Université Cheikh Anta Diop de Dakar

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INTERNATIONAL MASTER PROGRAMME IN ENERGY AND GREEN HYDROGEN (IMP-EGH)

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MASTER THESIS

Speciality : Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic :

A Review of the Supply Chain of Green Hydrogen Production in West Africa : Challenges and Opportunities

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Presented the September 20th, 2023 by :

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DECLARATION

I, Rayanatou Sidi Mahaman declare that this thesis and the work presented in it are my own and have been generated by me as the result of my original research. I do solemnly swear that:

1. Where I have consulted the published work of others or this, myself is always clearly attributed;

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DEDICATION

This master's thesis is entirely dedicated to my son Abdallah for my absence at the moment that he ever needs my presence, care, a warm embrace, maternal milk, etc... I understand that the decision I have made may be viewed as wrong, yet it was undertaken with the best of intentions. But rest assured dear son that I will try my best to give back what I have taken insha Allah.

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ABSTRACT:

Hydrogen started having more relevance with the energy crisis and climate change events. West African countries seem to be a solution to unlock a part of the energy shortage with its potential in green hydrogen estimated at up to 165,000 terawatt-hours per year by using wind and solar energy, of which 120,000 terawatt-hours could be produced for 2.50 euros per kilogram (*Edgar*, 2021). For West Africa to take advantage of its hydrogen potential and avoid the most predominated risks related to technology, environment, economy, and social aspects, a review of challenges and opportunities in the supply chain for green hydrogen production in West Africa could be an important step in shaping the future hydrogen business in that particular region. three countries are selected as case studies based on a review of their characteristics such as geography, political stability, support for renewable energy and green hydrogen development, and green hydrogen production potential, among others. A series of criteria are defined and assessed to understand and evaluate the current status of the supply chain for green hydrogen in West Africa based on a comparative methodology. This thesis provides an overview of strategies to address the challenges and opportunities for green hydrogen production in West Africa.

THE FRENCH VERSION OF THE ABSTRACT

L'hydrogène a commencé à prendre plus de pertinence avec la crise énergétique et les événements liés au changement climatique. Les pays d'Afrique de l'Ouest semblent être une solution pour pallier une partie de la pénurie d'énergie grâce à leur potentiel en hydrogène vert, estimé à jusqu'à 165 000 térawattheures par an en utilisant l'énergie éolienne et solaire, dont 120 000 térawattheures pourraient être produits pour 2,50 euros par kilogramme (Edgar, 2021). Pour que l'Afrique de l'Ouest puisse tirer parti de son potentiel en hydrogène et éviter les risques les plus prédominants liés à la technologie, à l'environnement, à l'économie et aux aspects sociaux, une revue des défis et des opportunités dans la chaîne d'approvisionnement de la production d'hydrogène vert en Afrique de l'Ouest pourrait constituer une étape importante dans la définition de l'avenir des affaires liées à l'hydrogène dans cette région particulière. Trois pays sont sélectionnés comme études de cas en fonction d'un examen de leurs caractéristiques telles que la géographie, la stabilité politique, le soutien aux énergies renouvelables et au développement de l'hydrogène vert, ainsi que le potentiel de production d'hydrogène vert, entre autres. Une série de critères sont définis et évalués pour comprendre et évaluer l'état actuel de la chaîne d'approvisionnement de l'hydrogène vert en Afrique de l'Ouest selon une méthodologie comparative. Cette thèse fournit un aperçu des stratégies pour relever les défis et saisir les opportunités de production d'hydrogène vert en Afrique de l'Ouest.

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INTRODUCTION:

1.1 Background

From 1880 to 2012, our planet's climate system experienced rapid transformations, accompanied by a global average temperature increase of 0.85 °C (Schickhoff et al., 2016). The Intergovernmental Panel on Climate Change (IPCC) has identified greenhouse gases as the primary catalyst for these changes, with anthropogenic activities playing a significant role. Governments, as well as national and international organizations, are now actively seeking to transition toward a sustainable and decarbonized energy landscape from 1997 in Japan with Kyoto Protocol until today. Various strategies have been implemented to address the problem which each nation is facing. For some nations, access to 100% of affordable modern energy is achieved (Sebastian, 2015). The crucial step is to switch from fossil fuel that generates harmful greenhouse gases to clean and sustainable fuel. Conversely, other nations particularly developing countries are looking for just 50% access to affordable modern energy by 2030 through an increase in renewable energy share (Bazilian et al., 2012).

However, such goals cannot be achieved by solely relying on traditional renewable energy sources, such as wind and solar looking at the fact that some industries, such as heavy-duty transportation, as well as steel and cement production are difficult to adapt to the green transition due to the challenge of electrifying their processes (Hainsch et al., 2022). This is just one illustration of why the global transition to green energy has led to a growing interest in green hydrogen as a clean energy carrier and this can satisfy both two categories of nations' needs and even more.

For countries with low access to affordable modern energy particularly in West African countries which are Benin, Burkina Faso, Cabo Verde, Cote d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo; the electricity access varies from 13% in Burkina, Niger to 96% in Cape Verde. Paradoxically, these countries that need electricity access have a huge green hydrogen potential. This means important significant volumes of green hydrogen from that region of West Africa with an abundance of renewable energy to regions with land resources and less renewable energy potential to produce green hydrogen. This could lead to a raise in this country's significant sustainability questions from green hydrogen production to its local use meaning the supply value chain.

1.2 Problem Statement:

As a consequence of climate change and the move to sustainable energy, alongside the energy crisis, green hydrogen has become a relevant alternative in the recent decade. West African countries seem to be a solution to unlock a part of the energy shortage with their potential in green hydrogen estimated at up to 165,000 terawatt-hours per year by using wind and solar energy, of which 120,000 terawatt-hours could be produced for 2.50 euros per kilogram (Edgar, 2021). A review of challenges and opportunities within the supply chain for green hydrogen production in West African countries could serve as an important step in guiding the future green hydrogen business in that particular region, as it will allow West Africa to take advantage of its hydrogen potential and avoid the most predominated risks related to technology, environment, economy, and social aspects.

1.3 Research Questions:

To meet the expectation of the West African countries while in the early stages of green hydrogen production, relevant steps have to be identified and addressed by asking:

- What is the status of the supply chain for green hydrogen production in West Africa?
- What challenges and opportunities do West African countries have when entering the green hydrogen market? What would be reasonable metrics for such an assessment?
- What strategies could the West African countries implement to address the challenges and opportunities identified?

1.4 Organization of the Study

After the presentation of the research question in section 1.3 the following section is focused on the work structure;

- The first part will introduce the topic of the master's thesis, the research questions, and the review literature on Green hydrogen projects planned and implemented in ECOWAS members, policies related to & supporting green hydrogen production in ECOWAS, and a review of supply chain needs for green hydrogen production.

- The second part: At the beginning of this section, three countries will be selected as case studies based on a review of their characteristics such as geography, political stability, support for renewable energy and green hydrogen development, and green hydrogen production potential, among others. Secondly, we will proceed with the identification of challenges and opportunities from the peer-reviewed literature, the content of the courses in the IMP-EGH master's program, and official reports on the region. Finally, an assessment of the identified challenges and opportunities will be done using a composite approach based on the technique employed for the development of the United Nation's Sustainable Development Goals index (Lafortune et al., 2018) by combining indicators from the H_2 Atlas project, and a thorough review of literature that address and assesses the criteria previously mentioned.
- Third part: It is focused on the interpretation and discussion of the assessment of the identification of challenges and opportunities, then it will end up with some recommendations from the interpretation of the assessment.

I. LITERATURE REVIEW:

Sub-Saharan Africa is the continent with the lowest carbon footprint, which currently stands at 4% of global emissions (Hannah, 2019). This means that, unlike other regions, West African countries need not prioritize emission reduction, as their current emissions are within agreed limits. Given this, as well as the continent's existing issues in terms of economic and social development, West African nations need to focus on boosting economic progress and lifting people out of poverty, while aiming for 100% renewable energy (Arona, 2022).

To achieve this goal, many West African countries started seeking strategies to reduce their liability on non-renewable energy and improve electricity access to many millions of people by raising the promotion of renewable energy resources. More recently, many of these West African countries are saddling partnerships around the world on green hydrogen development, the German Federal Ministry of Education and Research is one of the example partners to West African countries in green hydrogen development (Hans-Joachim, 2021).

1.1 Review of green hydrogen projects planned and implemented

To date, no ECOWAS country has implemented a large-scale green hydrogen project. However, there are some advancements in terms of research and development.

