solution as the electrolyte and are noted for their low cost and excellent durability, and which are frequently employed in large-scale hydrogen generation

Mulako et al. (2022) also confirmed how green hydrogen can be produced via thermochemical techniques such as high-temperature electrolysis or solar thermochemistry in Africa. High temperatures are used in these technologies to separate water molecules into hydrogen and oxygen. Moreover, it has numerous potential applications in industrial processes, transportation, and energy storage. One of the most promising applications of green hydrogen is in transportation decarbonisation. Hydrogen Fuel Cell Vehicles (FCVs) are propelled by hydrogen fuel cells, which turn hydrogen into electricity. FCVs release only water vapour and no hazardous pollutants, making them an environmentally friendly alternative to standard fossil-fuel-powered vehicles (Kar et al., 2022). To add, according to (IRENA; 2022) report, it explains how energy storage could also be another application for green hydrogen. It further said that since renewable energy sources such as the sun and the wind have erratic output and are intermittent or are not accessible all the time, then it is necessary to store extra energy by using it to electrolyze water to create hydrogen. Hence, green hydrogen could be utilized as a feedstock in industrial operations to create materials and chemicals including ammonia, methanol, and steel. And so, the use of green hydrogen in these procedures can greatly lower carbon emissions and aid in the industrial sector's decarbonisation.

Despite its potential, according to (Ishaq et al., 2022), green hydrogen production and utilization confront a number of hurdles. Their study extensively discussed the competitiveness of the cost of production as one of the most significant difficulties in moving fully into the green hydrogen economy. The study, in addition, retorted that low carbon hydrogen generation is currently more expensive than traditional hydrogen production technologies that use fossil fuels. However, as green energy sources become more widely available and electrolyser costs fall, the cost of green hydrogen is likely to fall. Another issue the study highlighted was the lack of infrastructure for producing, storing, and transporting green hydrogen. To fully fulfil green hydrogen's potential, the study further, suggested that there must be a building of a strong infrastructure to support its production, storage, and distribution. Also, there are numerous opportunities for the development of green hydrogen; hence, the move to a more sustainable economy provides an opportunity for the creation of new sectors and jobs in Africa.

Furthermore, (IEA, 2021) in the net-zero scenario roadmap by 2050, it was suggested that carbon free hydrogen as the main limitless energy source could help solve both the world's energy and climate issues. This energy carrier option is said to be made by breaking water molecules into hydrogen and oxygen with renewable energy sources such as wind, sun, or hydropower. So, this method of splitting water into its two components is known as electrolysis, and the hydrogen created from it is known as green hydrogen since it produces no greenhouse gases. Hence, in using renewable energy sources, water is electrolyzed to create green hydrogen, as a net-zero-carbon fuel. In utilizing clean energy, the electrolysis process divides water into its two constituents, hydrogen and oxygen. Also, the roadmap explained that due to the fact that green hydrogen is created without the release of any greenhouse emissions, it is seen as a clean and sole sustainable alternative to fossil fuels. Also, Green hydrogen sometimes referred to as clean hydrogen or renewable hydrogen is crucial for the shift to a low-carbon economy. Green hydrogen can be utilized as a vehicle fuel, a chemical process feedstock, or a form of renewable energy storage. West Africa has a lot of promise for renewable energy, especially solar energy. According to (IEA, 2021; Mentis et al. 2015; Dagdougui et al. 2011; and Ballo et al., 2020) research, the West African region could generate up to 12,000 MW of solar power by 2030, which could be used to create green hydrogen and the economic potential of green hydrogen in West Africa is considerable, with the potential to generate up to 1 million jobs by 2050.

Green hydrogen generation, which uses inexhaustible sources, has received a lot of attention because of its potential to decarbonize different industries. West Africa has a significant renewable energy potential but it is presently facing several energy challenges. The purpose of this literature review is to evaluate the economic potential of green hydrogen production in West Africa and to identify pertinent literature to support this analysis.

Renewable energy sources such as solar, wind, and hydropower have enormous promise in West Africa. The region gets an abundance of solar radiation, making it an appealing location for solar energy projects (Bazilian, et al., 2012). Furthermore, the region has a large potential for wind energy generation, with a capacity of 15 GW estimated (International Renewable Energy Agency, 2020).

The electrolysis of water, using electric power from renewable sources such as solar and wind is a method used to produce green hydrogen. The prospect for renewable energy in West Africa creates a sizable chance for the production of green hydrogen. Numerous studies have emphasized West Africa's promise of producing green hydrogen. For instance, a study by IRENA predicted that West Africa could produce over 1 million tonnes of green hydrogen annually by 2050 (IRENA, 2020). By 2040, the region could generate 60 GW of renewable energy, as per another study by the African Development Bank, which could be used to create green hydrogen African Development Bank (2020).

Moreover, the production of green hydrogen in West Africa has a lot of promise. Green hydrogen generation is a possibility given the region's enormous potential for renewable energy sources and the rising demand for decarbonisation. Green hydrogen presents a sizable economic opportunity for the area by being used in several industries and sectors, including transportation, industry, and power production (Agyekum et al., 2022). Also, utilizing green hydrogen can help the area become less dependent on fossil resources and increase energy security. Infrastructure for Hydrogen Development

The infrastructure needed to produce hydrogen in West Africa must be created. According to a study conducted by (Dean et al., 2022), building a hydrogen infrastructure in Africa could provide significant economic benefits such as job creation, improved energy security, and lower greenhouse gas emissions. Also, (Abouseada et al., 2022) discovered that developing a hydrogen infrastructure in West Africa could reduce energy costs and boost energy access for the people. Despite the substantial economic potential of West African hydrogen production, there are challenges that must be addressed. These include; a lack of suitable policy frameworks, limited funding for R&D, and lack of appropriate infrastructure.

Furthermore, the economic potential of producing blue and green hydrogen energy in West Africa is important. Carbon-free hydrogen-produced methods can generate employment; improve energy security, and lower greenhouse gas emissions. However, in order to realize the maximum economic potential of hydrogen production in the region, suitable infrastructure and policy frameworks must be developed. The findings of this literature review provide insights for future technical study and policy development in the field of West African hydrogen production.

Finally, West Africa's renewable energy potential creates a major opportunity for green hydrogen in the area. Several studies have emphasized the region's potential for green hydrogen generation, which has significant economic benefits. The use of green hydrogen can help the region's decarbonisation initiatives while also providing energy security. However, several obstacles, such as infrastructure and policy frameworks, must be addressed before West Africa can realize its full prospect for green hydrogen.

Green Hydrogen Production Process

Green hydrogen is gaining popularity as a carbon-free energy source in a variety of businesses throughout the world. Green hydrogen is an outstanding illustration of how the hydrogen generation process is gaining prominence as a means of creating an environment-friendly future. In this review, the study will look at the process of producing green hydrogen and its many ways, as well as the procedures required for the industrialization of African economies. From (Agyekum et al., 2022), it is generated by the electrolysis of water, where an electric current is used to separate hydrogen and oxygen molecules. This process is the most common method of producing hydrogen, and it is often referred to as the water electrolysis process. This process involves two main steps, for instance, there is electrolysis of water, as the first step, water is placed in an electrolytic cell that contains a cathode and an anode. Then, an electric power is passed through the water, and as a result, the water molecules break down into hydrogen and oxygen. This process can be represented by the following chemical equation:

$$\mathbf{2H_2O(l) \rightarrow 2H_2(g) + O_2(g)} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. (1)}$$

Also, in the second step, there is the purification and compression of Hydrogen. After the hydrogen has been generated, it is required to be purified and compressed to be used as fuel. The hydrogen is first purified by removing any impurities such as water and oxygen, which can be done through a process called Pressure Swing Absorption (PSA). After the purification process, the hydrogen is compressed to high pressure for storage and transportation as suggested by Agyekum et al., (2022). There are various methods for producing green hydrogen, each with its own set of pros and cons. Some of the most prevalent methods include:

Proton Exchange Membrane (PEM)

This is a popular method of producing green hydrogen because it is highly efficient and can generate high-quality hydrogen. This method uses a solid polymer electrolyte membrane that conducts protons and separates the hydrogen and oxygen gases. This method requires low temperatures and pressures and it is ideal for small-scale applications.

This technology has emerged as a promising approach for producing green hydrogen, especially in regions like West Africa, where renewable energy resources are plentiful. PEM electrolysis employs a solid polymer membrane as an electrolyte to facilitate the electrochemical reaction that separates water into hydrogen and oxygen. Studies show that PEM systems provide high efficiency and quick response times, making them well-suited for integration with variable renewable energy sources like solar and wind. In West Africa, with its abundant solar irradiance year-round, PEM technology can harness this resource to generate green hydrogen, thus aiding in energy diversification and sustainability.

Kalbasi et al., (2021) asserted that the techno-economic feasibility of PEM-based hydrogen production in West Africa is affected by various factors, including capital expenditures, operational efficiency, and the availability of renewable energy. Recent analyses reveal that although the upfront costs for PEM electrolysis systems may be higher than those of alkaline electrolysers, improvements in materials and manufacturing techniques are reducing these expenses. Additionally, PEM systems can function at higher current densities, allowing for smaller plant sizes, which is beneficial in urban areas or locations with limited space. Data indicates that when paired with local renewable energy initiatives, PEM technology can achieve competitive levelised costs of hydrogen (LCOH), making it a compelling choice for green hydrogen production in the region

Environmental sustainability is a crucial factor in adopting PEM technology for green hydrogen generation. Research shows that hydrogen produced through PEM electrolysis using renewable sources results in minimal greenhouse gas emissions, thus supporting West Africa's climate objectives. Furthermore, utilizing locally sourced renewable energy can bolster energy security and decrease dependence on imported fossil fuels. Incorporating PEM systems within a broader framework of sustainable development can also promote job creation and technological advancements. As West African nations seek to fulfil their energy requirements while tackling climate change challenges, PEM-based green hydrogen production offers a viable route to achieve both economic growth and environmental sustainability which is suggested by Kar, S., K. (2022).

Alkaline Electrolysis

Alkaline Electrolysis is one of the oldest and well-established methods of producing hydrogen. This technique uses a liquid alkaline electrolyte such as potassium hydroxide or sodium hydroxide, and it operates at high temperatures and pressures. The process is less efficient than PEM electrolysis, but it is more cost-effective for large-scale applications. This type of electrolysis indeed represents a foundational technology for hydrogen production, particularly in regions rich in renewable energy resources like

West Africa. By utilizing an alkaline electrolyte such as potassium hydroxide (KOH), this method effectively facilitates the electrochemical reaction that splits water into hydrogen and oxygen, making it a robust choice for large-scale hydrogen production.

The advantages of alkaline electrolysis, particularly its lower capital costs compared to Proton Exchange Membrane (PEM) systems, make it an attractive option for West African economies looking to harness their abundant solar and wind energy. The techno-economic viability of this technology is closely tied to several factors, most notably the cost and availability of renewable electricity. In areas like the Sahelian belt, where solar power is plentiful, alkaline electrolysers can achieve competitive levelised costs of hydrogen (LCOH), making them increasingly favourable for investment.

Operational efficiency is another critical aspect, with studies indicating that alkaline electrolysers can achieve efficiencies between 60% and 80% when paired with large-scale solar installations. This efficiency not only maximizes hydrogen output but also enhances the overall economic feasibility of projects. Furthermore, ongoing advancements in alkaline electrolyser technology continue to improve performance and reduce maintenance costs, further bolstering the appeal of this method for investors and policymakers.

From an environmental perspective, Hamukoshi et al., (2022) indicated alkaline electrolysis aligns well with the climate goals of many West African nations. Hydrogen produced through this method from renewable sources results in negligible greenhouse gas emissions, contributing to efforts aimed at reducing carbon footprints. Additionally, utilizing locally sourced renewable energy enhances energy security by diminishing reliance on imported fossil fuels. The socio-economic benefits of implementing alkaline electrolysis projects are significant. These initiatives can stimulate local economies by creating jobs in various sectors, including construction, operation, and maintenance. This job creation not only supports immediate economic growth but also fosters long-term sustainable development within the region.

In summary, alkaline electrolysis stands out as a promising pathway for green hydrogen production in West Africa. Its economic viability, environmental advantages, and potential for local development make it a strategic choice as countries in the region work to diversify their energy portfolios and transition towards sustainable energy systems. Continued research and investment in this technology will be essential for addressing existing challenges and unlocking the full potential of green hydrogen in West Africa's energy landscape. As the region moves forward, the integration of alkaline electrolysis with its abundant renewable resources could play a pivotal role in shaping a sustainable energy future.

Solid Oxide Electrolysis

Solid Oxide Electrolysis is a relatively new method of producing green hydrogen, and it is still in the initial phase. This method uses a solid oxide electrolyte that conducts oxygen ions and separates hydrogen and oxygen molecules. The process operates at high temperatures and pressures, and it has the potential to be more efficient than other methods. Also (SOE) is emerging as a promising technology for green hydrogen production, particularly in regions rich in renewable energy resources. Unlike traditional electrolysis methods, SOE operates at high temperatures (typically between 600°C and

1000°C), which allows it to utilize heat from renewable sources, thereby enhancing overall efficiency. Empirical studies indicate that SOE systems can achieve higher energy conversion efficiencies often exceeding 80% due to the thermochemical processes involved. In the context of West Africa, where solar and geothermal resources are abundant, SOE presents an attractive option for harnessing these energy sources to produce hydrogen sustainably as indicated in (Hamukoshi et al., 2022).

The techno-economic analysis of SOE in West Africa reveals several advantages and challenges. On the one hand, the high efficiency of SOE can lead to lower levelised costs of hydrogen (LCOH) when integrated with renewable energy systems. For instance, empirical data suggests that coupling SOE with concentrated solar power (CSP) or geothermal energy can significantly reduce operational costs while maximizing hydrogen output. However, the initial capital investment for SOE systems remains a barrier, as the technology is still in the developmental stage compared to more established methods like alkaline electrolysis. Further research and investment are necessary to scale up production and reduce costs, making SOE a more feasible option for widespread adoption in the region (Rahmouni et al., 2016).

Their finding observed that environmental sustainability is a critical consideration in the deployment of SOE technology for green hydrogen production. Empirical evidence demonstrates that hydrogen generated through SOE using renewable energy sources results in minimal greenhouse gas emissions, aligning with the climate goals of many West African countries. Additionally, the ability to utilize waste heat from industrial processes or power generation can further enhance the sustainability profile of SOE systems. This dual benefit of producing clean hydrogen while improving energy efficiency positions SOE as a viable solution for addressing both energy needs and environmental concerns in West Africa.

Moreover, the implementation of SOE technology has the potential to stimulate local economies by creating jobs and fostering technological innovation. As West African nations seek to diversify their energy portfolios and transition toward sustainable practices, investing in SOE can catalyse economic growth and energy independence. Empirical studies indicate that developing local expertise in SOE technology can lead to knowledge transfer and capacity building, ultimately empowering communities to participate actively in the green energy transition. In conclusion, while challenges remain regarding cost and scalability, the prospects for Solid Oxide Electrolysis in green hydrogen production in West Africa are promising, warranting further exploration and investment.

