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

Specialty: Economics/Policies/Infrastructure and Green Hydrogen Technology

Topic:

Comparing Levelized Cost of Electricity from Photovoltaics in West Africa and Germany

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Presented the 24/8/2023 by:
David Kindo Kamara

Main Supervisor	Co-Supervisor
Prof. Aaron Praktiknjo	Dr. Fama Gueye

Academic year 2022-2023

DECLARATION OF AUTHORSHIP

I, David Kindo Kamara declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

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DEDICATION

I dedicate this thesis to my beloved and amazing parents; your support has always been great and thank you for being the central pillar in my life.

ACKNOWLEDGEMENT

I would like to appreciate the support from the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), and all the partners (BMBF, H2 Atlas, Forschungszentrum Jülich, Abdou Moumouni University, Cheikh Anta Diop University, and RWTH Aachen University) of WASCAL for making this project very successful. The financial support through research grant and scholarship enabled me to finish my work, including the opportunity to pursue my masters at Cheikh Anta Diop University.

More specifically, I would like to express my sincere gratitude to my supervisor, Prof. Aaron Praktiknjo for the patience and guidance he offered to achieve the best from this project and the time he invested in seeing the completion of this work.

I would also like to recognize the tireless support of my co-supervisor, Dr. Fama Gueye for her tremendous inputs in making this project an accomplishment.

My profound thanks and appreciation to Jakob Kulawik, an assistant to my supervisor for his advice, training, and supervisory support through the research period. I would like to fully appreciate your availability and kindness during my stay at the institute.

I also extend a note of thanks to Prof. Peter Letmathe and his entire team for their support and ensuring that we received fulfilling training in acquiring the requisite skills and abilities for our career development throughout our stay in Germany.

My sincere gratefulness acknowledges the kindness of Dr. Assane Beye (Director of WASCAL, Senegal) and his entire team for their unwavering support in fulfillment of this journey. I also appreciate the help of my fellow colleagues of the same academic struggle for their assistance and encouragement in making this journey worth taking.

I would like to extend my sincere gratitude to my family, especially my father and mother who encouraged and believed in me during the entire journey.

Most importantly, I am grateful to God Almighty for His favor and strength on me to transverse this two-year journey in good health, and abundance of joy and provision.

ABSTRACT

The transition towards a decarbonized sustainable energy system in the world is the most efficient pathway through the use of renewable energy sources. The dependency on fossil fuels as sources of energy for the past decades has attributed to climate change and global warming through greenhouse gas emissions. West Africa in general is faced with threat of an energy crisis due to the growing population. Thus, there is an urgent need to find sustainable and climate-smart ways for generating energy for the growing population. Photovoltaics (PV) could potentially play a key role in the drive towards an energy transition. According to H2 Atlas, West Africa has enormous potential of solar resource for the production of energy through photovoltaics. On the other hand, Germany is aiming to leave the fossil-nuclear age behind, and paving the way for PV to play a central role in a future shaped by sustainable energy production. This thesis compares the levelized cost of electricity (LCOE) from utility-scale grid-tied solar PV systems in West Africa and Germany. The thesis focuses mainly on three countries in West Africa (namely: Sierra Leone, Burkina Faso and Niger) and Germany, the three countries are chosen based on the climatic regions in West Africa. The system capacity for Sierra Leone, Burkina Faso, Niger and Germany are 5 MW, 10 MW, 20 MW and 30 MW respectively. The comparative analysis considers the geographic location, the cost and the LCOE of the solar PV systems. An excel spreadsheet is used to calculate the LCOE and National Aeronautics and Space Administration (NASA) surface meteorological as well as Solar Energy (SSE) data sets from RETScreen have been used to obtain climatic data of each case study. Based on the assumptions of this thesis, the solar PV system produces, on average, about 20,854.89 MWh/yr of electricity available for grid export. This yields an average performance ratio and capacity factor 75.6% and 16.0% respectively. The levelized cost of electricity ranges from 0.0766 €/kWh to 0.1333 €/kWh in the absence of revenues and capital subsidies. These findings suggests that a cost-effective and environmentally efficient restructuring of West Africa and Germany power generation system is feasible. Solar PV is becoming increasingly competitive with conventional power generation due to the falling unit investment costs and increasing capacity. Thus, during the transition phase, efforts are required to improve and optimize the grid-integration of solar PV as well as to uphold the long-term security of the electricity supply.

Keywords: LCOE; Photovoltaics; West Africa; Germany; Solar PV System.