Below are listed some anecdotal, but telling examples:

- In August 2022, the global leader news website called Hydrogen Industry News & Market Intelligence announced that Burkina initiated the West Africa Project of Optimization of Solar Photovoltaic for the Production of Green Hydrogen (PV2H). The same project is also engaged in the study of assessing the potential for producing green hydrogen from biomass energy and determining the viability of a 1-megawatt waste power plant in Zagtouli, a village near the capital city of Ouagadougou. (redactoramexico, 2022).
- According to a report by "Renewable Now" in February 2022, Emerging Energy Corporation (EEC), a German energy solutions company, is set to collaborate with the government of the Republic of Niger to investigate and advance commercial green

hydrogen initiatives within the West African nation. Additionally, the EEC plans to make investments in a range of projects aimed at reducing carbon emissions from oil field operations and refineries in Niger by utilizing carbon capture technologies (Ivan, 2022).

- The German company Syntech Fuels GmbH intends to produce green hydrogen and synthetic fuels from waste, on the Cape Verdean islands. The initiative provides for the construction of two scalable green hydrogen production plants, on the islands of Santiago and Boa Vista, with the capacity for the production of synthetic fuels and related economic undertakings, namely in the fields of organic agriculture, drinking water, and irrigation, aquaculture, fertilizers, and high-purity chemical products. This was reported by " The Rio Times" (Reporters, 2022).
- Mali stands out as a promising location for the availability and use of white hydrogen (i.e. hydrogen found underground) in free form. Since the hydrogen in the discovered wells does not need to undergo electrolysis of any form, its exploitation price is much cheaper than the manufactured green hydrogen (Eric, 2023) & (Coy, 2023).

1.2 Review of policies related to & supporting green hydrogen production in ECOWAS

Hydrogen production is planned to begin soon in ECOWAS countries. This means that legislative frameworks have to be developed in the region to aid the coupling of hydrogen production with other industries. Although ECOWAS countries have yet to lay out their hydrogen strategies, hydrogen production by certain firms has already begun. While ECOWAS countries in general have specific laws which regulate renewable energy, their application is problematic and uneven (Ballo et al., 2022)

For instance;

Benin: the Law No. 2020 of 1st of April 2020 was established to guide the policy of energy in the country. It addresses the regulation capacity of the new generation and has as a goal to encourage the renewable energy sector, It also aims to raise national energy independence in the energy mix.

In **Burkina Faso**: Law No. 014-2017/AN of 20 April 2017 and Law no. 058-2017/AN of 20 December 2017, set to guide renewable energy and to regulate the condition of eligibility for the exemption from tax of solar equipment to reach in the electricity mix by 2030 50% renewable energy (PANEE, 2015).

Cape Verde: Law No. 14/2006 of 20 February and Law no. 39/2019 of 8 April to guide the renewable energy sector too and have as a goal to promote by 2025 and 2030 the 50% of electricity production from renewable energy sources (DGRNE, 2020)

Côte d'Ivoire: like in Burkina Faso, law No. 2016-862 of 03 November 2016 in Côte d'Ivoire exempts renewable energy materials from tax, and due to this law, the government wants multiple twice its energy efficiency by 2030.

The Gambia: In the Gambia, the legal, economic, and institutional basis of renewable energy resources are governed by the Bill/Act of 2013. In addition, to facilitate both power and non-power applications from import duty, the Ministry of Energy developed Energy Strategies.

Ghana: In Ghana, the renewable electricity generation target is to achieve 2030 1,353.63 MW, with a contribution of 220,000 jobs and 11 million tonnes of CO2. Act 832 provides for the development, management, and utilization to reach the goal of renewable energy policy by 2030(*PURC*, 2020)

Guinea: In Guinea, law No 2014/30/1/6/1/2/N comes with policies of grants, bonuses, subsidies, or loans at subsidies rates on renewable energies materials by exempting them taxes from import, in order to promote the implementation of energy saving measures for renewable energy (felixleno, 2020)

Guinea Bissau: The production, transport, distribution, import, and export of electrical energy within the country is regulated by Decree-Law No. 3/2007. However, no specific fiscal and investment frameworks or provisions exist for the energy sector currently(ALER, 2018).

Liberia: On July 6, 2015, the (RREA) Rural and Renewable Energy Agency has been established by Government. Its goal is to face challenges to the energy supply in rural areas, it ensures access to modern energy in an affordable, sustainable, and environmentally-friendly manner to boost political, economic, and social development in the country.

Mali: Renewable energies (RE) have taken priority in Malian public policy and strategic framework for growth and reducing poverty. Mali has several strategies, policies, acts, and regulations governing renewable energy. One of them is Law No. 03-006 of 21 May 2003, which aimed to implement rural electrification and domestic energy policy and regulatory framework.

Niger: The Electricity Law in Niger is No. 2016-05 of 17 May 2016, implemented by the Minister in charge of Energy. This law promotes the implementation of the entire energy policy framework and regulations, and increased financing for the country’s energy and economic growth.

Nigeria: From Act No. 6 of 2005, the Nigerian Electricity Regulatory Commission (NERC), made the Regulations on Feed-In-Tariff for Renewable-Energy-Sourced Electricity to develop, promote, and harness the Renewable Energy (RE) resources of the country and incorporate all viable national energy mix. The (NERC) intends also to enhance the attainment of the national targets on renewable-energy-sourced electricity.

Senegal: Senegal put in place law No. 2010-21 to orient by promoting renewable energy by granting a total exemption on taxes for the acquisition of materials for renewable power generation. This was done to facilitate the development of renewable energy projects.

Sierra Leone: In Sierra Leone, the Act (2011) was implemented with the purpose of committing the government to undertake various measures. These measures aimed to ensure that renewable energy becomes a substantial component of the country's energy portfolio within the next 15 years. In Sierra Leone, an act was put in place in 2011 to commit the government to measures for promoting renewable energy. This was done for renewables to occupy a significant part of the country’s energy portfolio for the next 15 years.

Togo: The Togo Government put in place Law No 2018-010 to establish the legal framework governing the equipment/materials, installations, and other necessary infrastructure for the production, storage, transport, distribution, marketing, and consumption of electricity based on renewable energy sources.

1.3 Review of Supply chain needs for green hydrogen production

Green hydrogen production requires the use of renewable energy sources and water. The renewable energy source can be Solar, Wind, Hydropower, and Geothermal. These renewables generate electricity that is going to be used for splitting water in electrolysis to produce Hydrogen (ENGIE, 2021).

1.3.1 Product development:

In the 1800s, the first hydrogen demonstration was made by water electrolysis and fuel cells cached the engineers' imagination. For over 200 years, hydrogen was used for the internal combustion engine fuel. Then in the 18th to 19th centuries, it was used for balloons and airships, and in the 1960s it propelled humanity to the moon. When its use became commonplace, especially in oil refining in the mid of 20th century, hydrogen was integrated into the energy industry where hydrogen in fertilizer (ammonia) helped to feed the global population.

Today, hydrogen's development is only expanding as it can be stored and utilized in many sectors, converting electricity to hydrogen and converting hydrogen back into electricity (*IEA*, 2019).