In all, green H_2 is a sustainable energy source created by splitting water molecules into H_2 and O_2 with carbon free energy sources as shown in (**Fig 1**). It is regarded as a renewable and environmentally friendly energy source that could to be employed in a variety of industries such as transportation, chemical processes, and energy storage. In recent years, various governments and organizations have launched projects to promote the production and the use of green H_2 in Africa. These programs aim to mitigate greenhouse gas emissions and shift to a low-carbon economy (Bhandari, 2022).

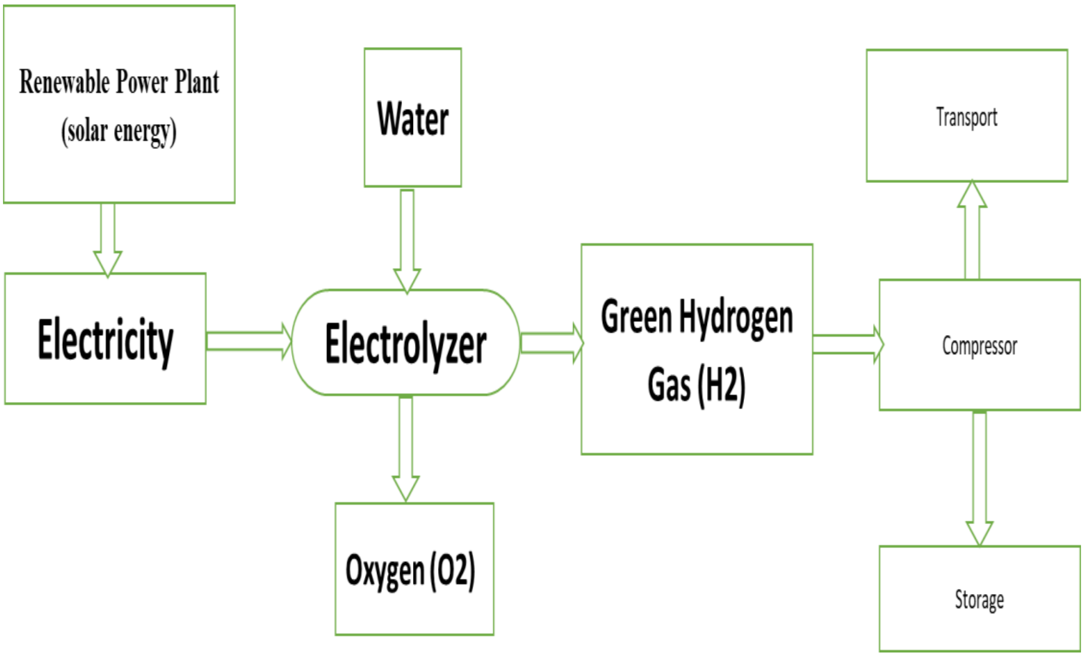


***Fig. 1:* Conceptual framework technical diagram for Green Hydrogen (H2) production chain from solar energy**
Source: Rahmouni S, et al. (2016)

Electricity Generation in West Africa

Worldwide population growth is anticipated to be outpaced by global energy usage. The lowest rate of electrification is seen in Sub-Saharan Africa (SSA), where more than 48% of the population lacked access to power in 2020 (World Energy Outlook, 2021). West Africa's electricity production encountered a number of difficulties and displayed notable geographical differences. For instance, in the year 2019, a population of about (367.42 million) had no access to electricity while 52.6% on average had access to electricity (AEP, 2019). The region has seen economic expansion with a 1479.03 ($) GDP per capita and rising energy consumption, yet many places still lack basic energy infrastructure and access to electricity. The expansion of energy services has not kept up with the population increase, despite efforts made (Mohammed et al., 2013; World Energy Outlook, 2021). Only Côte d'Ivoire, Ghana, Nigeria, Senegal and Togo have electrification rates above

50% in the study as shown in fig 2 below; the other nations have an average electrification rate ranging between 18%-49% as shown in **(fig.2)** (IEA, 2019; World Energy Outlook, 2021; AEP, 2019).

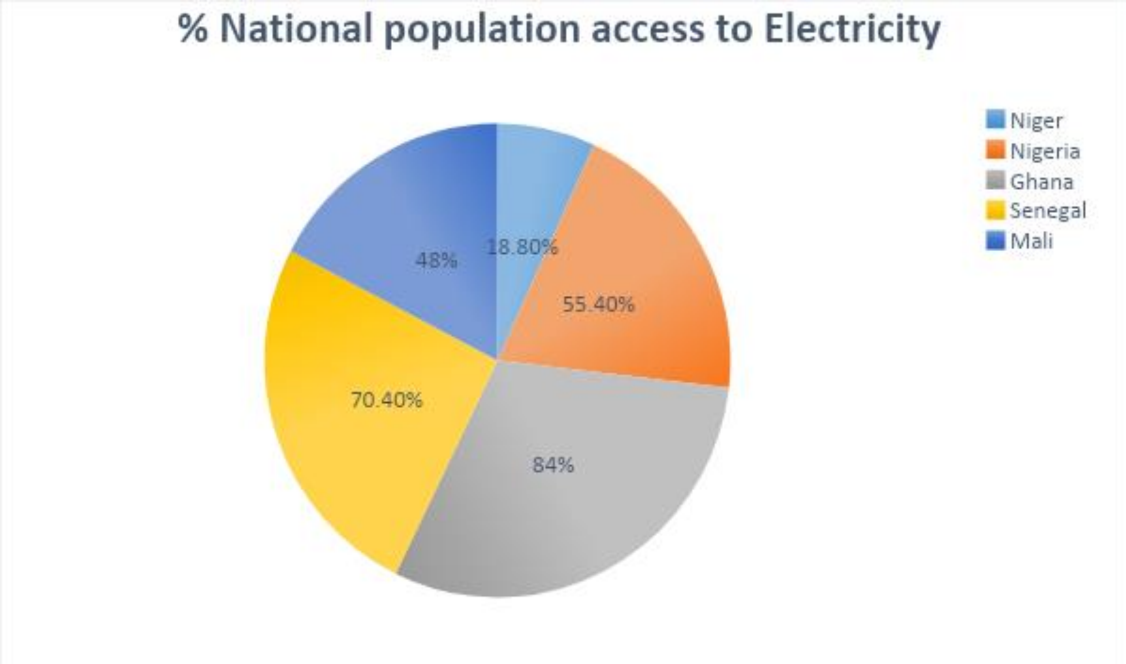


Fig. 2: **Selected countries' percentage access to Electricity in West Africa as of 2019**

Source: Tracking SDG7, World Bank and UN Population Database, AEP 2019

In light of the weak country planning capacity in the past, which resulted in bad policy and investment decisions, the difference in access to electricity and the overall low rates in SSA can be explained (Falchetta et al., 2021). Some African nations have come up with a strategy to deal with these issues based on utilising their rich energy potential, notably in hydropower, and by sharing power sources and facilities to achieve economies of scale and increase power output. Existing power pools include; the West African Power Pool (WAPP) for ECOWAS, the Central Africa Power Pool (CAPP) for ECCAS, the Eastern Africa Power Pool (EAPP) for COMESA, the Southern Africa Power Pool (SAPP) for SADC, and the Comité Maghrébin de l'Electricité (COMELEC) for UMA (IRENA, 2018; IRENA 2020; IEA, 2019). These power pools act as instruments for stimulating cross-border electrical power trading, regional energy integration, and increased energy security and dependability.

West Africa's total power generation capacity and generation of power are expected to reach 14.95 GW and 56.16 TWh, respectively, by 2020 (Löhr et al., 2022) due to the region's rising population. The distribution of electricity in the region is significantly influenced by the West African Power Pool (WAPP), which comprises 14 nations: Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo. The West African Power Pool (WAPP) aims to improve member country power system integration and promote electricity trade, which can help increase the availability of power in isolated and underserved regions. Up to this point, it is noteworthy that the WAPP has made efforts to increase West Africa's electrification rates.

The electrification rate in the area averages around 36%, although significant disparities exist among country electric power access rates and between different locations. For instance, electrification rates range from as low as 18.8% in Niger to 84% in Ghana (Ouedraogo, 2017). Many populations, especially those in rural areas, more rely on traditional fuels for their power needs, illustrating the energy access challenges faced by these communities. Energy insecurity is also a significant concern among WAPP member states due to an interrupted electricity system, inadequate technology, and dependence on fuel imports (Ouedraogo, 2017; IEA, 2019). The total installed capacity in WAPP amounted to about 14 GW in 2016.

The main source of electricity in the area is gas-fired power generation, with hydropower coming in as the second-largest source. However, there is still a sizable amount of untapped hydropower potential, more than 12 GW which is with great potential for hydroelectric development in nations such as Ghana, Nigeria, and Guinea (Bazilian et al., 2012, Ouedraogo, 2017). Only Senegal and Gambia have grid-connected wind energy potential, while solar power is still underutilised and is used mostly for decentralized energy production and off-grid power supply Dagnachew et al., (2018). Additionally, the bulk of power plants in these studied nations today generate energy using non-renewable resources like fuel oil, natural gas, hybrid stations and hydropower with each contributing 2% of the total.

Furthermore, in another study done in Algeria, Gouareh et al., (2015) said that the Algerian government has established an ambitious low-carbon power and energy efficiency programme intending to produce 40% of the country's electricity from renewable sources by 2030 to support sustainable growth and diversify its electricity output. For households, export, and the production of clean H_2 energy, the study further suggested that the programme established by the government must incorporate extensive solar energy generation so that Algeria can be well positioned to become a significant player in the global market of green H_2 energy in the future for its dedication to clean energy projects. Hence, for the region to get sustainable and equitable power systems, West African countries must work together in this laudable direction to maximise their potential for renewable energy sources and improve energy access. Such projects will indeed help the world and Africa migrate to cleaner, more reliable and decarbonised energy systems while also addressing the energy and water nexus issues in the local area such as water usage for producing green hydrogen.

Water Usage

Clean water is a limited resource that is vulnerable to a variety of competing demands all over the globe. According to the United Nations, more than 2 billion people reside in countries with severe water scarcity. The situation is expected to deteriorate as population and water demand grow and the effects of climate change worsen. According to data and estimates, nearly two-thirds of the global population, or four billion people, endure significant water shortages for a minimum of one month each year. Furthermore, over two billion people reside in nations with inadequate water supplies (IRENA, 2014; World Bank, 2020).

However, because water is needed as an input source for hydrogen generation, (Hamukoshi et al., 2022) argue that water stress may worsen as we work to combat the adverse effects of climate change. It takes a lot of water to generate steam during the reformation process used to make grey, blue, and green hydrogen. Nine kilograms of high-purity water is needed to produce one kilogram of green H_2 using electrolysis. Fresh water and wastewater that are easily accessible could be used to generate green hydrogen, but desalinated sea water must be used in electrolysers in desert regions and offshore wind/solar fields. Nevertheless, there are about 39 times as much seawater as fresh water on the planet (Mohamed et al., 2022).

Water usage and potential in West Africa are significant aspects of the region’s overall water resources management. The availability and distribution of water resources vary considerably due to the diverse climate and geography across the region. Also, this region is home to several major rivers, including the Niger, Senegal, Gambia, and Volta, which serve as important sources of water for irrigation, households use, and hydropower generation. These rivers offer great potential for agricultural development and electricity generation through the construction of dams and reservoirs (Esteves et al., 2015; IEA, 2018).

The region also has substantial groundwater reserves, which are an essential source of water for households and farming purposes, particularly in areas where surface water may be limited. Proper management of groundwater resources is crucial to ensure their sustainability. Together, (Yates et al., 2020) explained that these sums add to the water resources available for use in supplying both current requirements and the augmented demand brought on by the production of green hydrogen. An electrolyser electrochemically converts water into hydrogen and oxygen vapour. Water is delivered into the electrolyser, which uses electricity to work, and the electrochemical processes cause the water to change into protons, hydroxide ions, or oxygen ions, depending on the type of electrolyser deployed. Only water and power are needed when using an electrolyser. The electrolysis method, which uses low carbon energy to produce H_2 and O_2 gas, produces no carbon dioxide or particulate matter (Negrou et al., 2011).

Furthermore, about 500 tons of water and 50 tons of hydrogen are produced daily by an electrolyser with a 100 MW capability. If the system is water-cooled, the quantity of water required doubles. However, it is possible to significantly lower the amount of water needed for hydrogen production by using air conditioning or chiller systems to handle the majority of the cooling requirements. Green H_2 is being considered by some African countries as a possible strategy to strike a balance between energy and water security. Through the increased use of renewable energy sources, the aim is to increase the availability of electricity to millions of people in Africa, decrease reliance on fossil fuels, and uphold global climate commitments (IEA, 2020). For instance, in 2021, Namibia revealed a $9.4 billion project to produce green hydrogen, which would begin in 2026. Also in February 2022, South Africa announced plans to invest approximately $17.8 billion over the next ten years in a pipeline of green H_2 projects. Similar initiatives are underway in Mali, Ghana, and Nigeria at different stages of development to add green hydrogen to their energy portfolios (IEA, 2021; IRENA, 2022).

Economic Impact of Green Hydrogen

This section provides a literature review pertaining to the first and second objectives of the study. The diverse findings in the relevant literature underscore the necessity of this review to substantiate the study's findings.

To assist the West African region with its energy needs, hydrogen has emerged as a promising alternative power source. Given the abundance of limitless natural resources in the area, hydrogen produced in particular is getting traction. To ascertain its viability and contribution to the region's energy mix, an economic assessment of green H_2 generation capacity in West Africa is necessary. This part examines the financial aspects of the West African region's green hydrogen production potential. The economic viability of H_2 production in West Africa is determined by a number of variables, such as the accessibility of renewable solar power the necessity for investment, and production costs. According to a study conducted by Power et al., (2009) and

Oyedepo et al., (2020), Nigeria has substantial natural gas reserves and the prospect for large-scale H_2. The study also emphasized the importance of infrastructure investment, such as PV panel and electrolysis technology, to aid the growth of energy generation, which will be based on economic modelling of the electrical process equipment, and also allows one to determine the initial investment and ongoing operating expenses as well as net present value and levelised costs.

Ayodele et al., (2019) also researched the financial viability of hydrogen generation in South Africa. Given the country's abundant renewables and the potential for job creation, the study concluded that hydrogen production was fiscally feasible. The research also emphasized the importance of government policies and incentives to promote hydrogen production. Also, infrastructure investment is essential to the growth of low-carbon hydrogen in West Africa. This involves pipeline construction, storage facilities, and electrolyser technology development. Bouziane et al., (2009) analysed the economic viability of hydrogen produced in Algeria and it was discovered that infrastructure investment was a critical factor in determining the financial viability of hydrogen generation.

The growth of green H_2 production in West Africa can be significantly aided by government policies and incentives. According to Gouareh et al. (2015), policies and incentives are required to support the growth of the industry. Gouareh et al., (2018) not only examined the potential for green hydrogen in Algeria, but also, the study proposed incentives for investors, the creation of a law and regulatory framework, and the encouragement of R&D in their study. Furthermore, (Lens, 2019; Energy & Africa, 2020) explained that the expansion of the H_2 value chain has the ability to create new job possibilities, and provide substantial social and economic benefits to the region. Overall, the technical and economic analysis of West Africa's green H_2 potential emphasises its potential as a viable alternative energy source that can help address the region's energy challenges. However, infrastructure investment, government policies, and incentives, as well as environmental and social benefits, are critical factors to consider in bolstering the growth of green H_2. The results of this review of literature provide insights for future research and policy development to aid the growth of green hydrogen in West Africa, and this will improve social and environmental benefits in the region.