RESUME

La transition vers un système énergétique durable décarboné dans le monde est la voie la plus efficace grâce à l'utilisation de sources d'énergie renouvelables. La dépendance à l'égard des combustibles fossiles comme sources d'énergie au cours des dernières décennies a été attribuée au changement climatique et au réchauffement de la planète par les émissions de gaz à effet de serre. L'Afrique de l'Ouest en général est confrontée à la menace d'une crise énergétique en raison de la croissance démographique. Il est donc urgent de trouver des moyens durables et intelligents face au climat pour produire de l'énergie pour la population croissante. Le photovoltaïque (PV) pourrait potentiellement jouer un rôle clé dans la transition énergétique. Selon H2 Atlas, l'Afrique de l'Ouest dispose d'un énorme potentiel de ressources solaires pour la production d'énergie photovoltaïque. D'autre part, l'Allemagne vise à sortir de l'ère nucléaire fossile et à ouvrir la voie au photovoltaïque pour jouer un rôle central dans un avenir façonné par la production d'énergie durable. Cette thèse compare le coût actualisé de l'électricité (LCOE) des systèmes solaires photovoltaïques reliés au réseau à grande échelle en Afrique de l'Ouest et en Allemagne. La thèse porte principalement sur trois pays d'Afrique de l'Ouest (à savoir: la Sierra Leone, le Burkina Faso et le Niger) et l'Allemagne, les trois pays sont choisis en fonction des régions climatiques d'Afrique de l'Ouest. La capacité du système pour la Sierra Leone, le Burkina Faso, le Niger et l'Allemagne est respectivement de 5 MW, 10 MW, 20 MW et 30 MW. L'analyse comparative tient compte de l'emplacement géographique, du coût et du LCOE des systèmes solaires photovoltaïques. Une feuille de calcul Excel est utilisée pour calculer le LCOE et les ensembles de données météorologiques de surface et d'énergie solaire (SSE) de RETScreen ont été utilisés pour obtenir les données climatiques de chaque étude de cas. Sur la base des hypothèses de cette thèse, le système solaire photovoltaïque produit, en moyenne, environ 20 854,89 MWh / an d'électricité disponible pour l'exportation du réseau. Cela donne un ratio de performance moyen et un facteur de capacité de 75,6 % et 16,0 % respectivement. Le coût actualisé de l'électricité varie de 0,0766 €/kWh à 0,1333 €/kWh en l'absence de recettes et de subventions en capital. Ces résultats suggèrent qu'une restructuration rentable et efficace sur le plan environnemental des systèmes de production d'électricité en Afrique de l'Ouest et en Allemagne est réalisable. L'énergie solaire photovoltaïque devient de plus en plus compétitive par rapport à la production d'électricité conventionnelle en raison de la baisse des coûts d'investissement unitaires et de l'augmentation de la capacité. Ainsi, pendant la phase de transition, des efforts sont nécessaires pour améliorer et optimiser l'intégration au réseau de l'énergie solaire photovoltaïque ainsi que pour maintenir la sécurité à long terme de l'approvisionnement en électricité.

Mots-clés : LCOE; Photovoltaïque; Afrique de l'Ouest; Allemagne; Système solaire photovoltaïque.

ACRONYMS AND ABBREVIATIONS

Africa Mini-grids Program (AMP), 25
Alternating Current (AC), 30
Balance of System (BOS), 6
Capital Expenditure (CAPEX), 29
Côte d'Ivoire-Liberia-Sierra Leone-Guinea (CLSG), 12
Direct Current (DC), 30
Economic Community of West African States (ECOWAS), 26
ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), 6
Electricity and Distribution Supply Authority (EDSA), 11
Electricity and Generation Transmission Company (EGTC), 11
Electricity and Water Regulatory Commission (EWRC), 11
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1. INTRODUCTION

Reliable energy resource accounts are the foundation of energy planning in every country – this includes renewable sources. In order for a country to alleviate from poverty and insecurity, sustainable energy is a key pathway. The United Nations has identified 17 sustainable development goals (SDGs) that need to be treated and managed to guarantee a peaceful and sustainable existence for all living species on planet earth. To a large extent, the SDGs are interconnected, so that addressing one can simultaneously influence the other. SDG 7 which aims to provide everyone with access to affordable, reliable, sustainable and modern energy sources is pivotal in achieving all the other SDGs. Energy is essential for human well-being, economic growth, social equity and environmental protection.