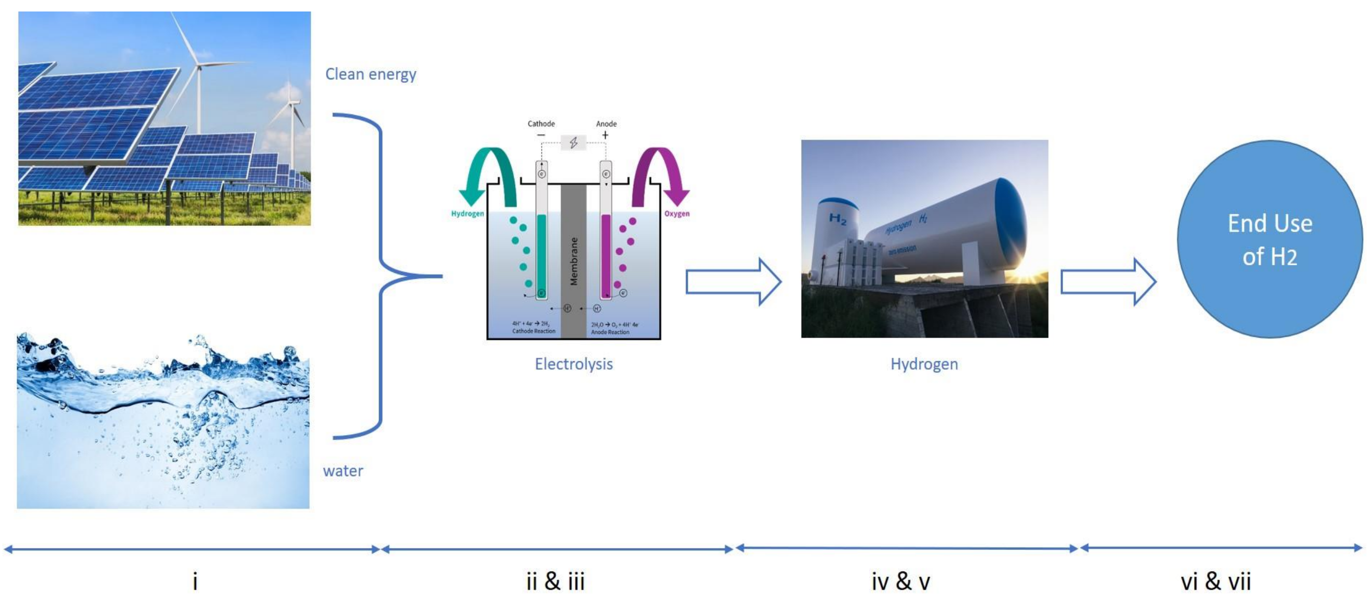

Figure 1: supply chain of green hydrogen production

Source: own illustration

Below is a clear explanation of Figure 1, taken from the IMP-EGH (International Master Program – Energy and Green Hydrogen) courses:

i. Power Generation: The electricity is generated by renewable energy sources, which serve as the input for the electrolysis process. Power generation may involve solar farms either by PV or CSP systems, wind turbines, or hydroelectric power plants. Depending on the source of energy used for water splitting, hydrogen has been cataloged by color, where “green” hydrogen, in particular, implies the process in which electricity is generated from emission-free sources such as wind and solar.
ii. Electrolysis: Electrolysis is the process of using electricity to split water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2). The electrolyzer consists of an anode and a cathode called an electrode, separated by an electrolyte, to facilitate this process.
iii. Hydrogen Production: Green hydrogen is produced through the electrolysis process. It requires capturing the hydrogen gas produced at the electrode called the cathode and ensuring its purity and quality.
iv. Purification and Compression: The produced hydrogen may undergo purification to remove impurities and compression to increase its density, making it suitable for transportation and storage.
v. Storage: Due to the intermittent nature of renewable sources such as wind and solar power, hydrogen storage is necessary to ensure a reliable supply. Storage options include underground caverns, salt domes, and compressed gas containers, depending on the scale and duration of storage required.
vi. Distribution: Green hydrogen can be distributed to end-users, such as fueling stations, industrial facilities, or power plants, through a network of pipelines, trucks, or other delivery methods.
vii. Utilization: End-users consume green hydrogen for various applications, such as transportation fuel, industrial processes, power generation, or as feedstock for chemical production.

1.3.2 Market & Distribution:

The yearly hydrogen demand worldwide is approximately 330 million tons. The existing market is based on the hydrogen proprieties: it is light, storable, reactive, has high energy content per unit mass, and can be readily produced at an industrial scale. with this one additional attribution of green hydrogen, its interest is growing worldwide: No direct emission of harmful gases (IEA, 2019). One of the desirable properties of Hydrogen is that it is reactive. On the other hand, it is explosive and this makes it challenging to transport. Strict measures need to apply. It would be good to elaborate on these to take a comprehensive look at the situation.

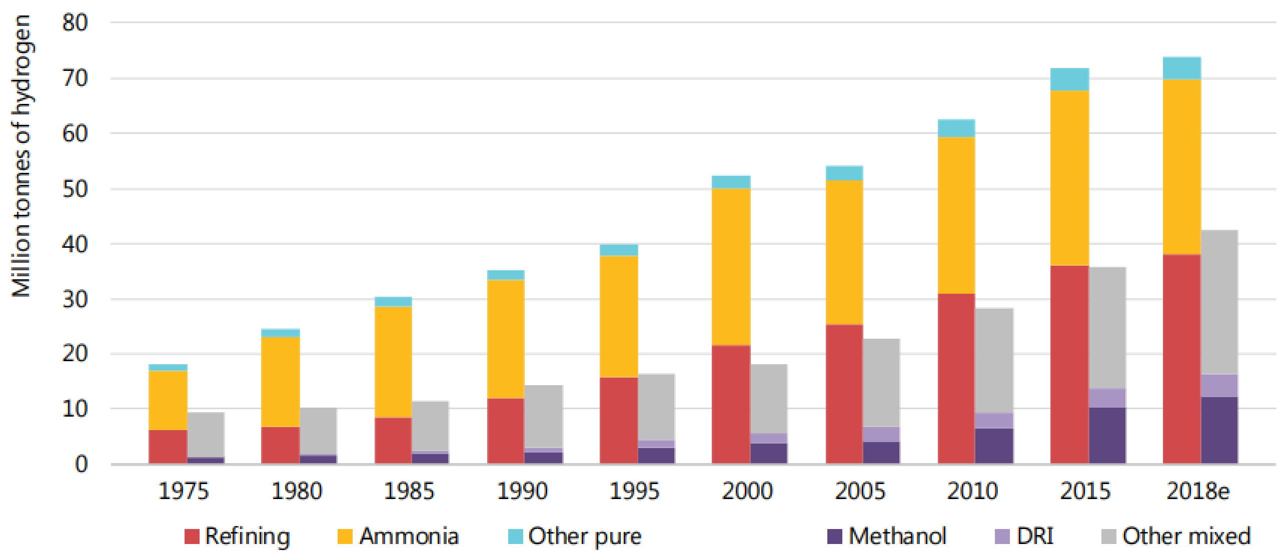

Figure 2: hydrogen demand worldwide

Source: the future of Hydrogen, iea, June 2020

II. METHODOLOGY

2.1Introduction:

This study employs a comparative methodology to investigate the review of the supply chain of green hydrogen production in West Africa: challenges and opportunities. By examining these challenges and opportunities within a comparative framework, the aim is to help us understand of the status of the supply chain for green hydrogen production in ECOWAS. Additionally, the study seeks to address questions such as: What challenges and opportunities do West African countries encounter when entering the green hydrogen market? What would be reasonable metrics for assessing the state of the supply chain? What strategies could the West African countries implement to effectively address the identified challenges and capitalize on opportunities? This methodology is chosen to enable a comprehensive analysis of the distinct attributes and commonalities within the context of the future green hydrogen production in ECOWAS, as well as to explore how various factors interact and influence the observed outcomes in West Africa countries. In response to this, the thesis adopts a novel approach that considers multiple dimensions, including environmental, social, economic, and technical aspects. Recognizing the need for depth while maintaining conciseness, the study narrows its focus to three representative ECOWAS countries, rather than attempting to encompass the entire West African region. This focused approach allows for a more detailed analysis while still addressing the intricacies inherent in the topic.

2.2 Selection of Comparative Cases

The ECOWAS nations will be systematically categorized based on various criteria such as:

- geographic position
- political stability (based on the sum of the score given by World Bank data under the worldwide governance indicator (*Worldwide Governance Indicators | DataBank*, 2021) in the government effectiveness, control of corruption, regulator quality, rule of law, and absence of violence).
- support for renewable energy (based on criteria, namely: the energy transition target, tax exemption from renewable energy equipment import, and plans of the governments for investment in renewable energy. These three criteria are found in the Law and Policy

Review on Green Hydrogen Potential in ECOWAS Countries (Ballo et al., 2022). These metrics will have scores ranging between low, medium, or high based on the scoring devised by the author of this paper.

- renewable energy potential in terms of concentrated solar power CSP potential, solar photovoltaic PV potential, and wind potential documented from ((IRENA, 2018) p. 23.)
- access to electricity (in percent of the total population found in the World Bank under the world development indicators (*World Development Indicators | DataBank*, 2020)
- socioeconomic development (in terms of human capital rating from 0 to 1) documented by (*World Development Indicators | DataBank*, 2020).