Chapter Summary

The chapter reviewed literature relevant to the study, grounded in past hydrogen research and current discussions on achieving a low-carbon economy. This literature was closely related to the study's objectives and provided the theoretical foundation for the research, this chapter took into consideration the various types of sources and pathways that can be used to produce both types of hydrogen efficiently and effectively. Empirical reviews conducted have shown that some countries in West Africa may hold diverse challenges, stages, efforts, and perceptions about the socio-economic impact of the decarbonisation agenda. As such, renewable energy and natural gas firms need to be encouraged even though West Africa has some economic and technical challenges for both green and blue hydrogen production. However, the region has an abundance of primary natural resources and hence a promising future in achieving the Hydrogen economy.

CHAPTER THREE

RESEARCH METHODS

Introduction

This chapter comprises several parts. The first part details a process of acquiring secondary data used in the thesis, while the second part, describes and explains the research strategy and the main methodology used in the thesis to assess the techno-economic modelling of Green H_2 from solar power to highlighting the most promising low economy in the third part of the thesis.

Data Source Assessment

This research relied on secondary sources of data obtained from World Bank, IRENA & IEA and other energy agencies reports, internal documents, and magazines from the international, regional, and national levels. This study further selects 5 countries from the ECOWAS region as the evaluation samples. These countries are; Nigeria, Ghana, and Senegal which are situated in the South-western part of the West African coastal region, while Niger and Mali are located in the North-western part of the West African inland region as shown in the study area map and in **(Table 1)**. The solar data are collected to estimate the existing level of green hydrogen production potential.

Additionally, the researcher considered certain parameters and representative technology for hydrogen production **(Table 8)** which will be the main aspect of techno-economic use in this work of hydrogen generation that will explode in the next decade in the sub-region. The data obtained are expected to estimate the production potential. For instance, for solar databases, the researcher obtains daily solar irradiation from the world, solar Atlas and IRENA Solar Energy of Africa regions dataset, derived from NASA's original data on power project datasets **(table 2)**. It is structured in Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI), and Diffuse Horizontal Irradiation (DHI) all in kWh/m2/day units. In this study, the researcher used only (GHI) data which these datasets typically include monthly averages of daily global solar radiation values measured on a horizontal plane and are readily accessible for various regions or countries yearly. This information corresponds to measurements of 5 countries' stations and estimations based on each country's local average solar radiation. Furthermore, in this study, the researcher organized the yearly average of daily solar radiation expressed in kWh/m2. For instance, (Rahmouni et al., 2016), in the study, they used a combination of spatial data in a Geographic Information System (GIS) with a techno-economic model to present an analysis of hydrogen demand for H_2 vehicles in the mobility sector as fuel in Algeria by 2045.

Research Strategy and Design

This thesis aims to investigate the potential future involving low-carbon hydrogen. in some West African countries as a low-carbon energy production region by adopting the critical techno-economic quantitative modelling approach. By embracing this approach, each country can enhance their comprehension of hydrogen's potential in the region's energy production capacities, along with its accessibility within an affordable market. Additionally, this method aims to uncover the hurdles shaping the current framework of the system by revealing the technical and economic interconnections, as well as the unrecognized limitations (Ballo et al., 2022b). In doing so, the researcher aims to provide insights and support key stakeholders in West Africa's energy production, facilitating informed policy adjustments to advance towards a decarbonized agenda.

Considering the ambiguities regarding the development of hydrogen technology for production objectives, this work adopts a techno-economic analysis approach as a means to enhance learning by fostering the exploration of technical potential and economic performance assessment using time series data (Löhr et al., 2022).

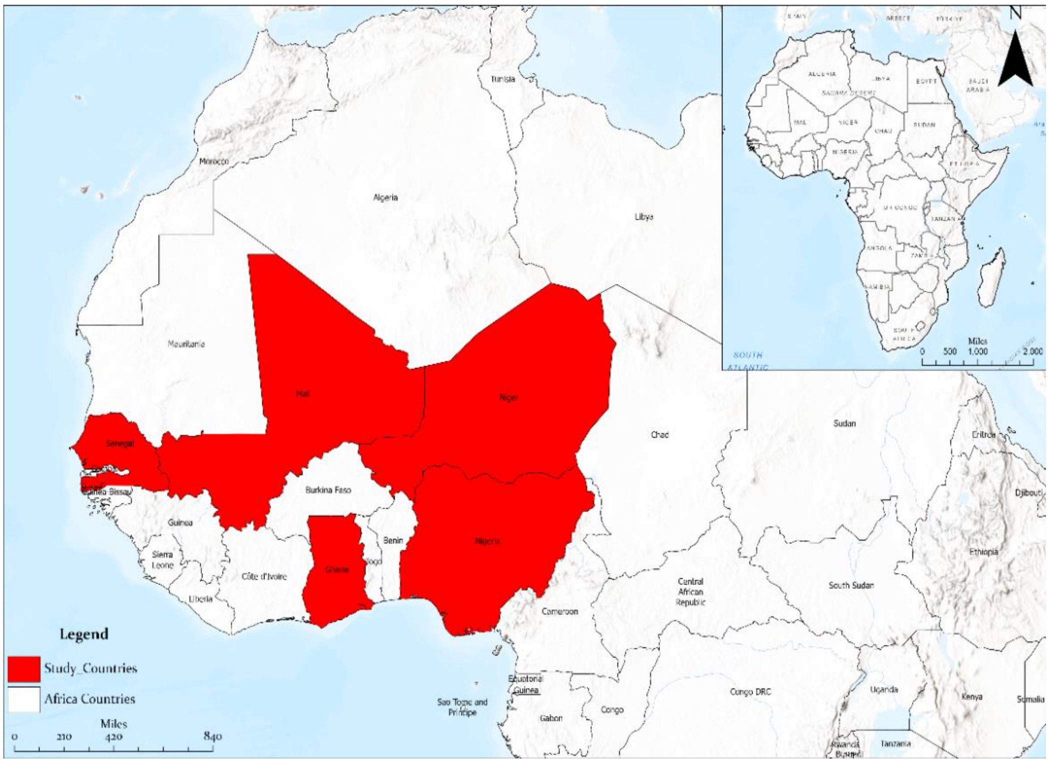
Study Area

The West African region is one of the (5^{th}) regions in Africa such as, North Africa, Central Africa, Southern Africa and East Africa, West Africa is specifically located in Sub-Saharan Africa (SSA). To conduct this study, the researcher selected 5 countries which are all low-income countries (World Bank, 2020) for analysis. These countries comprise; Nigeria and Ghana situated in the southern part of West Africa Gulf of Guinea Sea, and Senegal, which has a particular geographical position, it is located in the South-Western part of the West African coastal region while Niger and Mali located in the North-Western part of West African inland region and geographical coordinates as shown in the table below.

Table 1: Study Area

Country	**latitude**	**Longitude**
Ghana	8° 0' N	2° 00' W
Mali	17° 00' N	4° 00' W
Niger	14.8592° 00' N	6.4590°00' E
Nigeria	10° 00' N	8° 00' E
Senegal	14.6943° N	15.5953° W

Source: Solar map of Africa, 2018



Map of the study countries (source: by the author)

Ghana, Mali, Nigeria, Senegal, and Niger were selected as the study area for this thesis due to their diverse socioeconomic landscapes, which provide a rich context for comparative analysis of development challenges and opportunities in West Africa. These countries showcase a variety of ethnic groups, languages, and cultural practices, allowing for an exploration of how cultural factors influence social and economic policies. Additionally, their differing political dynamics offer insights into how governance and political stability affect regional development and cooperation. As key players in regional organizations such as ECOWAS, these nations are relevant for studying the impact of regional integration on trade, security, and development. Furthermore, they face significant environmental challenges, including climate change and desertification, which they address in various ways, providing a basis for examining adaptive strategies. Lastly, the interconnected economies of these countries through trade and migration patterns make them ideal for studying economic relationships and their implications for regional growth and stability according World Bank (2018).

Solar Energy Potential

The researcher accessed solar radiation databases or measurements for the 5 selected countries in West Africa through data sources including World Bank, IRENA & IEA Solar Africa and Atlas database, satellite-based datasets such as NASA's Surface Meteorology and Solar Energy (SSE) database or ground-based measurements (Mentis et al., 2018; Lewis, 2019; Kassem, 2020).

Solar energy is defined as energy derived from solar radiation. Photovoltaic (PV) systems harness a natural electronic process found in specific materials called semiconductors to generate energy directly from sunlight. Solar energy can be used to liberate electrons from these materials so that it can be forced to go through an electrical circuit and power electrical appliances (Agyekum et al., 2022). It is critical to evaluate the mean annual overall solar power collected to make an estimate the PVs electricity generating potential for a specific site (Eq. 2) below;

$$E_{PV} = \eta_{PV(Ta,GHI)} \times Area_{PV} \times GHI \quad \text{..............} \textbf{ Eq. (2)}$$

Where E_{PV} [kWh] is the power output of a PV unit, ηPV is the efficiency, APV [m2] is the PV area, Ta [°C] is the surrounding temperature, and GHI [kWh/m2] is the sun radiation incoming on the horizontal plane as shown in **Table 2**.

PV array positioning must maximise solar exposure. The panels could be mounted in different ways, such as manually tracking, passive tracking, active trackers, and tilt angles that can be adjusted. The least expensive and least energy-intensive mounting systems are fixed mounts. The majority of current commercial PV modules use two types of PV cells: c-Si and thin film (Koponen et al., 2016; Rehman et al., 2023). The monocrystalline and polycrystalline PV cells in the c-Si category, sometimes known as initial-generation PV, are the most economical of the widely used PV technologies (Lewis, 2019; Rehman et al., 2023). Their study also highlighted that there are second-generation PV, also known as the thin-film group and multi-junction cell, which refers to PV cells that generate energy using incredibly thin layers of semiconductor material. Third-generation PV, a group of developing technologies that include quantum dots and dye-sensitized organic PV cells, has the potential to be a feasible commercial option in the future. Today, all varieties of PV systems are often applied in several systems. Then, as will be explained below, the researcher conducted an analysis of the photovoltaic (PV) System by selecting a suitable PV technology based on variables including efficiency, cost, and regional availability (Monforti-ferrario et al., 2015)

Table 2: Monthly average of the solar irradiation received at horizontal plane of the selected countries in kWh/m2/day

	Niger	Nigeria	Ghana	Senegal	Mali
January	229.09	192.51	180.42	211.73	218.55
February	219	182.7	165.3	200.7	207.9
March	225.06	188.17	179.49	197.78	210.49
April	210.9	169.8	171	187.2	195.6
May	210.49	179.49	167.71	181.97	199.95
June	201.6	160.8	144	146.7	186.9
July	203.98	150.35	138.57	170.5	187.86
August	189.9	138.3	127.2	166.2	141.9
September	190.65	153.14	138.26	168.64	176.39
October	158.72	160.5	152.1	161.1	172.2
November	166.8	174.22	163.99	156.55	157.17
December	150.35	170.81	160.5	138	135.3
Annual	**2356.54**	**2020.79**	**1888.54**	**2087.07**	**2190.21**

Source: Worldbank, Atlas, Solar map of Africa, from January –December 2018

Photovoltaic (PV) System Design

In computing the estimated PV system capacity needed to produce the desired amount of H_2, take into account the system losses, conversion efficiency, and anticipated hydrogen generation rate. The electrolyser unit, which uses DC energy supplied by the panels to convert water molecules into hydrogen and oxygen, is the main component of the PV-based hydrogen production process (Mohammed et al., 2013; Dagnachew et al., 2017). The design of the photovoltaic system is essential in determining the necessary area of the PV facility to always provide an adequate power supply for the electrolyser.

We can estimate the appropriate surface area for the PV array by calculating the overall sun radiation received on the horizontal plane of the generator and the electricity required for the electrolyser. Given that the PV array's capacity factor is 37.5% and that each square metre can produce 149 W, an installation with a capacity of 10 tonnes per year would necessitate at least 2,731 m2 of PV cells. The research area would also need to support PV systems covering roughly 6 and 13 hectares, respectively, for a station intending to create 250 and 500 tonnes of hydrogen yearly. The surface area of the photovoltaic generator must be raised in accordance with the capacity of green hydrogen generation, as well as the size of the PV system, determined by the solar energy potential and the efficiency of the PV modules (Dagnachew et al., 2017).

Energy Requirements for Electrolysis

Next, the researcher calculates the electrolyser capacity by determining the amount of green hydrogen that would be needed to produce. For instance, this will be influenced by variables like the electrolyser's efficiency, conversion losses, and the pace at which hydrogen is produced. Simply put, the equation below (Eq. 3) shows how to calculate the energy needed for water electrolysis by multiplying the theoretical specific energy for electrolysis at a given $T^{o}c$ (in kWh/kg) by the yearly capacities for hydrogen production (in kg/year) and dividing it by the electrolyser's energy efficacy (Joshi et al., 2011). For instance, it was determined how much electricity would be required to produce 10, 250, and 500 tonnes of hydrogen annually. A distinct system energy needed for each electrolyser was established, from which the quantity of cells making up a well-sized electrolyser could be calculated as well as the power needs, and quantity of cells for electrolyser (Müller et al., 2023). The device that produces 10,000 kg per year could need 0.85 GWh yearly. The largest system, the 500 t/year unit, could need 4.85 MW, or 42 GWh yearly, while the 250 t/year per unit could need 2.42 MW. The cell stack is made up of several circular electrolysis cells that are connected to one another and have two electrodes on either side of an innovation. One cell stack is expected to consume 78 kW of AC power (Sarker et al., 2023) whereas stacks in the electrolysis cells would be needed for an installation of 500 t/year size.

$$E_{required\ for\ electolysis\ process} = \frac{Mass_{H2/year} \times E_{electrolyser\ specific\ energy}}{\eta_{electrolyser}} \quad \textbf{...Eq. (3)}$$

Sizing of the Generating Station of PV Electricity

Due to weather patterns, seasonal variations, and the resource's location, the production of renewable electricity is quite unpredictable. This is because energy is lost during every energy exchange. In order to size the energy supply unit, electrolyser working efficiency and energy losses by (Eq. 4) are first used to evaluate the technological potential. Then, meteorological data is used to estimate the energy supply unit's size (Bhayo et al., 2020)

$$E_{solar\ energy} = \frac{E_{H2}}{\eta_{electrliser} \times \eta} \quad \textbf{............................ Eq. (4)}$$

Where $E_{solar\ energy}$ [kWh] is the renewable energy production, E_{H2}[kWh] is the H_2 generated, $\eta_{electrliser}$ is the electrolysis efficiency, and η is in addition to the efficiency coefficient includes consideration of the losses.

Economic Analysis

Once the technical aspects of hydrogen generated prospect using limitless power sources could be established, an economic analysis that considers the system's advantages and disadvantages can be done. Utilising the levelised capital Cost, the economic assessment will be evaluated (Zhang et al., 2021; Al-qahtani et al., 2021). The overall life cycle cost and the total lifetime hydrogen output are both evaluated using the LCA equation. When operating at various scales, investing different amounts, or running for longer periods of time, it makes it possible to compare renewable technologies (Abouseada & Hatem, 2022).