However, millions of people across the world still lack electricity, clean cooking fuels and energy efficiency. The dependency on fossil fuels as sources of energy for the past decades has attributed to climate change and global warming through greenhouse gas emissions. According to Paris Agreement (COP 21), it's overarching goal is to hold "the increase in the global average temperature to well below 2ºC above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5ºC above pre-industrial levels" (UNFCCC). Nevertheless, to achieve the Paris Agreement (COP 21) goal and to promote a low-carbon society, it is urgent to better integrate renewable energies into energy supply systems. In this context, photovoltaics could potentially play a key role in the drive towards an energy transition. As indicated by H2 Atlas, West Africa has enormous potential of solar irradiation for producing electricity through photovoltaics (PV). Solar PV emerges as the prime source of West Africa's future energy system. However, much of this potential has been untapped and West Africa struggles with number of issues that affect its energy strategy resulting to low electricity access rate in the region. On the other hand, Germany is leaving the fossil-nuclear age behind, and paving the way for photovoltaics (PV) to play a central role in a future shaped by sustainable power production.

This paper focuses on the levelized cost of electricity (LCOE) from photovoltaics in West Africa and Germany, and how it varies based on different locations with different climate conditions. Additionally, it also factors out the key drivers influencing the levelized cost of electricity (LCOE) in West Africa and Germany.

Scope, Objectives and Research Questions

The scope of this thesis covers the levelized cost of electricity (LCOE) in West Africa and Germany, and its development in light of climate change and climate variability. It focuses mainly on Germany and three countries in West Africa namely; Sierra Leone, Burkina Faso, and Niger. The choice of consideration of the three countries is based on the climatic regions in West Africa. In addition, this thesis is restricted to crystalline silicon panels, grid-connected, and ground-mounted systems as baseline since the costs are to a large part similar on an international scale. The analysis of the LCOE is performed using an excel spreadsheet, and a sensitivity analysis is carried out to determine the robustness of the results.

In summary, the objectives for the thesis are:

I. Conduct a desktop study to establish the LCOE inventory;
II. Assess the solar energy resource potential for the chosen case studies;
III. Analyze photovoltaic systems in terms of techno-economic performance to determine the LCOE;
IV. Analyze the extent to which the LCOE is influenced by key cost drivers;
V. Conduct comparative and sensitivity analysis of different systems for the chosen case studies.

Four main questions frame the work developed in this thesis project. These are:

I. What are the photovoltaics trends by LCOE, installed capacity, generation and technology in West Africa and Germany?
II. What is the cost driving factors of LCOE?
III. How does the electricity production from solar and it's cost in West Africa compare to the situation in Germany?
IV. The potential of producing green hydrogen in West Africa considering electricity costs as a factor.

Structure of the Thesis

In the current chapter, a brief introduction of the study, its aim and context were provided. In chapter 2, an overview of the socio-economic structure of the different case studies. The energy situation and cost of electricity from photovoltaics are also discussed. In addition, the energy transition systems in the different case studies are also expounded. Chapter 3 introduces the methodological approach, procedures employed, and various scenarios selected are elaborated. The fourth chapter focuses on the analysis of the results obtained from the excel spreadsheet and carrying out seneitivity analysis to have an understanding about how the LCOE varies. Implications of results are discussed in the last chapter, which is then followed by conclusions and recommendations based on the findings of the study.

1. LITERATURE REVIEW

This thesis conducted a comprehensive literature review to identify existing research methodologies on levelized cost of electricity (LCOE) from photovoltaics, the choice of selection of the different case studies in West Africa, and it also gives a clear understanding of the socio-economic context in West Africa and Germany. It was derived from the review of peer-reviewed publications. The desk study presents an understanding of the energy context in West Africa and Germany and identifies the drivers influencing the cost of electricity in West Africa and Germany. In addition, the thesis elucidates the energy system transition in West Africa and Germany.

2.1. Previous Research LCOE

Mogmenga et al. (2019) focused on the economic and financial calculations concerning the production of electrical energy from photovoltaic installations connected to the grid in Burkina Faso. They also investigated the cost of energy produced by photovoltaics installations throughout their operational lives (taken here equal to 25 years) using the LCOE equation and compared with other economic parameters. The calculation for LCOE gives an average value of 60 Fcfa/kWh for a discount rate of 4%. ECREEE (2017) conducted an economic and financial analysis of 2.2 MWp Sal solar PV project in Cabo Verde, which was commissioned in October, 2010. The analysis of the estimated cost of generation conducted during the project preparation showed that the LCOE was just below the utility's cost of generation which was very high at that time. A new calculation of LCOE was done using the LCOE equation based on the original CAPEX and an estimate of the reinvestment that would be required for restoring the full generation capacity resulted in a cost of 0.14 €/kWh, which was comparatively favorable with the utility's cost of generation which stood at approximately 0.20 €/kWh in 2016.