Table 1: countries' classification

countries	Geographic position	RE support	RE potential in MW	Political stability	Socioeconomic development	Access to electricity in %
Benin	Coastal	Low	3,854	-1.7	NA	41.41
Burkina Faso	Landlocked	Medium	92,759	-3.4	0.4	18.96
Cape Verde	Island	Low		2.5	0.38	94.16
Cote d'Ivoire	Coastal	Low	31,680	-2.8	NA	69.68
The Gambia	Coastal	Low	1,425	-2.1	0.42	62.27
Ghana	Coastal	Low	22,538	-0.4	0.45	44.67
Guinea	Coastal	Low	42,457	-5	0.38	33.34
Guinea Bissau	Coastal	Low	3,727	-5.7	NA	85.87
Liberia	Coastal	0	3,104	-4.4	0.32	27.53
Mali	Landlocked	Low	410,432	-6	0.32	50.56
Niger	Landlocked	Low	668,223	-3.8	0.36	19.25
Nigeria	Coastal	Low	569,178	-5.7	0.32	55.40
Senegal	Coastal	Low	47,188	-0.7	0.42	70.37
Sierra Leone	Coastal	Low	2,127	-3.5	0.36	26.20
Togo	Coastal	Low	2,759	-3.3	0.43	54

Source: Own illustration

2.2.1 Overview of the countries selected

Selecting a country posed significant difficulty as shown in (**Erreur ! Source du renvoi introuvable.**), there were minimal similarities and substantial differences among the options. Additionally, the decision will be influenced by the data availability for assessing the chosen country. In this case, the need of priority is needed, and the choice has been made based on the socio-economic development, renewable energy potential, and support perspective. Burkina Faso (middle position), Liberia (worst case), and Nigeria (best case) are the selected countries. These will serve as reference benchmarks for the rest of the ECOWAS nations to identify and analyze the challenges and opportunities in the supply chain of hydrogen production.

Burkina Faso: Burkina Faso is a landlocked country with a population of over 20,951,639 people in 2019, a total land area of 274,220 square kilometers as total surface area, and relies on one main economic sector is agriculture ((*World Development Indicators | DataBank*, 2020)). The country faces various socio-economic challenges, including high poverty rates and limited access to education and healthcare. However, the government is working towards improving governance, promoting economic development, and addressing social issues.

Liberia: the country is located on the west coast of Africa, with 111,369.00 km 2, as its total land area and a population of 4,985,289 in 2019 (*World Development Indicators | DataBank*, 2020). The economy of Liberia is largely dependent on agriculture, mining, and forestry, even though the exploitation of these resources has raised concerns about transparency and equitable distribution of wealth. The government is working to attract foreign investment, improve infrastructure, and diversify the economy.

Nigeria: Nigeria has 203,304,492 habitats, on a surface area of 923,770 square kilometers ((*World Development Indicators | DataBank*, 2020)). It is the most populous country in Africa and the seventh most populous country in the world, and has one of the largest economies in Africa. It is heavily reliant on oil, with petroleum accounting for a significant portion of government revenue. However, the country is diversifying its economy by focusing on sectors such as agriculture, manufacturing, telecommunications, and services.

2.3 Identification of opportunities and challenges

Inspired mainly by the work of Ren et al., (2013) that discusses the driving factors that influence the sustainability of the hydrogen supply chain and mapping the cause-effect relationships to improve the sustainability of hydrogen supply chain criterion and mixed with the content of the IMP-EGH master's program courses, as well as the reality of the region, 9 criterion in the opportunity's subchapter and 9 criteria in the challenge's subchapter have been identified with regards to 4 aspects, which are Environment, social, economic, and technology.

Table 2: Criterions

Aspects	Opportunities criteria	Challenges criteria
Environment	Harmful gases and Fossil fuel consumption Renewable energy usage	Land use Water scarcity
social	Job Creation Social attractiveness Human Health and Safety of Employees Cultural influence Political Acceptability	Legal framework Human Health and Safety of Employees
Economic	Industries expansion	Financial risks Storage cost
Technology	Technological dependency	Domestic technology ability

Source: Own illustration

2.4Data collection

The data collection for the assessment of the identified challenges and opportunities is done using a composite of data from the development of the United Nation's Sustainable Development Goals index, world bank indicators, and combining indicators from the H_2 Atlas project, and a thorough review of literature that address and assesses the criteria previously mentioned.

ASSESSMENT

2.5 Environmental aspect

2.5.1 Avoided harmful gases and fossil fuel consumption

The avoided harmful gases refer here to the amount of CO_2 equivalent (carbon dioxide, methane, chlorofluorocarbons…) avoided depending on the green hydrogen technologies (renewable energy sources).

The table below contains the amount of CO_2 equivalent emissions range for hydrogen production from energy sources extraction from water and fossil fuels, estimated in kg CO_2 equivalent per kg of hydrogen. The table also includes the amount of fuel required to produce 1 kg of hydrogen. It showcases the significant environmental benefits of green hydrogen (depending on its power generation for its production) compared to the conventional form of hydrogen. When one (1) kilogram (kg) of hydrogen is used, it releases an impressive amount of energy ranging from 120 to 142 megajoules (MJ/kg) as taken from (Hsu, 2011). However, the crucial difference lies in the emissions, where green hydrogen emits zero emissions, whereas non-green hydrogen can reach the range of 2.49 to 22.88 kg of CO2 equivalent per kg of hydrogen, depending on the energy sources used for its production.

Table 3: Avoided harmful gases and fossil fuel consumption

Fuel Hydrogen Color	Energy source	Extracted from	Amount of CO_2 per 1 kg H2	Fuel used for producing 1 kg H2
Green	Solar	Water	0 kg	free
	Wind		0 kg	
	hydro		0 kg	
Non-green	Nature Gas		2.49 kg	117.1 cubic feet
	Crude Oil		17.76 kg	0.0211 barrel
	Coal		22.88 kg	7.8

Source: (world economic forum, 2020), (Hydrogen tools, 2023), (Andi et al., 2018)

2.5.2 Renewable energy usage

Renewable energy is converted to electricity for hydrogen production.

The table below displays two important variables related to renewable energy sources (wind, solar PV, hydro): average cost (€ct) per kWh and potential production (TWh) per year. From this, we can understand which country has not only much more renewable energy and much more affordable low-price energy.

Table 4: Renewable energy usage

Country	Energy source	Average cost (€ct) per kWh		Potential in Twh per year	
		2020	2050	2020	2050
Burkina Faso	Wind	8.88	6.88	389.35	398.35
	Solar PV	3.89	1.8	7,324.1	7,324.1
	Hydro	8.62	9.07	0	0.03
Liberia	Wind	27.8	21.55	0.09	0.09
	Solar PV	5.02	2.33	187.49	187.49
	Hydro	5.93	6.71	0.29	2.56
Nigeria	Wind	9.95	7.71	1,594.74	1,594.74
	Solar PV	4.01	1.86	20,572.67	20,572.67
	Hydro	14.37	14.37	5.28	33.67

Source: (*H2 Atlas Africa*, 2020)

2.5.3 Land availability

Land use represents the total used land for the establishment of a hydrogen production factory.

The table shows the percentage of the total area of the country eligible for the erection of onshore wind turbines and open-field photovoltaic parks. This land eligibility takes into account ecological, socio-political, and physical restrictions (e.g., nature conservation, settlements, or water surfaces).

Table 5: Land availability

Country	Land eligibility in % of the total area of the country	
	Wind onshore	Open-field PV
Burkina Faso	6.12	25.46
Liberia	0	2.17
Nigeria	9.04	22.28

Table 8. Source: (*H2 Atlas Africa*, 2020)

2.5.4 Water scarcity

Water scarcity is a notable issue in the production of green hydrogen, especially when relying on methods like electrolysis, which is the most widely used technique. To evaluate groundwater availability for research purposes in the field of green hydrogen, this assessment concentrates on determining the quantity of groundwater present in our specific area (H2 Atlas). The study takes into account various weather conditions, including drought, to quantify the sustainable yield of groundwater, providing minimum, and medium values measured in millimeters per year. Below is the table where the groundwater sustainable yield is stated for the three countries.

Table 6: Water scarcity

country	Threshold of sustainable groundwater yield	Yield in mm per year
Burkina Faso	Minimum	13.89
	Medium	7.06
Liberia	Minimum	201.82
	Medium	114.8
Nigeria	Minimum	104.46
	Medium	55.11

Source: (*H2 Atlas Africa*, 2020)

2.6 Social aspect

2.6.1 Job creation

Job creation represents the total number of employees that work by the whole hydrogen supply chain:

The following table provides an overview of the job potential in Megawatts (MW) based on power generation technologies (PV solar, wind energy) and green hydrogen production. Additionally, the table presents information on the skilled labor force of the total working-age population with intermediate education and the estimated labor force of the total population in Burkina Faso, Liberia, and Nigeria.