Estimation of Renewable Electricity Source Investment

The researcher conducts an economic analysis of electrical process equipment in this study. Estimating the initial investment and ongoing costs are made easier with the help of this analysis. The installation and subsystem costs have a big impact on the system's overall costs. The initial investment of the PV power facility, indicated as I_{PVcost} [$] (Eq. 5), makes up the entire funding in a solar photovoltaic (PV) system. This cost includes the cost of the PV panels C_{PV} [$] as well as the cost of the balance of the system (BOS) C_{BOS}[$] and the Operation and Maintenance (O&M) cost (Ankrah & Lin, 2020).

$$I_{PVcost} = C_{PV} + C_{BOS} \quad \textbf{.................... Eq. (5)}$$

Photovoltaic (PV) panels' costs have minimised significantly in recent years, largely due to increased supply competition (Pascaris et al., 2021). This has caused a dramatic shift in the market for PV cells worldwide, with an astonishing 111% annual growth rate from 2009 to 2010. The astounding total worldwide cell manufacturing of 23.9 GW at the end of the year 2010 demonstrated the soaring demand and improvements in manufacturing techniques. Despite the strong demand and difficulties caused by the limited availability of raw materials, PV panel module prices on average fell to an all-time low in 2015 (Pascaris et al., 2021). The typical module cost varied between 1.64 and 2.87 dollars per watt throughout this time, making solar energy a more competitive and financially viable alternative to fossil fuels (Boudries & Dizene, 2011).

The Balance of the System (BOS) and labour costs, which together account for around 50% of the overall PV system cost, should be considered when estimating the total cost of PV systems (Africa, 2022). This emphasises how important installation and subsystem optimisation are to achieving affordable and effective solar energy solutions. The comparatively simple Operation and Maintenance (O&M) requirements of PV plants are one of their benefits. The O&M responsibilities are simpler as compared to other power generation technologies. This is due to the presence of fewer moving parts and the absence of cooling systems (Rahmouni et al., 2016; Lewis, 2019). The constant O&M costs are frequently represented as a percentage of the expenses of the initial investment and typically vary from 1.5% to 5%. The spectrum of predictable and reasonable O&M costs further enhances solar PV's viability as a long-term sustainable energy solution (Cummins, 2021).

Electrolysis Cost

In several previous studies and projects, the economic modelling of electrolysers has received substantial consideration. The investment consists of three main cost components: capital, replacement, and Operation and Maintenance (O&M) expenditures. The size and capacity of the potential hydrogen generation facility have a substantial effect on the total investment in an electrolyser. Hydrogen, a clean and adaptable energy carrier with tremendous prospects for transitioning to a free carbon future, is produced in large part by electrolysers. The size of operations, efficiency levels, and capital expenses are some of the variables that affect how economically viable it is to use electrolysis to generate H_2. Therefore, thorough economic modelling is necessary to determine whether incorporating electrolysers into the energy infrastructure is sustainable (Bauer et al., 2022).

It is critical to take into account both the initial capital cost and ongoing operating costs when assessing the investment in an electrolyser. The expenses incurred over the electrolyser's life cycle, such as routine maintenance, component replacements, as well as labour and utility costs, are covered by the replacement and O&M costs. The overall amount of investment required is significantly influenced by the capacity of the hydrogen-producing facility and the economies of scale may benefit larger facilities, thereby lowering the specific capital cost per kWe (Esteves et al., 2015). The necessity for more compact and specialised designs, however, may result in higher particular capital expenditures for smaller-scale facilities. An essential element affecting the capital cost is the effective electrolyser efficiency. Increased hydrogen production per unit of consumed power can result from higher efficiency levels, which may lower the overall capital cost per unit of hydrogen output (Esteves et al., 2015; IEA, 2019; Bauer et al., 2022).

However, to make the most of the economic performance of electrolysers, scientists and engineers frequently examine different scenarios by changing variables like hydrogen production rates, operating times, power costs, and government incentives or subsidies. Nonetheless, this analysis highlights the most financially advantageous setups and operational approaches for incorporating electrolysers into the changing energy landscape. The adoption of hydrogen production through electrolysis can be facilitated, as well as assisting the worldwide transition to sustainability and greener systems, by continuously improving economic models and taking into account real-world data. As a result, the equation below (Eq. 6), (Al-qahtani et al., 2021) illustrates how the specific capital cost per kilowatt-electric (kWe) at nominal output is computed based on criteria such as the highest H_2 production rate necessary, the electrolyser efficiency, and the projected specific capital cost per kWe.

$$C_{elec} = C_{elec,u} \frac{M_{H2} \times K_{el,th}}{8{,}760 CF \eta_{elec}} \quad \textbf{.................... Eq. (6)}$$

Where C_{elec} [$] is the capital cost of the electrolyser, $C_{elec,u}$ [$/kWe] is the unit cost of the electrolyser, $K_{el,th}$ [kWh/kg] is the theoretical specific energy needed by the electrolyser, and CF is the capacity factor. Under the baseline scenario, it is assumed that an electrolyser unit cost of 368 $/kWe, with predefined target values aligning by (Müller et al., 2023). The researcher assumes that the replacement expenses annual operational costs equal 25 % and 2 % of the first cell investment.

Electrolytic Hydrogen Cost

Indeed, one important aspect that will have a big impact on the role of particular eco-friendly technologies in the future of hydrogen generation is the expense of creating hydrogen through electrolysis. Several important technological and financial factors have been considered when determining the financial viability of producing hydrogen by water electrolysis. The electricity consumption rate, which is set at 57.85 kilowatt-hours per kilogramme of hydrogen produced, is one of these characteristics. The initial capital outlay for creating the electrolysis facility amounts to 368 dollars ($) per kilowatt-electric (kWe) of electrolyser capacity. When maintenance and operational costs are taken into account, the electrolyser's expected operational life is 7 years (Yates et al., 2020).

According to (Yates et al., 2020; Kar et al., 2022; Sarker et al., 2023), the estimated project lifespan is 30 years which takes into account the hydrogen production system's entire economic lifespan, enabling a thorough assessment of the investment's long-term viability could be profitable. A discount rate of 6% has been used to take future uncertainties into account and to compare present and future expenses, allowing for the calculation of the net present value of the hydrogen generation project. Additionally, the electricity usage rate of 57.85 kWh per kilogramme of hydrogen represents the quantity of electrical energy needed to electrolyze a specific amount of hydrogen gas. To attain competitive hydrogen prices, it is crucial to maximise the electrolysis process's efficiency and use renewable electricity sources with low costs. This characteristic directly affects the whole cost of hydrogen generation. Likewise, the initial capital outlay required to build up the electrolysis facility with a certain capacity is represented by the investment cost of 368 dollars per kWe. The fees for purchasing and setting up the electrolysis equipment are included in this price. A major objective for increasing the financial prospects of hydrogen via electrolysis is to lower the investment costs. The development of new technologies, increased production volume, and economies of scale are some of the elements that can lower the initial investment cost of electrolysers.

Additionally, Yates and et al. (add the year) explained further that the electrolyser's operational life, which is set at 7 years, is crucial to the economic analysis. Depreciation and maintenance costs have a direct influence on the electrolyser's annualised cost. Improving the durability and reliability of electrolyser technology can extend its operational life, and reduce the cost per unit of hydrogen obtained. Also, the project's lifetime is a long-term consideration that accounts for the entire economic lifespan of the hydrogen production system. A longer project lifetime can enhance the economic viability of the investment, as the costs can be spread over a more extended period, making hydrogen production more cost-effective. And, the discount rate of 6% is utilized to assess the present value of future cash flows and evaluate the economic attractiveness of the hydrogen production project over time. It demonstrates the expense incurred due to capital allocation and records for inflation, interest rates, and other economic uncertainties that may impact the project's profitability.

The cost for each unit of hydrogen generated can be decreased by extending the operational life of electrolyser technology and increasing its durability and dependability. A long-term factor that takes into account the entire economic lifespan of the hydrogen-generating system is the project lifetime. A longer project lifespan can increase the investment's economic viability since the costs can be dispersed over a longer period, and enhance the efficiency of the hydrogen produced. Additionally, the present value of future cash flows and the project's long-term economic attractiveness are calculated using a discount rate of 6%. These factors; inflation, interest rates, and other economic risks that can affect the project's profitability, also show the opportunity cost of capital (Abouseada & Hatem, 2022).

Macroeconomic evaluations of hydrogen generation methods are dynamic and prone to modification as a result of changes in market conditions, regulatory changes, and technological breakthroughs. For hydrogen to develop as an eco-friendly and sustainable energy carrier and for the shift to a low carbon and environmentally friendlier energy future, thorough analysis especially taking these factors into account are crucial. To get a complete overview of the financial feasibility and potential role of hydrogen in future systems, it is also necessary to look at other factors when assessing the cost of electrolytic system, including the costs and availability of water, the efficiency of the electrolyser, and the potential for hydrogen storage and distribution (Zhang et al., 2021).

Net Present Value (NPV)

The net present value (NPV) represents the difference between the current value of a project's cash inflows and outflows. NPV is calculated using Eq. (7) ((Akpahou et al., 2023). An investment in hydrogen energy project is financially viable if the Net Present Value (NPV) is positive and is not acceptable if the NPV is negative.

$$NPV = \sum_i^n \frac{E_{n\,(kWh)}\ x\ Unit\ price(\frac{\$}{kWh})}{(1+r)^t} - C_O + \sum_i^n \frac{C_{O\&M} + C_{rep}}{(1+r)^t} \quad \text{..... } \textbf{Eq. (7)}$$

Where C_O is the initial investment cost, $E_{n\,(kWh)}$ is the energy produced, $C_{O\&M}$ is the annual operation and maintenance cost, C_{rep} is the annual replacement cost, r is the discount rate, n is the project's economic life, and for the year t.

Simple Payback Time (SPT)

The simple payback time (SPT) is the number of years needed for the monetary flow to match the initial investment. It also indicates the duration required for an owner to recover the initial cost through revenues or benefits. Eq. (8) below is used to calculate the simple payback time:

$$SPT = \frac{TC}{(E_{sav} + C_{sav}) - C_{O\&M}}$$

Where TC represents the project's initial capital cost, E_{sav} is the energy savings per year, C_{sav} reflects the yearly capacity savings, $C_{O\&M}$ is the annual operation and maintenance cost.

Levelised Capital Cost (LCC)

After that, the researcher will evaluate the cost of producing hydrogen by taking into account the electrolyser system's capital expenditures, maintenance costs, power costs, and other operating costs. In this study, the researcher uses equations that take these considerations into account to get the Levelised Capital Cost (LCC). Likewise, the researcher therefore examines the techno-economic analysis by estimating the capital expenditures related to the installation of PV systems, the purchase of electrolysers, storage facilities, and other infrastructure required for the production of green hydrogen. Also, taking into account the intended hydrogen generation capacity, the solar potential, and the PV efficiency, the researcher will be able to determine the necessary PV system size. System losses and capacity factors are two examples of variables that may require adjustments. For instance, the researcher used the equation shown below to determine the output of the PV system. In this study, the Levelised Cost of Hydrogen (LCOH) is computed by estimating the cost of the project's lifetime, operating and maintenance expenses, discount rate, and hydrogen output. Across the course of the project, LCOH reflects the entire expenses shown in the equations **(9&10)** below, as well as the cost per unit of creating hydrogen (Schulte et al., 2022). where the LCOH represents the Levelised Cost of Hydrogen, IC as Investment Cost ($), AOC as Annual Operating and Maintenance Cost ($/year), N as the Project

Lifetime (years), d as the discount Rate (as a decimal) and H2 production as the total Hydrogen Production (in Kg/ year).

$$\mathbf{LCOH} = \frac{IC + AOC}{\sum_{t=1}^{N}(1+d)^{t} \times MassH_2\ production} \quad \text{.......... Eq. (9)}$$

$$LCC = \frac{C_0 + \sum_{n}^{N} \frac{(C_{O\&M} + C_{rep})}{(1+r)^n}}{\sum_{n}^{N} \frac{E_n(kWh)}{(1+r)^r}}$$

Where LCC is the levised Captial Cost, $C_{O\&M}$ is the annual operation and maintenance cost, C_{rep} is the annual cost of replacement, r is the discount rate, C_O is the initial funding cost, N is the project's financial life, and for the year t

Table 3: Parameters used to estimate the Techno-economic analysis for Solar PV-Electrolyser systems and levelised cost of producing hydrogen by Electrolysis

Parameter	Value	Unit
Plant lifetime	10	Years
Discount rate	6	%
Electrolyser system		
Electrolyser efficiency	70	%
Cell stack lifetime	7	Years
Replacement cost	25% of direct installed capital	$
O&M cost	2% of direct installed capital	$/year
Unit price	368	$/kWe
Solar PV system		
Module efficiency	15	%
Unit price	1.5	$/kW
BOS cost	50% of total PV cost	$
O&M cost	5% of total PV cost	$/year

Source: Rahmouni S.,et al (2016)

Chapter Summary

The chapter delineated the methods employed to attain the study's results. Specifically, the quantitative method was adopted, aligning with the study's objectives. This section outlined essential components of the research methods, including research approach and design, study area, and secondary data collection. Additionally, the chapter provided a detailed discussion of the analysis of solar energy, the primary resource investigated in the study. The data analysis employed a techno-economic technique. These techno-economic parameters do not only provide insights into the technical analysis prospect of hydrogen but also provide perspectives into the financial prospects and profitability of hydrogen projects in the selected countries of Sub-Saharan Africa using solar energy and natural gas. Also, considerations of ethics, along with discussions on validity and reliability, were included to enhance the work's credibility.

CHAPTER FOUR

RESULTS AND DISCUSSION

Introduction

This chapter constitutes both technical and financial simulations of green hydrogen produced using inexhaustible solar electricity. It presents the findings and discussion regarding the study's research objectives concerning the evaluation of the possibility and prospect of hydrogen energy production in some West African countries with an abundance of sustainable sources like solar and also, the financial impacts of low carbon hydrogen economy in the sub-region. It finally discusses both the technical and economic prospects of hydrogen in the 5 countries selected as the study area.

Global Solar Resources

A parameter known as Global Horizontal Irradiation (GHI) is used to analyse the solar resources in the 5 countries selected as the study area. The annual averaged GHI values, with an average West Africa region temperature of 25.204 degrees Celsius for all 5 countries are provided graphically in **Table 2** above. The values of GHI were found to vary from 1888.54 kWh/m2 to 2356.54 kWh/m2/year. The maximum and minimum annual values of GHI are recorded in Niger and Ghana, with a value of 2356.54 kWh/m2/year and 1888.54 kWh/m2/year respectively. Moreover, it is observed that the highest and lowest national average values of air temperature are registered in Niger and Ghana with a value of 26.451 and 20.257 degrees Celsius respectively in this study. Moreover, the monthly geographical record of solar potential is a crucial step to be carried out to evaluate yearly the countries with optimum solar potential. As shown in **Table 2** the accessible solar energy radiation varies significantly in the selected countries in the West African region.