Fraunhofer ISE (2013) presents findings on the LCOE of renewable energy technologies with a focus on PV. It predicts future cost and market developments through 2030 based on technology-specific learning curves and market scenarios. Fraunhofer ISE (2023) photovoltaic report forecast the solar PV capital cost and balance of system (BOS) separately for Germany to project the LCOE, using learning curves. It also presented the LCOE for PV power plants in 2021, which is from 3.1 to 5.7 €-ct/kWh.

Huld et al. (2014) focused on mapping the cost of electricity from grid-connected and off-grid PV systems in Africa. They considered cost of PV system installations in terms of initial investments, operations and maintenance, as well as discount rate for LCOE calculation. Akpahou et al. (2023) investigated techno-economic analysis of utility-scale grid-tied solar photovoltaic in Benin republic. They employed a breakdown of initial capital cost in terms of photovoltaic module, balance of system (BOS), miscellaneous, feasibility study, development and engineering, and operations and maintenance cost to calculate the LCOE.

Brunet et al. (2022) focused on analyzing the extent to which the operation of on-grid solar power plants found in Burkina Faso, Madagascar, Morocco, Rwanda, Senegal, and South Africa is a vector for sustainable development. The results identified the role of government in enhancing solar PV sustainability for poverty alleviation.

However, it gleaned that for the LCOE to be favorable and attractive so as for it to reach grid parity, government should provide capital incentives and subsidies in order for it to be affordable and sustainable.

2.2. Selection of Countries in West Africa

The choice of selection of countries within West Africa is based on the climatic zones in the region. West Africa has four distinct climate zones namely: Guinean zone, Sudanian zone, Sudano-Sahelian and Sahelian zone (Emetere, 2017). The climatic zones of West Africa are shown in Fig. 1.

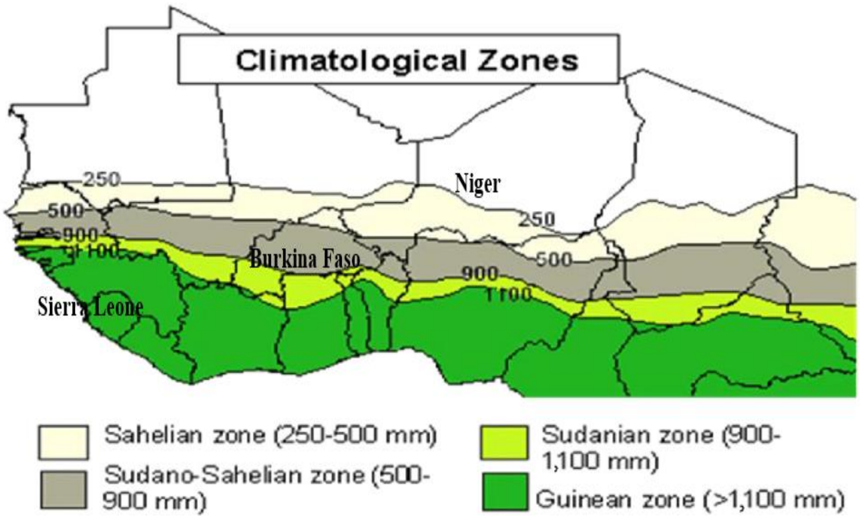

Figure 1. Climate zones in West Africa. Adopted from FAO

The Guinean zone has an annual precipitation greater than 1100 mm. The Sudanian zone has an annual precipitation ranging between 900 mm and 1100 mm. The Sudano-Sahelian zone has an annual precipitation ranging between 500 mm and 900 mm. Lastly, the Sahelian zone is a region of perennial vegetation with an annual average precipitation ranging between 250 mm and 500 mm. Sierra Leone is in the Guinean zone with a tropical rainforest. Burkina Faso has three climate zones with a semi-arid climate from north to south: the Sahelian zone in the north, the Sudano-Sahelian zone in the center, and the Sudanian zone in the south. Niger typically is in heart of the Sahelian zone with an arid climate, the transitional zone between the tropical West African coast and the Sahara Desert. Thus, from the Guinean zone to the Sahelian zone the temperature increases and further results to increase in solar irradiation across the different climate zones. However, based on the increasing solar irradiation from south to north across the different climate zones, Sierra Leone, Burkina Faso, and Niger were selected as case studies in West Africa.

2.3. Social and Economic Context of West Africa and Germany

This section identifies how the economic activities affect and shape social processes in all case study countries. It also highlights how the social and economic factors influence one another.