Table 7: Job creation

	PV solar		Wind		H2 - production
	installation	O&M	installation	O&M	
Labor	7.14 jobs/MMW	0.3 jobs/MW	5.68 jobs/MW	0.29 job/MW	0,17 jobs/MW
Burkina Faso	Labor force: estimated in 2018 to be 7,340,573; 66.75% of the total population				
	Labor skill: 51.22% of the total working-age population with intermediate education				
Liberia	Labor force: in 2017, it is estimated of 2,126,460; 77.90% of the total population				
	Labor skill: 54.56% of the total working-age population with intermediate education				
Nigeria	Labor force: in 2019, it is estimated of 67,373,496; a percentage of 59.01 of the total population				
	Labor skill: 64.41% of the total working-age population with intermediate education				

Source: (Fashina et al., 2018), https://scholarworks.iu.edu/dspace/bitstream/handle/2022, (Luigi et al., 2019), (*World Development Indicators | DataBank*, 2020)

2.6.2 Social attractiveness

Social attractiveness represents the acceptability and attractiveness of society to the performance of the hydrogen supply chain.

Green hydrogen is gaining significant attention and is considered highly attractive for several reasons:

Table 8: Social attractiveness

Area of attractiveness	Reasons
Renewable Energy Source	Green hydrogen can only be produced from renewable energy sources. This makes green hydrogen more attractive as it provides clean, sustainable energy and contributes to the global shift toward decarbonization.
Energy Storage	Green hydrogen has the potential to be stored and can be later converted as electricity or used directly as fuel (e.g. in fuel-cell cars). This makes hydrogen attractive by helping in balancing the energy grid and providing a reliable power supply that depends on storage
Versatility	Green hydrogen's attractiveness can be explained by its versatility, meaning it can be used in various sectors, including transportation, industry, and cooling. It can be utilized in fuel cells to power electric vehicles, as a feedstock in industrial processes, or for cooling applications in buildings.
Energy Intensity	Hydrogen has a high energy content per unit of mass, making it an efficient fuel for power generation and transportation. It has a higher energy density than batteries, allowing for longer ranges and quicker refueling times. This makes it a potential solution for decarbonizing heavy-duty transportation, such as long-haul trucks, ships, and airplanes.
Energy Independence	Green hydrogen production can help ECOWAS countries reduce their dependence on fossil fuels and enhance energy security. By utilizing domestic renewable resources for hydrogen production, nations can reduce their reliance on imported fossil fuels, diversify their energy mix, and achieve greater energy independence.

Technological Development	The growing interest in green hydrogen has spurred significant research and development efforts, leading to advancements in electrolysis technologies, hydrogen storage, and infrastructure. This progress is expected to drive down costs and improve the overall efficiency of green hydrogen production and utilization in the near term.
Job Creation and Economic Opportunities	The transition to a hydrogen economy presents significant job creation and economic growth opportunities. The establishment of green hydrogen value chains, including production, infrastructure, and utilization, can stimulate economic activity, attract investments, and create new employment opportunities.

Source : Own illustration

2.6.3 Human Health and Safety of Employees

The human health and safety of employees is a measure of the effects of all the processes in the hydrogen supply chain on the health and safety of the employees. It has been reported that human health decreased in the employment of energy systems (cite the source).

What makes hydrogen dangerous?

Table 9: Human Health and Safety of Employees

Risks and safety challenges of working with hydrogen	
Ignition	Hydrogen needs only minuscule amounts of energy to ignite: 0.011 MJ (vs. to methane which needs 0.28 MJ and gasoline which needs 0.8 MJ to ignite).
flammability	4–75% flammable by volume. Hydrogen flames are very pale or, in daylight, even invisible to the naked eye. They emit a specific type of ultraviolet radiation. Therefore, dedicated flame detectors are required to reliably warn of fires. Hydrogen is not toxic and much lighter than air and disappears quickly, allowing the fuel to disperse relatively rapidly if the fuel leaks, making it more secure than other spilled combustibles Eljack & Kazi, 2021).
Odor	Hydrogen cannot be detected by smell. Natural gas and propane are also odorless gases, however, a sulfurous odorant is added so that people can detect them. There are currently no known odorants light enough to move together with hydrogen at the same dispersal rate. Odorants can also contaminate fuel cells.
Permeation	Hydrogen molecules are tiny and can easily penetrate materials. Appropriate selection, handling, and upkeep of all materials that come into contact with hydrogen is crucial.
Gas pockets	Hydrogen has a lower density than air – and even than hydrocarbons like methane. A very light gas (57 times lighter than gasoline vapor and 14 times lighter than air), it can be dispersed quickly, potentially before gas detectors can even detect the leak.
CO alarms	In some applications, carbon monoxide (CO) also needs to be monitored. These carbon monoxide (CO) sensors are also sensitive to hydrogen, so false alarms may occur.

2.6.4 Cultural influence/wellbeing

Cultural influence represents the positive influences of the hydrogen supply chain on the culture of the local regions.

The following table presents a comprehensive social indicator ranging from least to most advantageous effects (*H2 Atlas Africa*, 2020). It illustrates the potential sites for renewable energy projects, aiming to enhance electricity accessibility and provide social benefits. The primary criterion for prioritizing locations is the level of electricity access, with a particular emphasis on areas with limited access. Additionally, attention is given to densely populated regions where the impact can benefit a larger number of people. Furthermore, other factors considered include targeting areas with a higher poverty rate and greater unemployment rate within the overall labor force.

Table 10: Cultural influence/wellbeing

Country	Social impact
Burkina Faso	A medium impact
Liberia	Low impact
Nigeria	Very high impact

Source: *H2 Atlas Africa*, 2020

2.6.5 Legal framework and political acceptability

The legal framework represents the laws that regulate green hydrogen production and its market. Political acceptability represents the acceptability of the hydrogen supply chain from the political perspective, and it is a measure of the support and satisfaction of the hydrogen supply chain from the government (H2 Atlas, 2020).

The table below explains the Political and regulatory framework assessment in investment feasibility and governance framework regarding green hydrogen projects. The two composite indexes are based on the Doing Business methodology and World Governance Index normalized to the region (*H2 Atlas Africa*, 2020). From this below, we can understand the favorable and ready country in investing in H2.

Table 11: Legal framework and political acceptability

Country	Political and regulatory framework indicator
Burkina Faso	Favorable
Liberia	Less favorable
Nigeria	Less favorable

Source: (*H2 Atlas Africa*, 2020)

2.7 Economic aspect

2.7.1 Financial risks

In developing countries, the financial risks of such green hydrogen projects could be related directly to these factors: the potential sponsor of the project, the share or balance of the interest, scalability, regulatory development, and the hydrogen market. The table below gives an overview of these different factors.

Table 12: Financial risks

country	Potential sponsor	Material cost and quality	Scalability	Regulatory development	(Hydrogen demand)
Burkina Faso	National: the willingness of the Burkinabe government International: BMBF Organization: WASCAL	Replacement of the electrolyzer regularly, renewable electricity generation, and hydrogen storage cost	The absence of scale and training is needed in such a project (PANEE, 2015).	Currently, regulatory development is absent but the government intends to move ahead with the project	NA
Liberia	NA	Change in the electrolyzer, renewable electricity generation, and hydrogen storage cost	Scale is insufficient, and the need for training (LPRC, 2022).	NA	NA
Nigeria	National: non-interest by the government International: BMBF Organization: WASCAL, Hydrogen Office	Change in the electrolyzer, renewable electricity generation, and hydrogen storage cost	Large skills in industries, refinery of oil and natural gas	No existing regulatory development in Nigeria, and the government does not show interest in green hydrogen	Local demand is there, especially in the metallurgy and fertilizer industries

Source: Own illustrastion

2.7.2 Storage cost

The storage cost refers to the discounted cost per unit of hydrogen storage. The following table demonstrates the levelized cost of hydrogen storage (LCHS) for seven different technologies, taking into account projected capital expenditure (CapEx), operational expenditure (OpEx), and the efficiency of these storage technologies. This evaluation is done to know the most efficient storage system that requires less energy input to store hydrogen, which helps reduce the variable cost in OpEx significantly and hence reduces LCHS (Abdin et al., 2022).

Table 13: Storage cost

Hydrogen storage methods	Compressed gaseous hydrogen	Liquid hydrogen	SC-Salt cavern	Metal hydride	Liquid organic hydrogen carrier	NH3-Ammonia	Methanol
Storage efficiency	92%	76%	94%	78%	71%	42%	50%
LCHS (4 months)	24 $/kg	62$/kg	3$/kg	48$/kg	18$/kg	135$/kg	100$/kg

Source: (Abdin et al., 2022)

2.7.3 Industries expansion

Industries expansion indicates the potential industry most suitable to emerge alongside the hydrogen project. The table below shows a comparative potential industry in green hydrogen vs. petroleum projects.