Table 4: Monthly average of the solar energy produced (kWh), amount of energy required by the electrolyser(kWh) and the mass (Kg) in Niger

Niger	Epv/kWh	Eh2/kWh	MassH2/Kg
January	2084023	1312934	21918.77
February	1992234	1255108	20953.38
March	2047362	1289838	21533.19
April	1918549	1208686	20178.39
May	1914819	1206336	20139.17
June	1833947	1155387	19288.59
July	1855598	1169027	19516.31
August	1727513	1088333	18169.17
September	1734335	1092631	18240.92
October	1443869	909637.8	15185.94
November	1517373	955944.9	15959.01
December	1367728	861668.6	14385.12
Total	**21437350**	**13505531**	**225468**

Source: author’s analysed data

Table 5: Monthly average of the solar energy produced (kWh), amount energy required by the electrolyser(kWh) and the mass (Kg) in Nigeria

Nigeria	Epv/kWh	Eh2/kWh	MassH2/Kg
January	1751256	1103291	18418.88
February	1662015	1047069	17480.29
March	1711775	1078418	18003.64
April	1544664	973138.2	16246.05
May	1632813	1028672	17173.16
June	1462791	921558.4	15384.95
July	1367728	861668.6	14385.12
August	1258110	792609	13232.2
September	1393108	877658.3	14652.06
October	1460062	919839.1	15356.25
November	1584872	998469.6	16668.94
December	1553852	978926.6	16342.68
Annual	**18383046**	**11581319**	**193344.2**

Source: author’s analysed data

Table 6: Monthly average of the solar energy produced (kWh), amount energy required by the electrolyser(kWh) and the mass (Kg) in Ghana

Ghana	Epv/kWh	Eh2/kWh	MassH2/Kg
January	1641274	1034002	17262.14
February	1503727	947348.3	15815.5
March	1632813	1028672	17173.16
April	1555580	980015.5	16360.86
May	1525651	961160.2	16046.08
June	1309962	825276.2	13777.57
July	1260566	794156.4	13258.04
August	1157133	728994	12170.18
September	1257746	792379.8	13228.38
October	1383648	871698	14552.55
November	1491810	939840.6	15690.16
December	1460062	919839.1	15356.25
Annual	**17179973**	**10823383**	**180690.9**

Source: author's analysed data

Table 7: Monthly average of the solar energy produced (kWh), amount energy required by the electrolyser(kWh) and the mass (Kg) in Senegal

Senegal	Epv/kWh	Eh2/kWh	MassH2/Kg
January	1926099	1213443	20257.81
February	1825760	1150229	19202.48
March	1799197	1133494	18923.1
April	1702951	1072859	17910.84
May	1655374	1042886	17410.44
June	1334524	840750.1	14035.9
July	1551032	977150	16313.02
August	1511915	952506.3	15901.61
September	1534111	966490.1	16135.06
October	1465520	923277.8	15413.65
November	1424129	897201.3	14978.32
December	1255380	790889.7	13203.5
Annual	**18985992**	**11961175**	**199685.7**

Source: author's analysed data

Table 8: Monthly average of the solar energy produced (kWh), amount energy required by the electrolyser(kWh) and the mass (Kg) in Mali

Mali	Epv/kWh	Eh2/kWh	MassH2/Kg
January	1988141	1252529	20910.33
February	1891258	1191493	19891.36
March	1914819	1206336	20139.17
April	1779365	1121000	18714.53
May	1818937	1145930	19130.72
June	1700222	1071140	17882.13
July	1708955	1076642	17973.98
August	1290859	813240.9	13576.64
September	1604613	1010906	16876.56
October	1566497	986892.8	16475.67
November	1429769	900754.6	15037.64
December	1230819	775415.8	12945.17
Annual	**19924253**	**12552279**	**209553.9**

Source: author’s analysed data

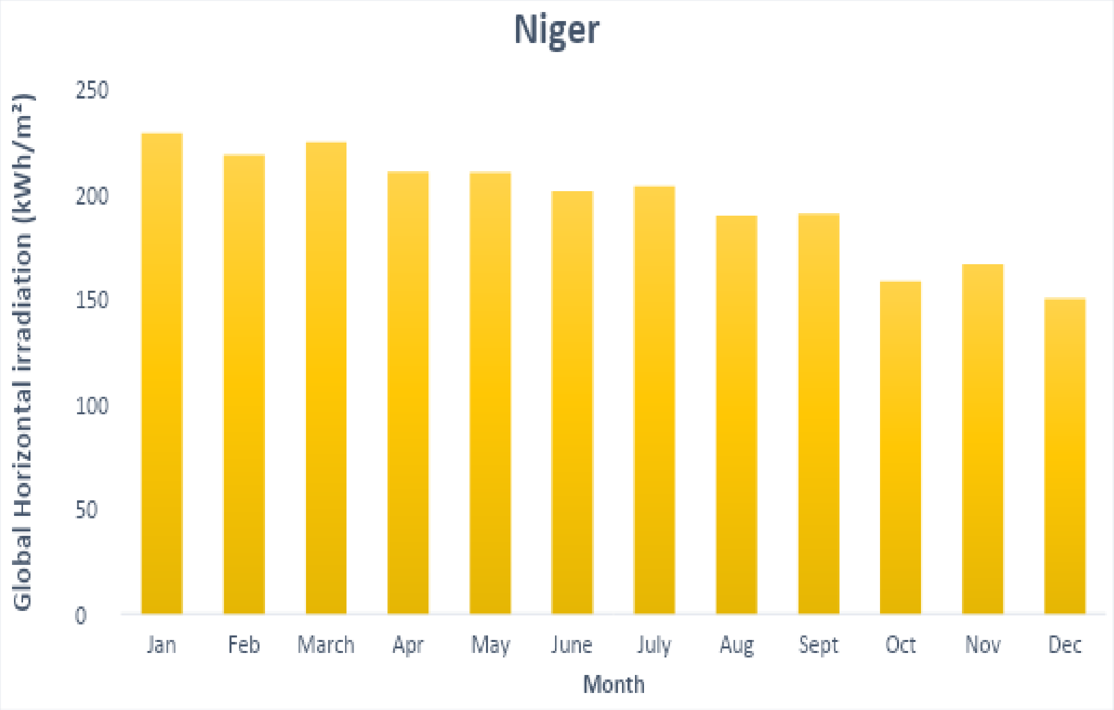


Fig. 3: **Monthly average of the solar irradiation at horizontal plane in Niger**

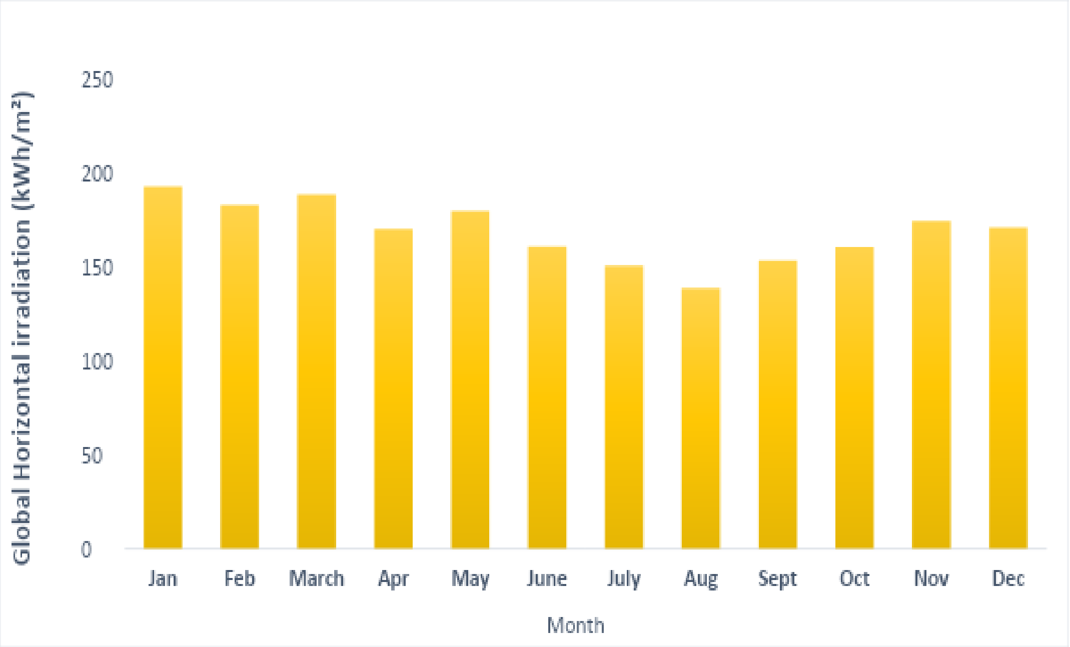


Fig. 4: **Monthly average of the solar irradiation at horizontal plane in Nigeria**