Sierra Leone

Sierra Leone is located along the west coast of Africa with a tropical rainforest climate, it has a total area of 72,300 km^2, and a population of 8.4 million with a 2.2% annual population growth (World Bank, 2023). Sierra Leone had a civil war which ended 2002, since then, Sierra Leone has made remarkable progress in consolidating peace and security country-wide and rebuilding its economy which was nearly destroyed by the decade-long conflict (Mestre, 2015).

Sierra Leone real GDP growth in 2022 was 2.8% from 4.1% in 2021 due to impact of Russia's invasion of Ukraine. Inflation in 2022 was 26.1% from 11.9% in 2021 driven by food, fuel inflation and depreciation of Leone. Sierra Leone is characterized by high poverty of 59.2% in 2022, income inequality (Gini coefficient of 0.357 in 2018), and high youth unemployment of 70%, compounded with skills mismatch. The fiscal deficit declined to an estimated 4.8% of GDP from 7.3% in 2021 due to higher grants. Public debt increased to an estimated 92.9% of GDP from 79.8% in 2021. The country is trapped at high risk of debt affliction (AfDB, 2023c).

Despite this notable progress, the fundamental drivers of fragility continue to pose significant downward risks for the country's development. High rates of youth employment, gender inequality, high levels of perceived and real corruption, weak human and institutional capacities and poor economic governance systems, especially public financial management (PFM) and revenue management systems, constrain the Government's capacity to implement its development agenda. Limited physical infrastructure, especially in energy, water supply and roads, inhibit inclusive and sustainable growth and limits the country's ability to implement its transformation agenda (Mestre, 2015).

Burkina Faso

Burkina Faso is a West African landlocked Sahelian country with a semi-arid climate. It has a total area of 274,220 km^2 and a population of 22.1 million with a 2.7% annual population growth. Burkina Faso is a low-income country with limited natural resources. Its economy is largely based on agriculture, although gold exports are on the rise. More than 40% of the population lives below the poverty line (World Bank, 2023).

Real GDP growth in 2022 was 3.2% from 6.9% in 2021 because of extractive activities fell following the closure of several mines for security reasons. Other factors in the economic slowdown were sociopolitical instability, military coups, a deteriorating security environment, and the attack of Russia's invasion of Ukraine. Inflation jumped to 14.4% in 2020 due to higher imports of food products and oil. The security context and resulting humanitarian crisis have exacerbated poverty in rural areas, estimated at 51% in 2019 as well as unemployment of 57% of the population (AfDB, 2023a).

Niger

Niger is located in the heart of the Sahel with an arid climate, has a total area of 1,267,000 km^2 and a population of 25.2 million with a 3.7% annual population growth. It has a poorly diversified economy, with agriculture accounting for 40% of its GDP. More than 10 million people (41.8% of the population) are living in extreme poverty. Niger is grappling with an influx of refugees fleeing conflicts in Nigeria and Mali. The United Nations High Commissioner for Refugees (UNHCR) had identified 294,467 refugees and almost 350,000 displaced persons in the country in 2022 (World Bank, 2023).

Real GDP growth rebounded to 7.2% in 2022, on strong performance across all sectors, particularly primary and tertiary services (which grew 7%). Inflation exceeded the West African Economic and Monetary Union (WAEMU) target of 3%, fueled by higher consumer food prices and the deteriorating international economic situation. The social situation remains precarious with extreme poverty of 42% in 2021 (AfDB, 2023b).

Germany

Germany is a European country and a founding member of the European Union (EU), it has a total area of 357,590 km^2, and a population of 83.1 million with a 0.0% annual population growth (World Bank, 2023). Germany is the top economic power in Europe and the fourth globally. After experiencing a historic recession following the COVID-19 pandemic, the country's economy grew throughout the first three quarter of 2022 driven by the ongoing recovery in private consumption. Nevertheless, Germany only grew an estimated 1.5% in 2022, slower than in 2021 which was 2.6%. due to the consequences of Russia's invasion in Ukraine (Santander, 2023).

Germany's economic success is based on its export-oriented manufacturing sector, especially in vehicles, machinery, chemicals, and electronics. Its economy is also characterized by its social market model, which combines a free market with a strong welfare state and labor unions. However, Germany faces some economic challenges, such as high energy costs, aging population, and trade imbalances (EU, 2023).