Table 14: Industries expansion

	potential industries	
Green hydrogen project	Metallurgy	steel
	Ammonia Production	Agriculture or as a form of hydrogen storage
	Green Chemicals and Materials	green fertilizers, bio-based plastics, and synthetic fuels
	Cement industry	fuel
Petroleum project	Petrochemical	manufacture plastics, synthetic fibers, rubber, solvents, detergents, paints
	Plastic	packaging materials, consumer goods, automotive parts, construction materials
	Textile	polyester, nylon, and acrylic
	Pharmaceutical	lubricants for equipment, and solvents for extraction

Source: Own illustration

2.8 2.4. Technological aspect

2.8.1 Technology development potential

The concept of technology development potential is defined as the evaluation of each technology concerning its potential for future development and measured by its relative status (Chang et al., 2011).

In green hydrogen, the most important part of the supply chain is obtaining renewable energy at a convenient price and the technology development potential is related to cost reduction, engineering took from a webinar Africa H2 council. The following table gives an overview of the electricity generation from solar, wind, wave, and biomass 2010-2021.

Table 15: Technology development potential

technology	Cost reduction[1]		Engineering	
	USD/kWh	percent change	Future development[2]	Maturity[3]
Photovoltaic	0.417-0.048	-88%	1. Behind-the-meter batteries 2. Electric-vehicle smart charging 3.Renewable power-to-hydrogen	Non-mature
CSP	0.358-0.114	-68%		
Wind onshore	0.102-0.033	-68%		Non-mature
Hydropower	0.039-0.048	+24%		Mature
Bioenergy	0.078- 0.067	-14%		Mature

Source: (Chang et al., 2011)

2.8.2 Domestic technology ability

Domestic technological ability refers to the relative level of domestic technologies in the hydrogen supply chain (Ren et al., 2013).

[1] (IRENA, 2021)
[2] (IREANA, 2019)

Table 16: Domestic technology ability

Value of the supply chain of GH2	Burkina Faso	Liberia	Nigeria
Production technology	NA	NA	RES developers
Storage technology	NA	NA	Chemical company
Transportation technology	NA	NA	Pipeline, port, and marine transport
Distribution technology	NA	NA	NA

Source: Own illustration

2.9 Limitation

The limitations of the above methodology have been branded with many obstacles that limited the overall work particularly in the:

Limited Availability of Data: Green hydrogen production in West Africa is still in its very early stages, and comprehensive and reliable data is scarce. The limited data availability has hindered the depth and accuracy of the review.

Lack of Case Studies: Due to the relatively newness concept of green hydrogen production within West Africa, there exists a scarcity of extensively documented instances and tangible illustrations to reference. This constrains the capacity to offer substantial substantiation and practicality.

Geographical and Socio-Economic Variability: West Africa is a vast and diverse region with varying economic conditions, political landscapes, and infrastructure. The thesis struggled to which countries the thesis will focus on.

Political and Policy Factors: The success of green hydrogen production in West Africa is likely influenced by political stability and government policies. Analyzing and predicting the impact of these factors is challenging due to their dynamic and unpredictable nature.

Language and Accessibility Barriers: Research papers and relevant literature related to green hydrogen especially in energy renewable in West Africa are published in various languages, and some are readily accessible, and this hinders the inclusion of certain countries.

Market Viability: While the thesis identifies opportunities, it might not dig deeply into the market viability and demand for green hydrogen in the region, which is crucial for successful implementation.

III. RESULT & DISCUSSION

CHALLENGES

3.1Environmental Aspect

3.1.1 Land availability

Land availability is an important factor in determining the feasibility of green hydrogen production and the potential of renewable energy development in each country.

As indicated by the given data in (Table 5, see references there) in the assessment section, Nigeria has approximately (580,000 square kilometers) 9.02% of its total area eligible for onshore wind turbines, which is the highest percentage compared to other countries. Liberia has no eligible area for onshore wind turbines and Burkina Faso has only 6.12% (29,500 square kilometers). While in an open field of solar PV, Burkina Faso has the largest percentage with (101,000 square kilometers) 25.46% compared to Liberia with (6,000 square kilometers) 2.17% and Nigeria with (910,000 square kilometers) 22.28%.

Despite all, even Burkina Faso showcases a notable land availability for solar in percentage, while Nigeria and Liberia present less, the irradiance in solar is much higher in Nigeria (4 times than the Burkinabe solar irradiance) and the Nigerian total land area is also much larger than all the two countries).

3.1.2 Water scarcity

Water availability plays a crucial role in green hydrogen production, green hydrogen production relies on renewable energy sources, such as solar or wind power, to power the electrolysis process, but it still requires a significant amount of water. Let us discuss the implications of water availability for green hydrogen production in each of our three countries according to the given data of (Table 6, see source there):

Burkina Faso faces a considerable challenge in water availability for green hydrogen production. The available water resources are scarce and limited with a minimum groundwater sustainable yield of 13.89 mm per year and a medium yield of 7.06 mm per year. Green hydrogen production requires substantial amounts of water for water electrolysis. The low water availability may hinder the country's green hydrogen production scalability. Burkina Faso would need to explore alternative water sources, such as wastewater, or consider innovative water-efficient technologies to overcome this challenge for example drawing sea water from Benin which a coastal country through underground pipelines.

Liberia has relatively better water availability than Burkina Faso, and Nigeria as indicated by the data from Table 6. With a minimum groundwater sustainable yield of 201.82 mm per year and a medium yield of 114.8 mm per year. In terms of water availability, Liberia has a higher potential for green hydrogen production. However, it is important to note that green hydrogen production still requires significant amounts of water. While Liberia's water resources seem more abundant, careful water management is essential to ensure sustainable usage. Monitoring water consumption in hydrogen production, implementing water-efficient technologies, and considering the needs of other sectors that rely on water resources will be important for maintaining water availability.

In Nigeria, the minimum groundwater sustainable yield is 104.46 mm per year and the medium yield is 55.11 mm per year, the available water resources are limited. Nigeria is a populous country with diverse water needs for agriculture, industry, and domestic use. Integrating green hydrogen production into this context may strain the already limited water resources. To overcome this challenge, Nigeria would need to adopt efficient water management practices, explore alternative water sources, and prioritize water allocation to ensure sustainable usage and prevent conflicts between sectors.

In all three countries, water availability poses a critical challenge to green hydrogen production. While Liberia appears to have better water resources compared to Burkina Faso and Nigeria, it is essential to strike a balance between water demand for hydrogen production and other critical sectors.

And what about CO_2 emissions reduction?

3.2 Social Aspect

3.2.1 Human Health and Safety of Employees

The safety of green hydrogen in West African countries, particularly in Burkina Faso, Liberia, and Nigeria, is an important aspect that needs careful consideration to ensure the protection of people, infrastructure, and the environment through a strong input effort in infrastructure safety, training, and education.

Most West African countries suffer from green hydrogen infrastructure to one extent to another, furthermore, infrastructure safety, so building and maintaining safe infrastructure is important for green hydrogen investment. This includes ensuring the integrity of hydrogen storage tanks, pipelines, and transportation systems. In these countries, where infrastructure development might be a challenge, it is essential to prioritize safety considerations during the planning and construction phases. Regular inspections, adherence to safety standards, and implementing measures to prevent leaks and mitigate risks are vital to safeguarding the public and minimizing potential hazards.

Then, come training and education, which are essential for individuals working with or around green hydrogen facilities. It is important to establish training programs that educate workers about the properties of hydrogen, safe handling procedures, emergency response protocols, and the use of personal protective equipment. These programs should be tailored to the local context and consider the specific needs and characteristics of Burkina Faso, Liberia, and Nigeria.

3.2.2 Legal Framework and political acceptability

With a favorable Political and Regulatory Framework indicator, Burkina Faso demonstrates a supportive legal framework for green hydrogen projects by raising investor confidence and encouraging private sector participation (see Table 10). Additionally, the political acceptability of the hydrogen supply chain from the government's perspective shows support and satisfaction from the government toward green hydrogen projects. This support can be instrumental in providing incentives, attracting investments, and creating an enabling environment for the growth of the green hydrogen industry. For Liberia, it has a less favorable Political and Regulatory Framework indicator and this is mainly due to many limitations or gaps in its laws and regulations not only in renewable energy sectors but also the non-interest in the green hydrogen field from the government. Then, in Nigeria, the less favorable political and regulatory framework is principally due to the non-interest of the government that brake the laws and regulations in the green hydrogen field.