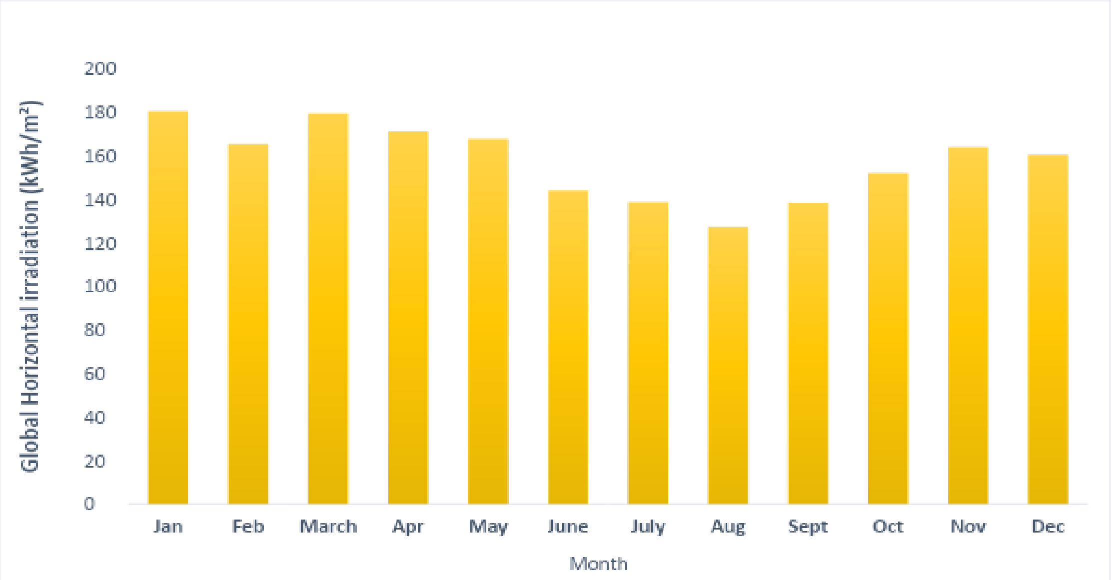


***Fig. 5*: Monthly average of the solar irradiation at horizontal plane in Ghana**

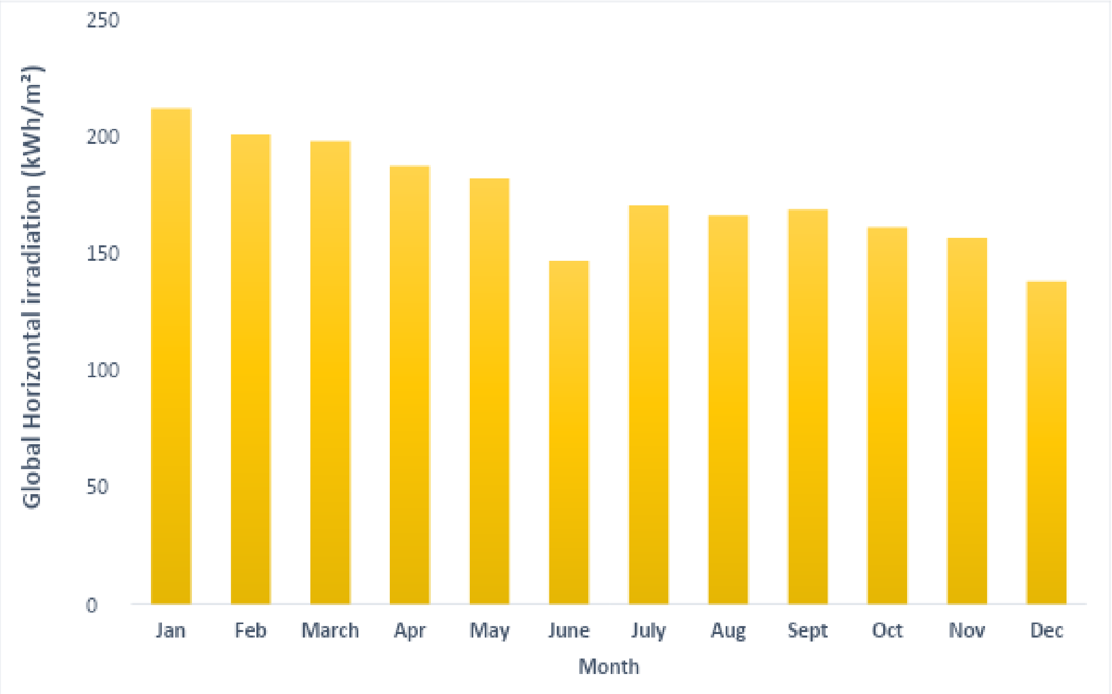


***Fig. 6:* Monthly average of the solar irradiation at horizontal plane in Senegal**

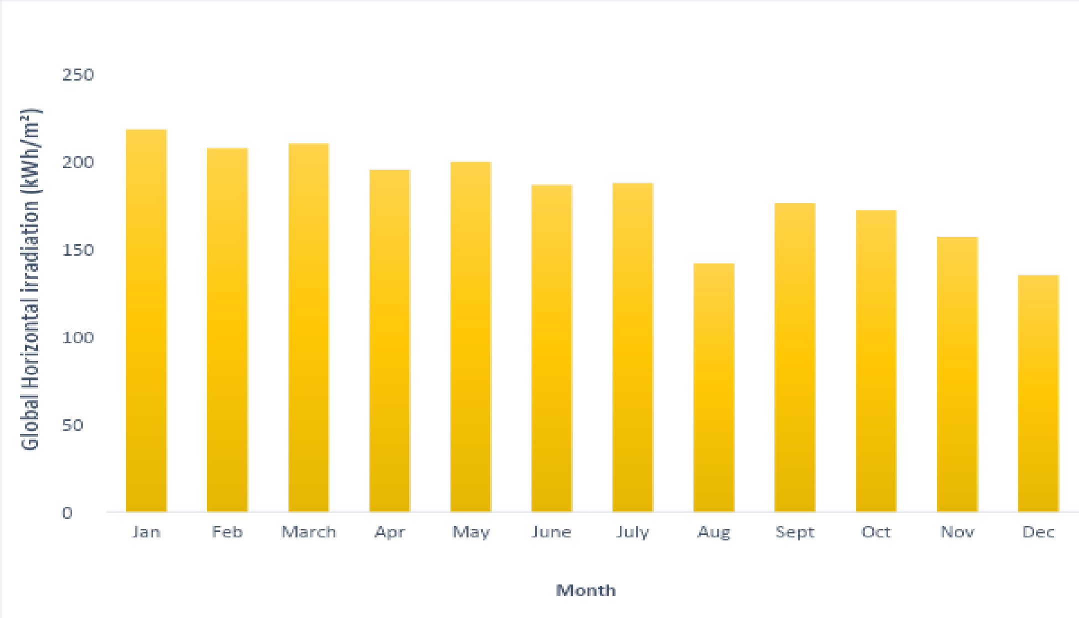


Fig. 7: **Monthly average of the solar irradiation at horizontal plane in Mali**

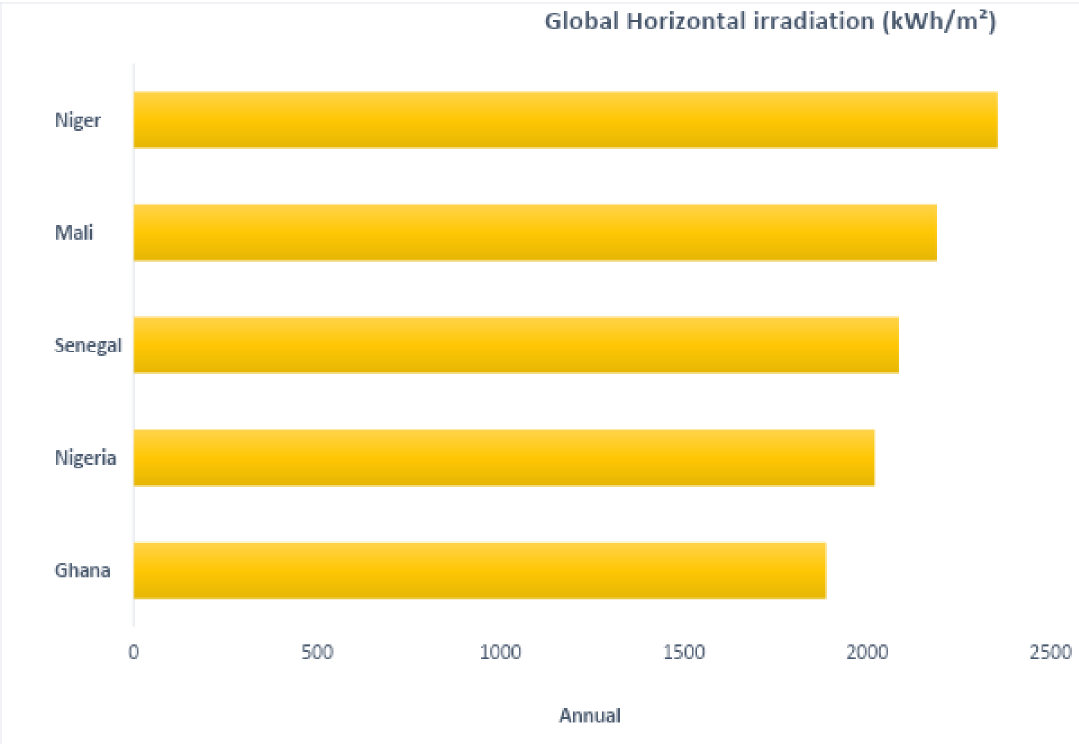


Fig. 8:**Annual average of the solar irradiation at horizontal plane in the selected countries**

From the selected countries in West Africa, it appears that some countries on the coast as well as certain inland countries on the northern side have a more promising monthly radiation than others for harnessing of solar resources for electricity generation required for the electrolyser system. In specific, three locations comprise a high solar possibility, which correspondingly to Niger, Senegal and Mali with solar energy as shown in **(Fig. 3, 5 and 7).** This observation could be that these countries are located in the Sahara Desert zone as reported by (Rahmouni et al., 2016). For instance, in **Fig. 8** the location gives a clear advantage of renewable abundances in the region as compared to other countries. To add, Niger has the highest monthly average variations of the solar irradiation which are observed in January and March and which afterwards observed a decrease through December of the year with a value of 135.3 kWh/m2/day respectively. In Mali, as shown in **Table 4.12**, the analysis observation also shows quite similar trends where the monthly highest average variations are recorded in January and March but later observed a decrease through till August where there is more decrease, as observed in October than Niger, before picking up till the end of the year. Finally, in **Fig. 8**, Senegal has the same situation where there is a record of high values in January and December at 211.73 kWh/m2/day and 138 kWh/m2/day respectively.

Also, in **Fig. 4,** the location even though as a coastal country, is seen to be the fourth highest solar energy region due to its geospatial position where the highest of monthly average fluctuations in solar irradiation was received in January and then slowly decreased in June but subsequently picked up again from July and increased through till the end of the year. Furthermore, this trend is also observed in more coastal countries and other locations close to the earth's equator line as in **(Fig. 3, 4, 5, 6, 7, and 8)**

Solar Energy Generation

In this study, Microsoft Excel spreadsheet software is used to compute the monthly average solar Global Horizontal Irradiation (GHI) of each selected country. After the computation, the resulting values were used to estimate the ideal energy for future PV system installations in all selected locations. Microsoft spreadsheet is used to estimate the viability of a solar-based PV system in the selected countries in the West Africa Region as shown in **Table 2**. The mean monthly power generation from the proposed system is shown in **Table 3-7**.

Figure 8 above shows the annual solar power produced required for the proposed PV electrolyser system in each country. For instance, it is observed that the highest annual value of solar power estimation generated is recorded in the North-western part of West African inland regions such as; Niger (latitude 14.8592° 00' N, longitude 6.4590°00' E), and Mali (latitude 17° 00' N, longitude 4° 00' W) with 19.924 GWh, and 21.437 GWh respectively, meanwhile in the South-western part of West African coastal region such as; Nigeria (latitude 10° 00' N, longitude 8° 00' E), Ghana (latitudes 8° 0' N, and longitudes 2° 00' W), and Senegal (latitude 14.6943° N, longitude 15.5953° W) observed the lowest with 18.383 GWh, 17.180 GWh, and 18.986 GWh respectively. In all, it is shown that Niger has the peak annual average solar energy generated and required for the solar panel-water electrolysis system for green hydrogen production.

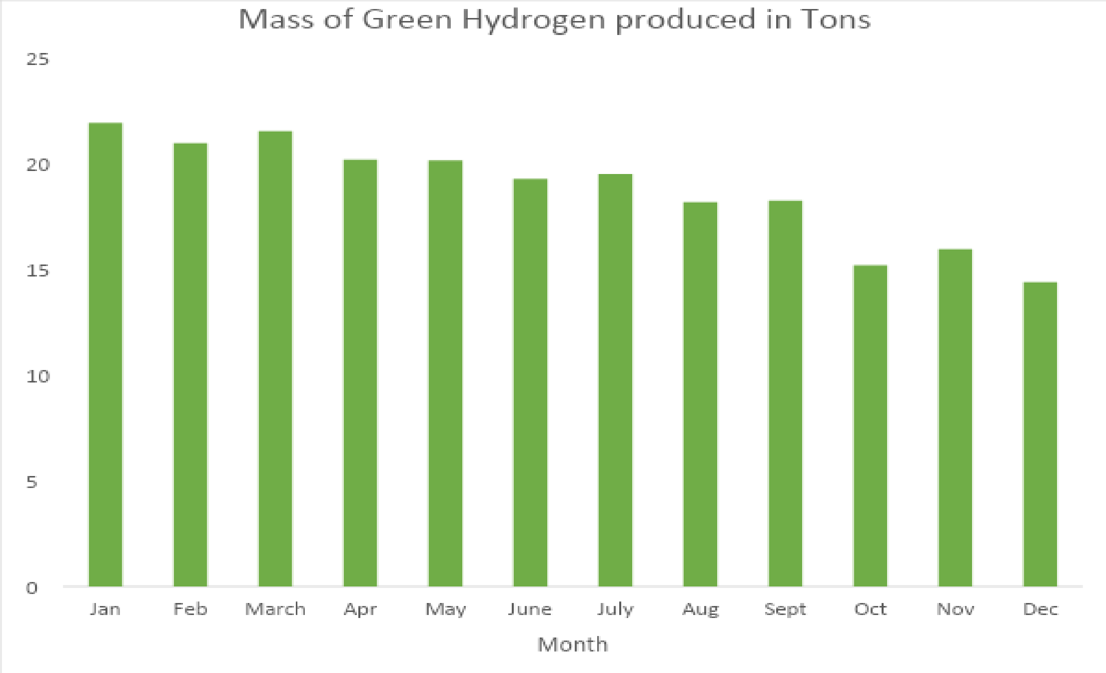


Fig. 9: **Monthly hydrogen production from the solar irradiation at horizontal plane in Niger**

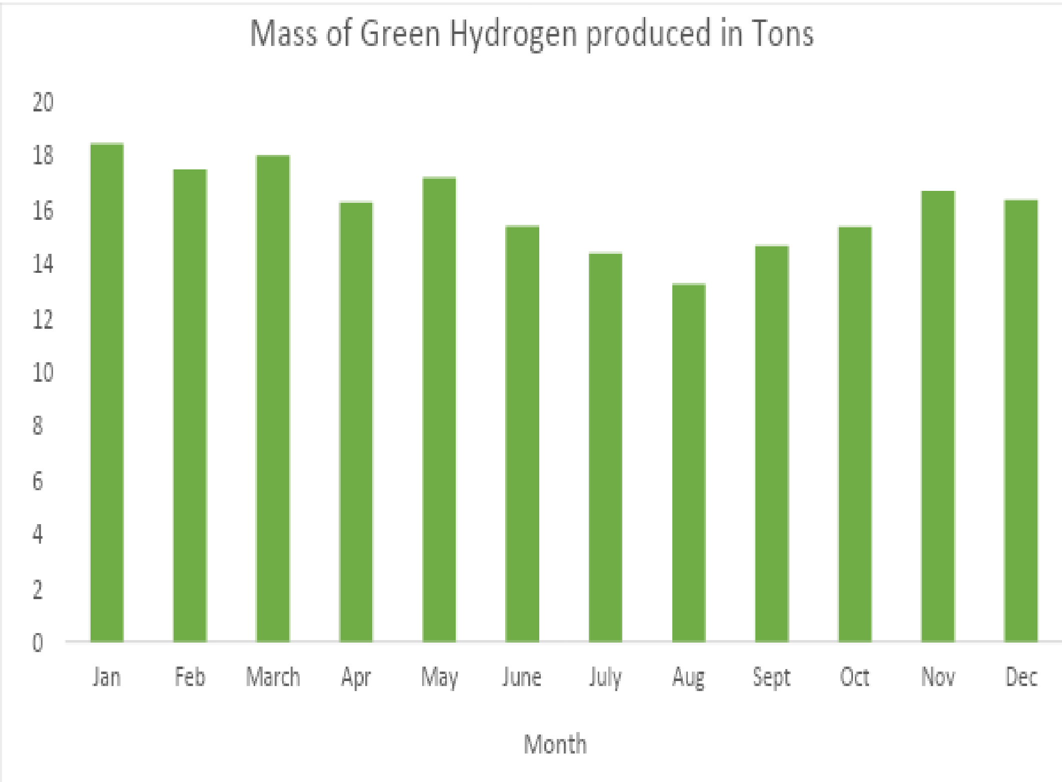


Fig. 10: **Monthly hydrogen production from the solar irradiation at horizontal plane in Nigeria**

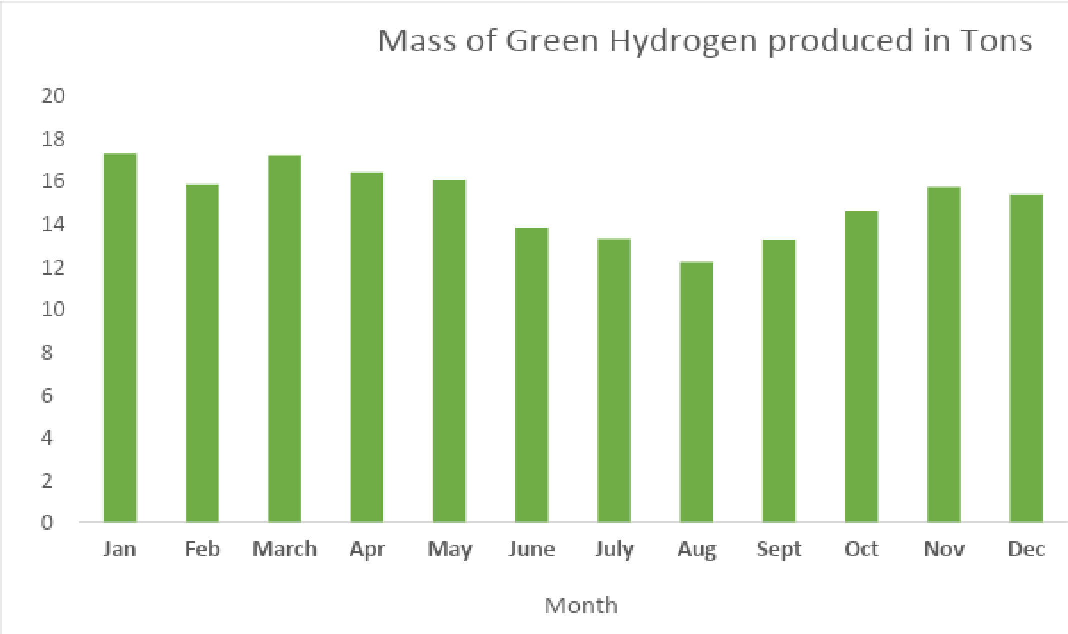


Fig. 11: **Monthly hydrogen production from the solar irradiation at horizontal plane in Ghana**

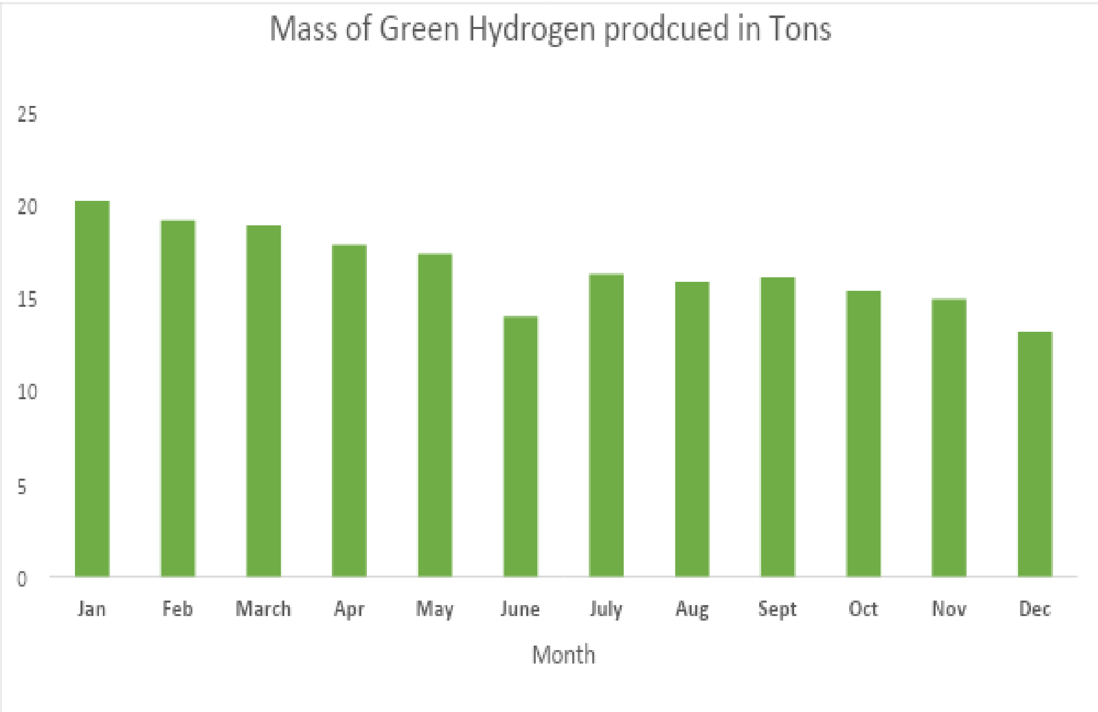


Fig. 12: **Monthly hydrogen production from the solar irradiation at horizontal plane in Senegal**