Table 1. Main socio-economic profile of the four countries

Main Indicators	**Sierra Leone**	**Burkina Faso**	**Niger**	**Germany**
Total area - km² (2020)	72,300	274,220	1,267,000	357,590
Population (2021)	8,420,641	22,100,683	25,252,722	83,196,078
Population growth - annual % (2021)	2.2	2.7	3.7	0
Rural population - % of population (2021)	57	69	83	22
Access to electricity - % of population (2020)	26.2	19	19.3	100
Life expectancy at birth, total - years (2021)	60	59	62	80
Human capital index - scale 0-1 (2020)	0.4	0.4	0.3	0.8
GDP - Billions USD (2021)	4.04	19.74	14.92	4,262.77
GDP per capita - USD (2021)	480	893.1	590.6	51,203.60
GDP growth - annual % (2021)	4.1	6.9	1.4	2.6
Inflation - annual % (2022)	27.2	14.3	4.2	6.9
Unemployment, total - % of labor force (2022)	3.6	5.2	0.5	3

Source: (World Bank, 2023)

2.4. Energy Context in West Africa and Germany

This section presents the energy sector of the different countries under study, it also highlights the composition of the energy sectors, their installed capacities and future targets. It also identifies the challenges faced in the energy sectors of the different countries.

Sierra Leone

Although Sierra Leone is endowed with energy potential in various forms including biomass from agricultural wastes, hydro and solar power, it remains underutilized. Energy consumption is largely dominated by biomass sourced from fuelwood and accounts for 80% of the energy used. Imported petroleum products, the next largest source of energy, are mainly for power generation and account for 13% of energy consumption. The power sector is small, with less than 150 MW of electricity generation capacity connecting less than 150,000 customers with the cost of electricity heavily subsidized. The entire country lacks a stable and reliable public power supply and domestic demand remains significantly unmet (ITA, 2021).

As of March 2019, the installed electricity generation capacity from renewables in Sierra Leone was 113 MW. This is made up of 75 MW of hydropower, 4 MW of solar and 34 MW of bioenergy. The nationwide electrification rate was recorded at 5% (estimated at 12% in urban areas and 2% in rural areas) in 2018 (Energy Catalyst, 2020). The current electricity supply is challenged by generation capacity and seasonal variation and electricity is disseminated using inadequate and ageing transmission and distribution networks. It is delivered at a very high cost with Sierra Leone having one of the highest electricity tariffs in the sub-region. There numerous waterfalls for hydropower facility, Bumbuna Dam, with a peak of 50 MW during the rainy season, has a reduced output of 8 MW in the dry season (ITA, 2021).

The government has demonstrated a strong commitment to expanding the energy sector despite many major challenges over the past years. The enactment of relevant legislative reforms laid the foundation for the restructuring of the sector, which created the Electricity and Water Regulatory Commission (EWRC) in 2014, unbundled the former National Power Authority (NPA) into the Electricity and Generation Transmission Company (EGTC), and the Electricity and Distribution Supply Authority (EDSA) in 2015, and enabled the development of Independent Power Producers (IPP) projects. The EWRC focuses mainly on the regulatory aspects and sets tariffs for consumers and tariffs between EGTC/IPP, while the EGTC focuses on electricity generation and transmission. EDSA holds a monopoly as the single buyer from IPPs and the single seller to consumers (ITA, 2021).

Other initiatives undertaken by the government include the establishment of a Rural Renewable Energy Project (RREP) to support increased access to rural energy resources and a Rural Electricity Board and a Rural Electricity Fund to promote and make electrification widely available in all regions, a Renewable Energy Empowerment Project to develop a knowledge base of existing renewable energy policies. The Côte d'Ivoire-Liberia-Sierra Leone-Guinea (CLSG) interconnection project, under the West African Power Pool (WAPP) program (ITA , 2021). The construction of this line is part of the backbone of the Mano River Union countries and the priority projects of the WAPP Master Plan. The WAPP project aims at providing affordable and reliable electricity supply to the four countries with a giant hydropower plant in Ivory Coast serving as the generation hub, with the evacuation and distribution lines passing through Liberia to Sierra Leone and to Guinea (AfDB, 2020).

As a result of the cost of electricity provision from ageing power plants in Freetown and in Sierra Leone more generally, with high operations and maintenance (O&M) costs, the country is largely dependent on temporary electricity supply. This includes electricity from a floating power plant called Karpowership, at a monthly cost of approximately US$2 million, that is moored at the Freetown's harbor, and contracted to supply 50 MW electricity. This, together with other factors, including commercial and technical losses amounting to 45% generation, makes Sierra Leone's energy sector financially unstable (Hirmer et al., 2021).