To address these challenges would involve improving the legal framework, enhancing regulatory clarity, and increasing government support to create an enabling environment for green hydrogen investments. Developing a robust legal and regulatory framework and gaining political acceptability are crucial steps in attracting investments, fostering innovation, and ensuring the long-term success and sustainability of the green hydrogen sector in Burkina Faso, Liberia, and Nigeria.

3.3 Economic Aspect

3.3.1 Financial risk

Accordingly, to Table 11, Burkina Faso has the potential for green hydrogen project initiation, driven by the willingness of the Burkinabe government and the presence of international and ECOWAS organizations in the country, indicating political support and interest in exploring green hydrogen's potential. However, the country's heavy reliance on imported materials for the entire green hydrogen supply chain poses challenges, as price fluctuations and potential compromises by equipment suppliers could hinder the project's functioning. Ensuring strong project management becomes important in such circumstances. Additionally, Burkina Faso faces scalability issues due to the absence of necessary infrastructure and expertise, which may impede the expansion of green hydrogen production and distribution. The current absence of regulatory development poses another obstacle, as clear and supportive regulations are essential to attract investments and ensure the long-term viability of the green hydrogen sector. The lack of information on hydrogen demand further complicates the assessment of the market potential and economic feasibility of the green hydrogen supply chain in the country.

At present, Liberia lacks sufficient information on potential sponsors and regulatory development for green hydrogen projects, indicating a lack of active pursuit in this area. The country faces challenges related to scalability and training, as insufficient scale and expertise could hinder the successful implementation of green hydrogen projects. However, the hydrogen demand in Liberia leaves a significant gap in understanding the market potential and economic prospects for green hydrogen adoption in the country.

Nigeria's green hydrogen prospects face a major setback due to the lack of interest from the government. Government support plays a crucial role in attracting investments, developing regulations, and fostering a conducive environment for green hydrogen projects. Similar to other countries, the cost of changing the electrolyzer, renewable electricity generation, and hydrogen storage impacts the economic feasibility of green hydrogen projects in Nigeria due to the need to import material. Although the country benefits from a large industrial base and expertise in industries like oil and gas, specific education for green hydrogen technologies remains necessary to fully utilize the country's potential for scalability. The absence of existing regulatory development poses a significant hindrance to the growth of the green hydrogen sector, as it may deter potential investors from committing resources to such projects. Despite the presence of local demand in industries like metallurgy and fertilizer, realizing this potential relies heavily on government interest and supportive policies.

Overall, it can be said that addressing issues related to material costs, scalability, regulatory development, and hydrogen demand is vital to unlock the full potential of green hydrogen adoption in Burkina Faso, Liberia, and Nigeria. Moreover, fostering government support and regional collaboration could play pivotal roles in accelerating the growth and success of green hydrogen projects in these nations.

3.3.2 Storage cost

Among the seven methods of hydrogen storage from Table 13 (Compressed gaseous hydrogen, Liquid hydrogen, SC-Salt cavern, Metal hydride, Liquid organic hydrogen carrier, NH3-Ammonia, methanol), SC-Salt Cavern can be chosen. This storage method is distinguished by its cost-effectiveness at $3 per kg of H2 and efficient storage with a capacity of 94%. However, the feasibility of its implementation relies on the geological suitability of Burkina Faso, Liberia, or Nigeria where it is intended to be utilized. In addition to SC-Salt Cavern, alternatives for hydrogen storage can also be considered, such as ammonia and methanol. Both these methods exhibit lower storage efficiencies at 42% and 50%, respectively, compared to SC-Salt Cavern. Additionally, they are relatively expensive, with ammonia costing $135/kg and methanol priced at $100/kg. Despite these drawbacks, there are distinct advantages to each method which is really in need in this West African region. Methanol offers easy usability, particularly in transportation, making it a valuable option in that context. On the other hand, ammonia finds significant utility in agriculture, which has a high demand for this compound.

3.4Technological aspect

3.4.1 Domestic technology ability

As mentioned in the analysis part Table 14, Nigeria shows promise in the renewable energy sector, with a growing number of hardware and software developers focusing on various aspects of renewable energy technologies. These developers could contribute to the research and development of green hydrogen production technologies. The country has also a significant presence of chemical companies that could potentially contribute to the development of hydrogen storage technologies. Nigeria's existing infrastructure includes pipelines, ports, and marine transport, which could be adapted for transporting hydrogen. However, it is essential to note that transporting hydrogen is different from traditional fossil fuels and may require additional safety measures and infrastructure upgrades.

In contrast, the analysis indicates that Liberia and Burkina Faso currently lack significant progress in the domestic technology ability for the hydrogen supply chain. Even with Nigeria's advancements, which are a few steps ahead of Liberia and Burkina Faso, all three countries face significant challenges in developing the necessary technology for the green hydrogen sector. The technology required for establishing a viable and efficient green hydrogen supply chain remains a considerable obstacle for these nations.

OPPORTUNITIES

3.5Environmental aspect

3.5.1 Avoiding harmful Gases and fossil fuel consumption

Avoiding harmful gas emissions and reducing fossil fuel consumption are important environmental goals that can be achieved through green hydrogen production, particularly when compared to hydrogen produced from fossil fuels. The comparison made in Table 3 during the analysis takes into account the fuel used for hydrogen production and the equivalent CO2 emissions per 1 kilogram of hydrogen. Moreover, green hydrogen production necessitates no fuel consumption, relying instead on renewable energy sources that can be harnessed without cost. To contextualize all of these factors within the West African context and based on the literature review, it can be stated:

As a major oil-producing nation, and the only one among the 3 selected countries producing non-green hydrogen, Nigeria is confronted with significant challenges associated with fossil fuel consumption and CO2 emissions. However, Nigeria has been making strides in diversifying its energy mix by investing in renewable sources such as solar. Nigeria is ranked as the 2nd West

African country with the highest solar potential (see Table 1). Adopting green hydrogen produced from solar will help Nigeria and the rest of the ECOWAS countries that produce non-green H_2 decrease their reliance on fossil fuels, reduce CO_2 emissions, and promote cleaner and more sustainable energy options.

Green hydrogen offers a promising pathway to mitigate harmful gas emissions and reduce fossil fuel consumption in the whole ECOWAS region and can ensure the use of renewable energy in the production process and is essential to maximize environmental benefits and achieve substantial CO_2 emission reductions in these western African countries.

3.5.2 Renewable energy usage

Back to the Table 4 it is stated that:

Burkina Faso: The country has significant solar and wind energy potential. However, its hydro potential is very limited compared to the other two countries. Liberia has considerable hydroelectric potential due to its many rivers and water resources. It also has less favorable solar and wind energy conditions, making it a less promising region for renewable energy development. Then, Nigeria can be seen as a country with a vast potential for renewable energy sources, including solar, wind, and hydro.

Still in Table 4, it can be notified that in Burkina Faso, the average cost of electricity from solar PV is the lowest compared to wind and hydropower, indicating that solar energy is a cost-effective option for the country. Then in Liberia, the cost of electricity generation from wind and solar PV is relatively higher in 2020, making these options less cost-competitive compared to Burkina Faso. However, the projected cost reduction by 2050 indicates that these renewable sources may become more financially viable in the future. Liberia's hydro potential offers a cost-effective option, with relatively stable costs over time. Like Burkina Faso, Nigerian solar PV has the lowest average cost, making it an attractive renewable energy source. Wind energy costs are moderate, and hydroelectric power costs remain stable over time. While hydro is relatively more expensive than other sources, it still provides a stable and dependable energy supply.

All three countries have significant renewable energy potential, and the average cost of electricity generation varies for different sources in each country. Solar PV seems to be the most cost-effective option across all three countries, while wind and hydro provide valuable alternatives.

3.6 Social Aspect

3.6.1 Job Creation

From Table 7 (see all references there also), the general labor force in Burkina Faso accounts for 66.75% of the total population. The labor skill percentage, representing the working-age population with intermediate education, is 51.22%. Considering the job potential in power generation technologies, the installation of solar PV systems creates approximately 7.14 jobs per megawatt (MW), while wind energy installation generates around 5.68 jobs per MW. The operation and maintenance of solar PV and wind energy facilities contribute 0.3 jobs per MW and 0.29 jobs per MW, respectively. Regarding hydrogen production, it creates around 0.17 jobs per MW. These figures indicate the potential for employment opportunities in the growing green hydrogen industry in Burkina Faso.