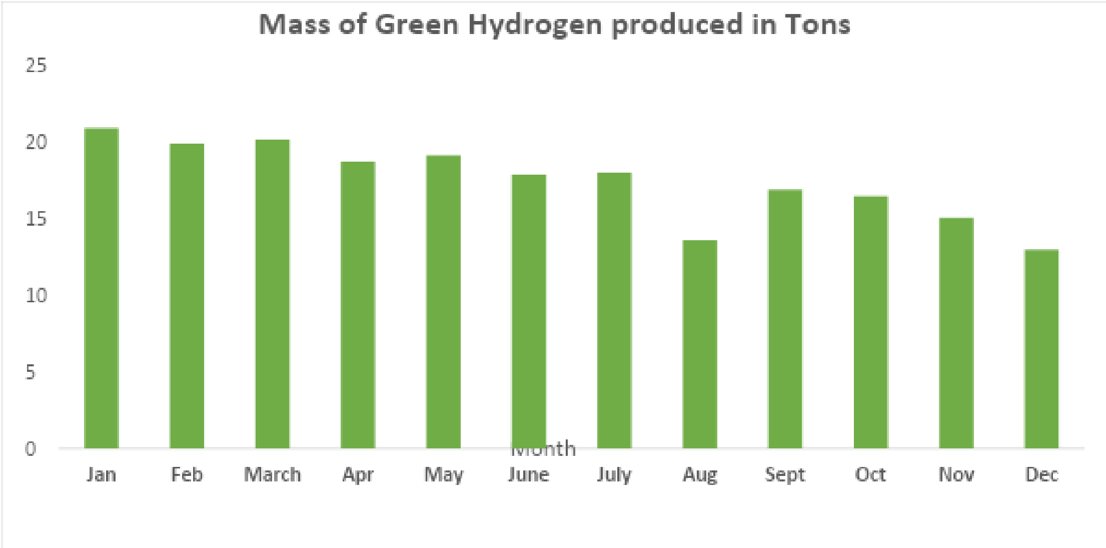


Fig. 13: **Monthly hydrogen production from the solar irradiation at horizontal plane in Mali**

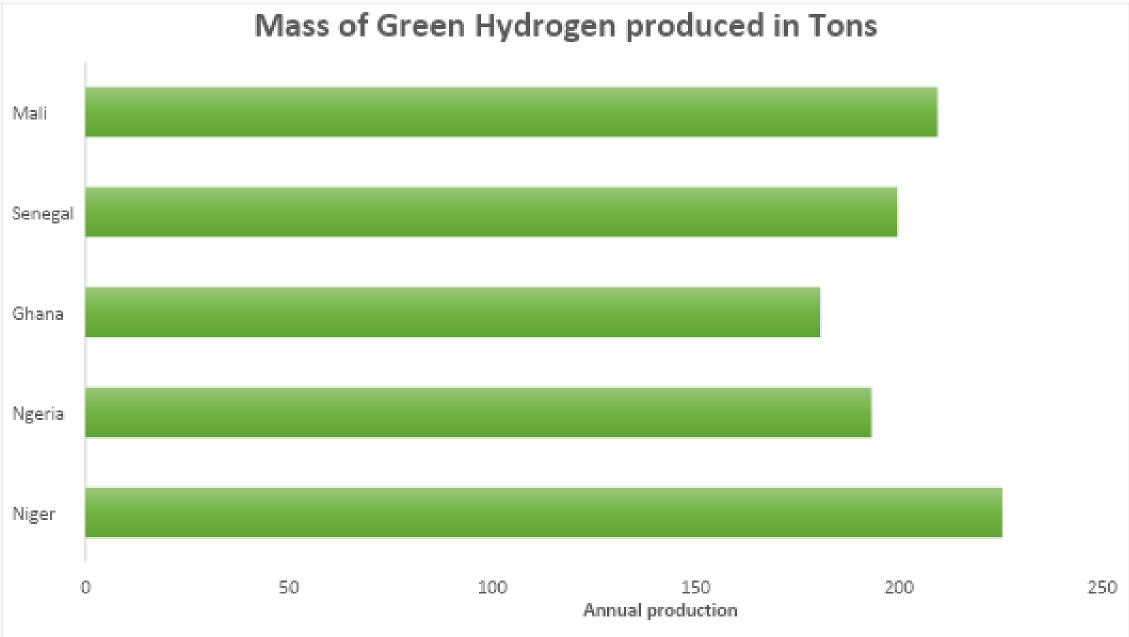


Fig.14: **Annual hydrogen production from the solar irradiation at horizontal plane in all the selected countries**

Estimation of Solar Hydrogen Production

As observed in the preceding results, hydrogen produced utilising inexhaustible sources is primarily linked to the PV and wind energy potential, which directly impacts the power from every source. Hence, there is a direct correlation between the projected hydrogen produced and the potential for renewable electricity. Nonetheless, the allocation of low carbon hydrogen from solar across the various countries behaves differently, attributed to the diverse nature of solar irradiation as well as the specific geographic location, climatic conditions, and technological constraints. **Fig. 14** shows the estimated potential of solar renewable electricity for each country.

On the individual national level as seen in **Fig. 9** and **13**, the monthly PV-based hydrogen generation potential in Niger, and Mali varies in a quite small range. For instance, in Niger, the highest estimated green hydrogen potential is seen in January and March by 22 tons/month and 22 tons/month respectively to the lowest obtained potential which runs from August with the value of 18 tons/month to December with 14 tons/month. In Mali, it was also observed that 21 tons/month were produced in January and 20 tons/month in March as the highest-level production over a year, while the lowest solar hydrogen estimated occurred in December with an amount of 13 tons/month before picking up in the subsequent month.

Also, in Senegal **(Fig.12)**, even though it is a coastal country, the study observed a close value to that of the inland country such as Niger and Mali, and this is due to its proximity to the Sahara Desert. The analysis has shown that the country also has higher production of renewable solar hydrogen production in January and March but a bit lower as compared to the countries mentioned above, and the values are 19 tons/month each with the lowest observed starting from June to December where it ranges between 15 to 17 tons/month.

As compared to coastal countries of the West African region such as Nigeria and Ghana, the estimated solar renewable-based hydrogen generated also varies significantly across a wide range per month as shown in **Fig. 9, 10,**

11,12 and **13**, where the highest estimated hydrogen produced in Nigeria per month was obtained in January and March by 18 tons/month each and the lowest obtained value in July and August by 14 tons/month and 13 tons/month respectively. In Nigeria, Senegal, and Mali, the sum of hydrogen potential for solar PV power over a year with a total of 193 tons/year, 200 tons/year, 192 tons/year and 190 tons/year as shown in **Fig. 16**, showing the optimal regions in West Africa for projects of low carbon hydrogen generation among the coastal countries. Ghana also produces 181 tons/year as the second optimal region in West Africa for projects of solar hydrogen production among the coastal countries after Nigeria. In addition, for monthly capacity production, the location, of Senegal, gives an advantage as compared to that of Niger, and Mali. For instance, in January and March, the solar hydrogen produced is 20 and 19 tons/year respectively and the lowest value is 14 and 13 tons/month in June and December. This could account for the proximity to the Sahel region and this could also be observed in other countries.

According to the results obtained, and for illustration purposes, the work classifies the results into two classes. The first class comprises countries with the potential to produce hydrogen through PV energy due to geographical location. These regions are concentrated in close proximity to the Southern and South-western part of the Sahara Desert parts of West Africa; namely: Niger, Mali and Senegal. The second class includes countries with the possibility of producing hydrogen from solar PV but reserve more attraction to investment due to access to electricity and others. In this class, we find Ghana and Nigeria of the Southern Gulf of Guinea of the West African region. So, in the Southern region, solar energy is less suitable due to the albedo effect but more attractive, this effect explains that regions with vegetation, cloud cover, dust and sand have a relatively high albedo effect which is a measure of sunlight that is reflected by the earth surface. However, in the northern countries, while extensive hydrogen is produced using solar energy is more feasible, it is less appealing.

Economic Analysis

To determine if the project is financially feasible and sustainable, analysing the financial possibility of solar PV-hydrogen production plants is beneficial for both investors and policymakers.

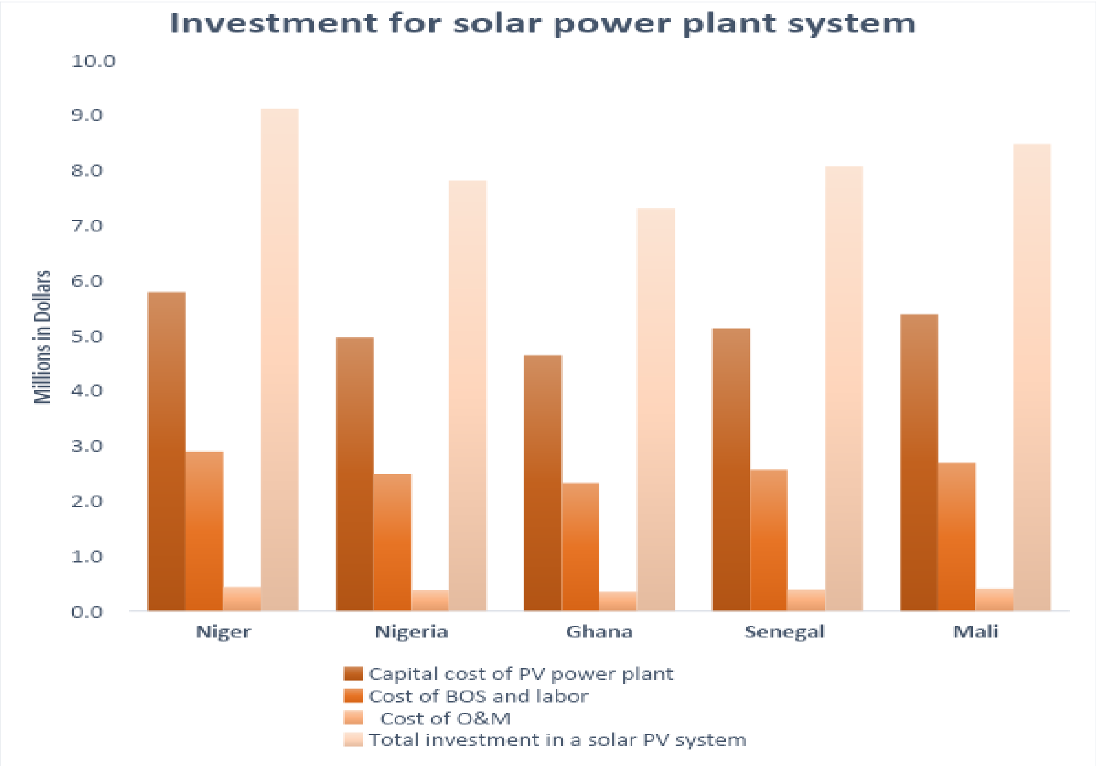


Fig. 15: **The total capital cost of renewable electricity source plant system for all the selected countries**

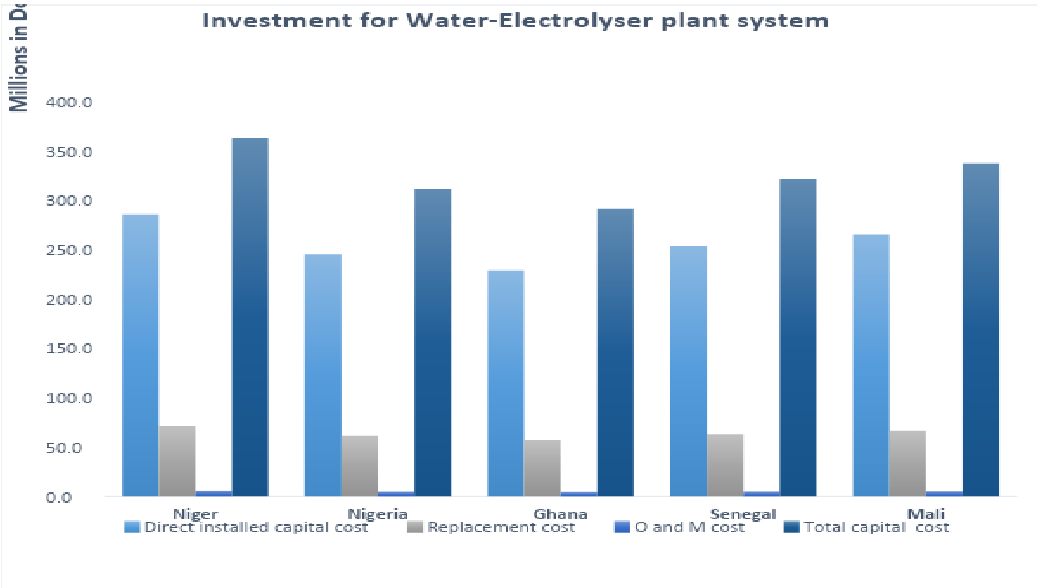


Fig. 16: **The total capital cost of the water Electrolyser plant system for all the selected countries**

Table 9: Parameters used in economic simulation for Solar PV - Electrolyser systems and levelized cost of producing hydrogen by electrolysis

	Niger	Senegal	Ghana	Nigeria	Mali
LCC, $/kWh	26.04	23.30	20.40	22.99	24.68
NPV, $(million)	12,1	11,90	9,8	11,8	11,94
Internal Rate of Return	17%	15%	11%	14%	16%
Simple payback/years	7.3	7.8	8.7	8.1	7.5
LCOH, $/kg	55.34	52.34	60.56	61.78	54.21

Source: Author’s data analysis

The economic analysis worksheet in the Excel spreadsheet has parameters such as discount rate and this work did not include the rate of inflation, reinvestment rate, interest rate of debt and other variables in the analysis. Based on the input variables, Simple payback, Net Present Value (NPV), and Levelised Capital Cost (LCC) were also determined. **Table 8** shows the financial parameters used in this work including electrolyser and module efficiency, Unit price, discount rate, debt ratio, O & M cost, replacement cost, project life and other parameters which served as input variables.