According to the 2015 Sustainable Energy for All (SE4ALL) Country Action Agenda, the Sierra Leonean Government has set targets that will see an increase electricity access from 13% in 2013 to 92% by 2030, and the renewable energy level from 43,464 GWh in 2013 to 111,780 GWh by 2030 (Energy Catalyst, 2020). Fig. 2 and Fig. 3 below shows the population with access to electricity, and the electricity consumption, generation and import respectively in Sierra Leone.

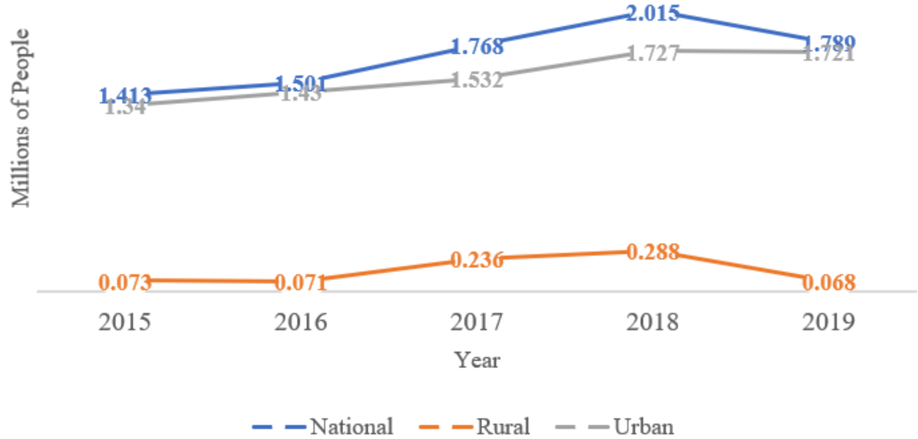

Figure 2. Population with access to electricity in Sierra Leone (AEP, 2020c)

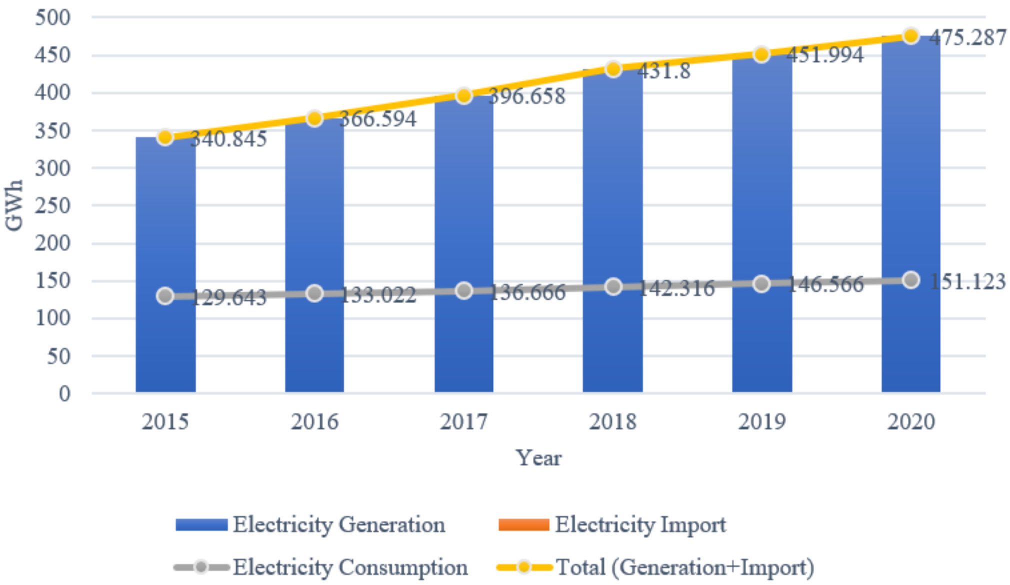

Figure 3. Electricity consumption, generation & import in Sierra Leone (AEP, 2020c)

Burkina Faso

Burkina Faso is a landlocked country with energy resources limited to some hydro-electrical installations. Without any oil domestic resources, Burkina Faso must import all of the hydrocarbons needed to fuel the country. For its oil products, the nation strongly relies on the refineries and oil terminals of bordering countries that have access to the sea (Côte d'Ivoire, Ghana, Togo, and Benin) (Ouédraogo, 2010). Burkina Faso's total installed electricity generation capacity is 324.1 MW in 2020, with most of the electricity produced from imported fossil fuels. The existing and overall installed capacity is not able to meet the countrywide electricity demands, thus, more than half of what is generated locally is imported from the neighboring Ivory Coast (90%), Ghana (9.5%) and Togo (0.5%) (Masumbuko, 2021). Burkina Faso's energy context is characterized by (Moner-Girona et al., 2017):

1. Predominance of biomass energy use with an 80% of the primary energy consumption
2. Dependence on imported fossil fuels
3. Very low deployment of renewable energy technologies
4. Low access to modern energy

The amount of the population with access to modern energy services in Burkina Faso is still very low (19% of the population has access to electricity), with only 2.3% of the rural population having access to electricity (World Bank, 2023).