Liberia has a labor force comprising 77.90% of the total population, and the labor skill percentage with intermediate education is 54.56%. The high labor force participation rate and intermediate education levels indicate significant job potential in green hydrogen production in Liberia. In Nigeria, the labor force represents 59.0% of the total population, and the labor skill percentage with intermediate education is 64.41%. In Burkina Faso, Liberia, and Nigeria, there is a significant potential for job creation in the green hydrogen sector, considering the labor force participation rates and skill levels. The installation and maintenance of renewable energy systems, such as solar PV and wind energy, can generate a considerable number of jobs per MW. Additionally, hydrogen production itself contributes to job creation in the sector. This can lead to economic growth, improved living standards, and a sustainable transition towards a greener and more diversified energy landscape.

3.6.2 Social attractiveness

Green hydrogen production in Burkina Faso, Liberia, and Nigeria can have several social advantages. Firstly, it will contribute to the energy mix's diversification, reducing fossil fuel dependency and increasing energy security. This will lead to improved access to clean and reliable energy, benefiting both rural and urban communities. Additionally, green hydrogen projects have the potential to create employment opportunities, particularly in the renewable energy sector. These jobs will help reduce poverty, enhance local skills, and provide economic stability. Furthermore, the adoption of green hydrogen aligns with global climate goals, enhancing Burkina Faso, Liberia, and Nigeria's international standing and promoting sustainable development in the region. In order to maximize these social benefits, an international collaboration and partnership with a comprehensive approach that addresses challenges and promotes inclusivity is required.

3.6.3 Cultural influence/wellbeing

Overall, the hydrogen supply chain has the potential to positively influence the culture of local regions in Burkina Faso, Liberia, and Nigeria. By prioritizing renewable energy projects in areas with limited electricity access, dense populations, higher poverty rates, and unemployed populations, the social benefits can extend to various aspects of cultural well-being. These benefits may include increased economic opportunities, improved living conditions, preservation of cultural practices, and empowerment of local communities. By considering and addressing these social indicators, the hydrogen supply chain will promote sustainable development while respecting and enhancing the cultural fabric of the local regions.

3.7Economic Aspect

3.7.1 Industries expansion

The development of a green hydrogen supply chain in Burkina Faso, Liberia, and Nigeria has the potential to revolutionize various industries, leading to economic growth, and sustainability. Probably it will give a push in facilitating the emergence of industries such as the metallurgy industry, ammonia production industry, green chemicals and materials industry, etc.

The metallurgy sector, particularly steel production, stands to benefit from the presence of green hydrogen as an eco-friendly and efficient reducing agent in direct iron ore reduction, replacing the use of non-green hydrogen. Conventional steel manufacturing processes heavily rely on carbon-intensive methods, but using green hydrogen for direct reduction reactions can significantly reduce carbon emissions. Nigeria and fellow West African countries blessed with abundant iron ore deposits have the opportunity to leverage their green hydrogen reserves to attract investments in advanced and eco-friendly steel manufacturing facilities. This approach could replace the expensive practice of importing steel, thereby conserving funds within these nations. Furthermore, it might also be worthwhile to consider initiating the importation of steel themselves. The growth of the metallurgy sector would create job opportunities, promote industrialization, and strengthen the countries' position in the global steel market.

Ammonia, a critical component in agriculture and key to fertilizer production can leverage green hydrogen as a feedstock to replace fossil fuels in the Haber-Bosch process (method of manufacturing ammonia economically (Carl et al., 2022)), thereby decreasing greenhouse gas emissions. Burkina Faso, Liberia, and Nigeria being agrarian economies, have substantial agricultural potential. By producing green ammonia, these countries can not only boost agricultural productivity but also have the potential to become ammonia exporters (as exemplified by Nigeria's existing ammonia exports (OEC, 2021)). Additionally, ammonia can serve as a form of hydrogen storage, allowing excess green hydrogen generated during periods of high renewable energy output to be stored and later converted back to hydrogen, ensuring a stable and reliable supply of green hydrogen.

The green chemicals and materials industry could also be pointed out as an expected industry to emerge along the supply chain of green hydrogen, because green Hydrogen can serve as a vital feedstock in producing various green chemicals, such as ammonia-based fertilizers and bio-based plastics. Additionally, green hydrogen can be used to synthesize clean synthetic fuels, contributing to the defossilisation of the transportation sector. The emergence of a green chemicals and materials industry would create new economic opportunities, promote sustainable practices, and reduce the reliance on traditional, carbon-intensive chemicals and fuels.

3.8Technological aspect

3.8.1 Technology development potential

Depending on each country, Burkina Faso, Liberia, and Nigeria possess vast renewable energy potential, with solar energy dominating more in some cases. However, the technology development potential of green hydrogen is not solely reliant on renewable energy potential; it involves advancing renewable energy systems whether photovoltaic, concentrated solar power, wind turbines, or hydropower, improving efficiency, and reducing costs. Innovations in energy storage technologies, such as battery systems and power-to-gas solutions, can ensure a stable green hydrogen supply even during low sunlight periods.

Fortunately for West Africa, technology development in green hydrogen is not limited by location, as knowledge and expertise can be easily imported and shared between countries. This presents a significant opportunity for Burkina Faso, Liberia, and Nigeria to adopt and adapt global advancements in green hydrogen technology. By learning from worldwide developments and embracing international collaboration, these countries can accelerate their technology development and play a meaningful role in the global transition towards sustainable and green hydrogen solutions.

RECOMMENDATIONS & CONCLUSION

RECOMMENDATIONS

West Africa has renewable energy potential that needs to be harnessed by many methods and green hydrogen production seems to be one of them. However, to fully capitalize on the opportunities and effectively address the challenges within the green hydrogen supply chain, a firm dedication is required and commitments should be tailored to embrace sustainability principles, ensuring that the entire process of green hydrogen production until its end use is approached sustainably.

Below, some recommendations are provided based on what has been learned and understood during the writing period:

In water management: Governments and stakeholders need to develop comprehensive water management strategies that account for the needs of various sectors, promote water efficiency in the hydrogen production process, and explore alternative water sources to ensure sustainable green hydrogen production without compromising water availability for other essential uses.

- Safety: Enhancing safety awareness and knowledge among employees, emergency responders, and the general public can significantly minimize the risks associated with green hydrogen production.
- Policy and framework: prioritize the development of a supportive regulatory framework, encouraging private sector participation, and fostering an enabling environment for green hydrogen investments.
- Context matter: Evaluate the specific requirements and applications to make informed decisions about hydrogen production in a given country according to its reality.
- Education: Prioritize skill development programs and ensure the availability of training opportunities (such as the International Masters Program in Energy and Green Hydrogen) to match the growing demand for skilled workers in the green hydrogen industry.
- Last but not the least, a unique project could be extended to multiple countries based on their individual strengths. For instance, Ivory Coast, abundant in humidity, could be a primary contributor to hydrogen production, harnessing water from the air for the

electrolysis process. Meanwhile, Mali's richness in renewable energy resources makes it an ideal candidate to supply the electricity needed for hydrogen production through electrolysis. Additionally, Ghana's wealth of universities and experts offers an opportunity for providing specialized training to the workforce involved in the green hydrogen sector and fostering the development of innovative technologies. By leveraging the distinctive attributes of each country, this collaborative approach can pave the way for a sustainable and prosperous green hydrogen supply chain across West Africa.

CONCLUSION

This master's thesis digs into a comprehensive review of the supply chain of green hydrogen production in West Africa (ECOWAS region), highlighting the challenges and opportunities that lie ahead. The analysis has shed light on the critical environmental, social, economic, and technological aspects that need to be addressed for the successful implementation of green hydrogen projects in the ECOWAS region.

The findings illuminate a landscape rich with potential, where West African countries possess abundant wind and solar resources that can contribute significantly to green hydrogen production. But, a multitude of challenges, including technological gaps, infrastructure limitations, economic constraints, and social factors, must be navigated to fully unlock this potential.

The challenges related to technology domestic ability, water scarcity, human health and safety, legal frameworks, and economic feasibility pose significant obstacles to the region's green hydrogen ambitions. However, the opportunities presented by avoiding harmful fossil fuel consumption, utilizing abundant renewable energy sources, and fostering job creation and cultural well-being could lead to transformative benefits for the region.

Addressing the challenges and seizing the opportunities presented require strong government support, collaboration among stakeholders, and strategic investments in research, infrastructure, and human resources. By adopting on these routes, West African nations can not only overcome obstacles but also position themselves as key players in the emerging green hydrogen market, fostering sustainable development and contributing to a greener energy future.

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