Based on the input variables, the NPV, and other financial parameters were calculated using an Excel spreadsheet. Odoi-Yorke et al., (2023) and Akpahou et al., (2023), highlighted in their research that the NPV and payback period are the primary factors in evaluating the financial feasibility of a solar PV-based energy project. According to this analysis, the NPV values for all regions are positive as shown in **Table 9** above, this indicates that the proposed project is projected to be financially and economically viable (Akpahou et al., 2023). The simple payback period, which is the time needed for recuperation of the project's initial investment, is shown in **Table 9**, **Figures 15** and **16**. In this study, the estimated prospect of solar PV-Hydrogen production projects in Niger has the shortest payback period of 7.3 years followed by Mali and Senegal with 7.5 years and 7.8 years respectively, while Nigeria and Ghana have the longest payback period of 8.1 years and 8.7 years respectively. In addition, it is found that Ghana has the lowest levelised capital cost of PV electricity of 20.40 $/kWh followed by Nigeria and Senegal with a value of 22.40 $/kWh and 23.30 $/kWh, while Niger and Mali have the highest electricity cost of 26.04 $/kWh and 24.68 $/kWh respectively as shown in **Table 9** above. Further analysis of the project was conducted by estimating the value of the levelised cost of hydrogen LCOH of the estimated solar PV-Hydrogen production project. **Table 9** presents the outcome of this analysis for all selected countries. The proposed PV project in Niger has the lowest LCOH of 55.34 $/kg followed by the one in Mali and Senegal with 54.21 $/kg and 52.34 $/kg respectively, while Ghana and Nigeria have the highest LCOH of 60.56 $/ kg and 61.78 $/ kg respectively.

More so, the overall initial investment of inexhaustible power source plant systems for all the selected countries varies as shown in **Figure 15** above, where the total capital investment of solar PV plant required for the generated hydrogen is 9 million dollars in Niger followed by Mali with 8.7 million and Senegal with 7.7 million dollars, while Nigeria and Ghana observed the lowest values of 6.9 and 6.6 million dollars respectively.

In addition, the analysis of the overall capital expenditure of the Water Electrolyser Plant System for all 5 selected countries showed a significant similarity to the country-based annual investment as compared to that of the solar PV power plant. Here, the analysis observed total investment in Niger to be 380 million dollars, Mali 354 million dollars and Senegal with 320 million dollars, while Nigeria and Ghana recorded around 300 and 295 million dollars respectively as shown in **Figure 16** above.

Chapter Summary

In this chapter, the results and discussions of the study's data were presented concerning the targets outlined. The section also outlined key economic viability assessment of the solar PV-based hydrogen in the countries concerned. The chapter specifically discussed the technical aspects and economic potential evaluation of carbon-free hydrogen energy. Lastly, the chapter analysed the various factors that make green hydrogen production more profitable and attractive to investors, government, local population and other stakeholders within the value chain to participate massively in the sustainable hydrogen energy sector. The following chapter presents a summary of the study's findings, conclusions drawn from those findings, and recommendations.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

Introduction

This section provides an overview of the primary findings, conclusions derived from these findings, and recommendations for policy considerations, along with suggestions for future research.

Summary

The study aimed to assess the economic and technical feasibility of solar PV-based hydrogen in five (5) selected countries within the Western African Region. Specifically, the objectives were to evaluate the solar radiation potential in these countries, analyse the possibility of PV-based hydrogen production, and assess the financial viability of hydrogen generation in these West African nations.

The study utilized the secondary data analysis method and adopted a quantitative research design to align with its objectives. Solar radiation data was used to compute the amount of PV electric power required to generate a specific amount of PV electricity for the produced green hydrogen. Data obtained was processed using Microsoft Excel Spreadsheet and analysed using technical and economic parameters such as Mass, energy generated, amount of electricity required, investment costs, levelised cost of energy, net present value, simple back time, return on investment, and internal rate of return. Also, mathematical analysis was carried out on the quantity of power and Hydrogen produced. In Chapter Four, the outcomes were presented in tables and figures and thoroughly discussed. The subsequent section outlines a summary of the study's key findings.

This work offered a comprehensive examination and relevant discussion on the technological and financial capacity of carbon-free hydrogen in academic literature. The study's findings provide valuable information that could shape policies. The major findings include insights on the potential of solar radiation assessment, which aligns with the first objective in five (5) selected areas in West Africa required for the generated PV power for the low carbon hydrogen, the study found out that there were high amounts of global irrationally horizontal value with higher solar electricity in some countries as compared to others. This is because the majority of the countries located around the Sahara Desert tend to have a lot of solar irradiation. It was also observed that Mali, Niger and Senegal have value in terms of solar energy. This implies a positive economic viability of generating PV-based electricity in these regions, while Ghana and Nigeria recorded a quite low amount of solar energy, hence, the last generation of PV-based electricity demanded hydrogen generation.

Regarding the second research objective on the prospects of low carbon hydrogen in the West African region, the study found that the quantity of kilogramme of hydrogen generated per year of the selected countries is quite high and shows positive prospects for hydrogen production in the region of Africa. This is because even though there are infrastructural, technological and economic challenges, all the countries showed a great amount of hydrogen produced yearly, and this could result in more viable ways of decarbonising the energy sector in the region as well as improving not only the safety and quality of the environment but also, the socio-economic wellbeing of the population in these countries.

Finally, the third research objective centred on assessing the financial viability of green hydrogen energy generation in the selected countries in West Africa. The study found that all the projects which could be undertaken regarding this objective could be economically viable. This is because most of the economic modelling parameters do look promising. For instance, the Net present value of the estimated projects across all the countries selected after analysis showed a positive value. This has heavily impacted the rate of return on investment and payback time of the estimated projects. Nonetheless, in the future, when more development of the hydrogen energy sector and other parameters are taken into consideration, there could be more options for these countries to capitalise on. Thus, any enhancement in the hydrogen sector that is technological, infrastructural, and the operations in these countries will lead to improved viable economic satisfaction of investors.

Conclusions

This work showed an overview and important literature on the prospect of green Hydrogen energy and its techno-economic feasibility in 5 selected countries in the West African region within academic literature. Furthermore, the study estimated the possibility of hydrogen generation through water electrolysis utilising weather data, observations, and technical models. This involved three main aspects: evaluating solar potential, estimating electricity generation, and analysing the possibility of solar renewable-based hydrogen generation. The feasibility of the hydrogen prospect was examined and determined. In conclusion, the following points can be inferred:

The available solar irradiation fluctuates within a relatively narrow range, with the highest irradiation occurring in Niger equals 2413 kWh/m2/year to the lowest irradiation in Ghana of 1692 kWh/m2 yearly. From the analysis, it appears that Southern regions, including certain areas of the Southern Sahara Desert, show more promise than others for harnessing solar resources for generating energy and producing hydrogen. However, the projected solar power and hydrogen potential do not significantly differ among all the selected countries. The yearly solar PV electricity potential varies from 21.44 and 17.18 GWh as shown in **Table 3-7**. In Niger and Ghana, for instance, the corresponding low carbon hydrogen generation prospect from solar photovoltaic panels equals 225.47 as the highest and 180.70 tons/year as the lowest respectively. In Niger, Mali, and Senegal, at the North and East-west side of West Africa, these countries have the highest possibility of generation exceeding the estimated 225.47 tons/year, 209.96 tons/year and 199.69 tons/year respectively of low carbon hydrogen. It could be suggested that countries like Mali, Niger and Senegal are ideal for large-scale solar hydrogen production initiatives as compared to Ghana and Nigeria with 193.34 tons/year and 180.69 tons/year respectively.

Further, Ghana exhibits substantial possibility for funding in hydrogen owing to its ample renewable energy resources, particularly solar, according to (IRENA, 2022). Additionally, the study pointed out that the possibility for hydrogen investment is bolstered by the country's efforts to broaden the energy blend and lessen dependence on traditional fuel. Also, Nigeria presents a complex landscape for green hydrogen investment. While the nation possesses plentiful renewable energy sources like solar, challenges such as inadequate infrastructure, regulatory uncertainties, and political instability pose significant hurdles to investment (Ballo et al., 2022a). Despite

Nigeria's ambitious renewable energy targets and policies, Regulation, implementation bottlenecks and limited access to financing hinder the scalability of green hydrogen projects (Ballo et al. 2022b).

Also, Ballo et al. (2022b) further suggested Nigeria's vast population and industrial base create significant energy demand, making the transition to green hydrogen imperative for sustainable development. Despite the country's renewable energy targets, challenges such as corruption, bureaucratic hurdles, and policy inconsistency hinder investment in the sector (Ballo et al. 2022b). They highlighted the challenges of the dominance of the fossil fuel industry and resistance to change that pose further obstacles to green hydrogen adoption in Nigeria. Additionally, Mali, Niger and Senegal are emerging as a promising destination for green hydrogen investment. These territories offer ample opportunities for renewable energy development. With abundant solar and wind resources spread across, these countries have the natural potential to be key players in renewable hydrogen. The government's commitment to renewable energy development, evidenced by initiatives like the Scaling Solar program and the National Renewable Energy Plan, provides a supportive framework for carbon-free hydrogen projects.

The profitability of low-carbon hydrogen is underpinned by several factors. Ghana's abundant solar resources offer favourable conditions for renewable energy generation, a critical component of green hydrogen production as shown in this study. Additionally, Ghana's stable political environment and supportive regulatory framework, including incentives for green energy projects, enhance the profitability of green hydrogen ventures (IRENA, 2022). Furthermore, the increasing global need for clean energy and low carbon initiatives present export opportunities for Ghanaian green hydrogen producers, potentially boosting profitability in Ghana's revised National Determined Contribution 2020 report highlighted in (IRENA, 2021). Nigeria's renewable energy targets and government incentives provide a conducive environment for profitable investments (Ballo et al. (2022a). Moreover, they exclaimed Nigeria's strategic location in West Africa positioned itself as a potential hub for green hydrogen export, further enhancing profitability prospects.

Mali, Niger and Senegal's commitment to renewable energy development and favourable policy environment contribute to the profitability outlook for green hydrogen generation. The public initiatives to attract funding for inexhaustible energy projects, combined with Senegal's abundant solar and wind resources, create opportunities for profitable green hydrogen ventures as observed in this study Additionally, these countries' strategic location as a gateway to West Africa and Europe position's it favourably for green hydrogen export, potentially enhancing profitability (Ballo et al., 2022a).

Furthermore, having the lower electricity price in Ghana with 0.12$/kWh (IEA, 2024), green hydrogen production may present opportunities for economic viability and competitiveness. Lower electricity prices reduce the operational costs of electrolysis, rendering green hydrogen more affordable as compared to fossil fuel-based alternatives (IRENA, 2021). Moreover, supportive government regulations and incentives, like feed-in tariffs and investment incentives, can further enhance the feasibility of green hydrogen projects in low electricity price environments by reducing investment risks and increasing investor confidence (World Bank, 2020). Leveraging these opportunities requires strategic policy interventions and targeted investments to capitalize on the economic potential of environmentally friendly hydrogen generation in low electricity price environments (Ballo et al., 2022b).

However, high electricity prices pose significant challenges to the feasibility of environmentally friendly hydrogen generation. In countries like Nigeria, Senegal, Mali and Niger where electricity costs are relatively high; 0.16$/kWh, 0.167 $/kWh, 0.171$/kWh and 0.178 $/kWh respectively. Due to the high price, operational expenses of electrolysis will increase, impacting the overall competitiveness of green hydrogen (World Bank, 2021 and IEA, 2024). Moreover, without supportive government policies to mitigate these challenges, investors may perceive green hydrogen projects as financially risky, thus, deterring potential investments. Tackling these challenges necessitates a multifaceted strategy involving tariff reforms, investment incentives, and regulatory measures to reduce electricity costs and improve the attractiveness of low-carbon hydrogen projects.

Moreover, Public policies play an important role in shaping the feasibility of H_2 production. Enabling regulations, like green energy objectives, feed-in tariffs, and financial incentives, can stimulate investment in green hydrogen projects by reducing financial risks and increasing investor confidence (IRENA, 2020). For instance, Ghana's Renewable Energy Act of 2011 stipulated a legal framework for renewable energy projects, offering incentives like tax breaks and feed-in tariffs (IRENA, 2020). Similarly, Nigeria and Senegal's National Renewable Energy Plan and Niger and Mali's Renewable Energy Development Project demonstrate government commitment to renewable energy, by fostering an enabling environment for green hydrogen initiatives.

Nevertheless, each of the selected West African countries that are; Ghana, Nigeria, Senegal, Mali, and Niger offer opportunities for investing and profitable green hydrogen production, addressing the challenges such as infrastructure readiness, political regulatory uncertainties, and investment condition barriers is essential for realizing the full profitability potential. Techno-economic analyses that consider these factors are instrumental in informing investment decisions and maximizing returns in green hydrogen ventures in the region.

Finally, the study's findings indicate that harnessing the projected hydrogen possibility could significantly improve the standard of living in the study area. This could be achieved through job creation, skill development, reduced reliance on oil and gas, and fulfilling commitments to lower greenhouse gas emissions and fight climate change. Furthermore, in the coming years, tapping into this solar renewable energy possibility for extensive hydrogen generation could position these countries as major global suppliers of electricity and revolutionize the energy landscape through hydrogen as a key energy sub-sector.

Recommendations

Based on the research findings and conclusions from this work, the following suggestions were proposed;

1. Government of each country in the West African region should develop a strategy for attracting international and national investors through the rapid advancement of the green hydrogen Roadmap and the amendment of the

existing, and new policy laws, as well as request the traditional authorities for the rapid transformation of environmentally friendly hydrogen in the region for the utmost benefits of the people in promoting sustainable development across board to strengthen the entry of investors that will contribute to crucial wealth creation and enhance the local economy.

2. Public authorities such energy commission of each country and green hydrogen energy companies should implement small-scale economic strategies, like environmentally friendly alternative initiatives, to imbue the national financial framework with greater purpose.

3. Firms involved in Green Hydrogen energy projects, as key stakeholders, should be prompted to include sustainability clauses in their employment agreements. This way, any alternative initiatives they offer could be considered an additional source of income for the population in the countries of destination.

4. Hydrogen energy firms should have their operations regularly assessed to improve technical and economic innovation and ensure general acceptance. These assessments could be conducted annually to adapt to evolving trends in sustainable hydrogen energy. This would help obtain maximum satisfaction from consumers and stakeholders within the hydrogen energy value chain.

5. Finally, since green hydrogen technology is a new energy space venture, education and seminar initiatives should be arranged to educate inhabitants on the economic benefits and drawbacks of Green Hydrogen processes, including potential local economic disruptions. This approach could help with more positive perceptions and promote continuous dialogue among organisations and the host community.

Suggestions for Further Research

Although the work offered a valuable understanding of the prospect of techno-economic hydrogen generation from solar renewable in the context of the industry, the results cannot be applied to the whole sector of hydrogen energy and other renewable industry potential in the West African region. This is because the study focused on a few parameters of the feasibility of hydrogen energy from both technical and economic standpoints in only five (5) countries namely; Ghana, Nigeria, Mali, Senegal and Niger and thus the analysed data and values obtained do not necessarily show the overall situation throughout other hydrogen energy estimated projects. The study suggests that future research should expand to include other types of inexhaustible resources like wind, wave, bioenergy, and other projects in the industry as well as the countries in the region and also, research on the perceived environmental impacts of environmentally friendly hydrogen production activities in the selected countries in the West Africa region.

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