The electricity production of Burkina Faso in 2015 mainly relied on hydropower (6% of total electricity capacity) and thermal-fossil fuel generation (about 63% of the total power generation capacity). All petroleum products are entirely dependent on imports by road at high cost from ports over 1,000 km away, since the country has no crude oil reserves or refining capacity. As for natural gas, Burkina Faso has no natural gas production, consumption, or reserves. In rural areas the main source of energy is the utilization of traditional biomass (Moner-Girona et al., 2017).

The technical potential of renewable energy generation consists of small hydro (38 MW), solar PV (82.55 GW), biomass (1.075 GW) and wind (9.881 GW). Despite of the availability of such potential, much is still to be done in order to harness it for useful gain. Currently, renewable electricity accounts for about 12.5% of the total share of electricity produced in 2017. The existing infrastructure consists of aged hydropower plant of 32 MW capacity and 283 MW of thermal generation as of the end of 2015. The country's state-owned utility Société Nationale d'Electricité du Burkina (SONABEL) has had to deal with multiple challenges in providing electricity in urban and semi-urban area, some of these include frequent power shortages, aging generation capacities, heavy reliance on fossil fuels (Masumbuko, 2021).

The Proposed Renewable Energy Action Plan (PANER) was developed by the Ministry of Energy in order to provide regulation and guidance on renewable energy matters for the period 2015 to 2030. This burrows heavily from existing global and regional initiatives such SE4ALL, Renewable Energy Policy for ECOWAS, and the Regional Program for Development of Renewable Energy in West African Economic and Monetary Union (UEMOA). The diversification of the energy mix is sought with PANER by laying down targets to expand the existing renewable energy capacity from 32 MW in 2010 to 150 MW in 2020 and further to 318 MW by 2030. Concerning rural electrification, settlements with more than 1,500 households living very far off from the main grid, decentralized systems are considered. These include small-scale solar PV plants and hybrid off-grid solutions with diesel generator set. PANER provides projections of growing the current rural population being served by mini-grids and off-grids to 13% in 2020 and 27% in 2030 (Masumbuko, 2021). Fig. 4 and Fig. 5 below shows the population with access to electricity, and the electricity consumption, generation, and import respectively in Burkina Faso.

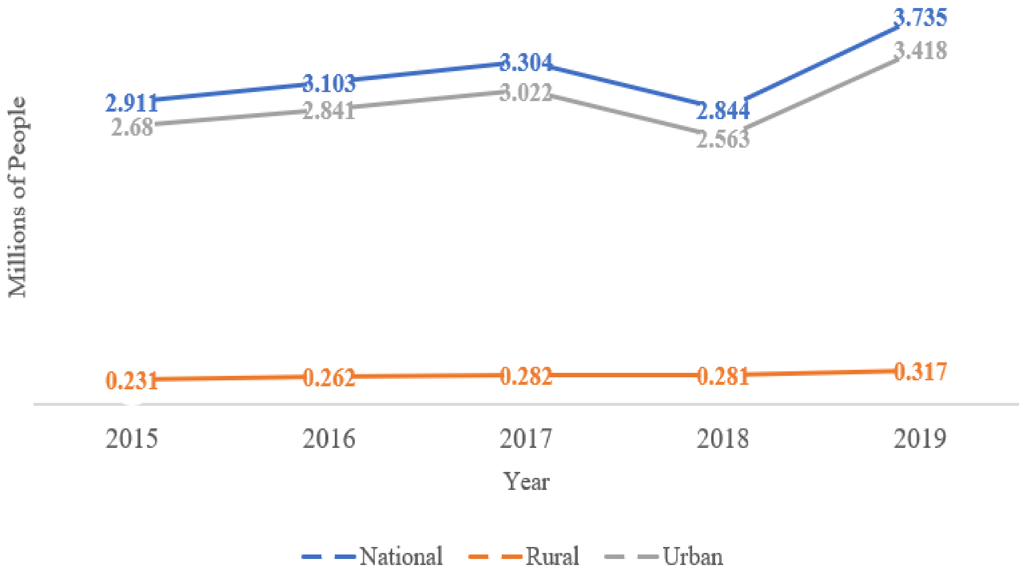

Figure 4. Population with access to electricity in Burkina Faso (AEP, 2020a)

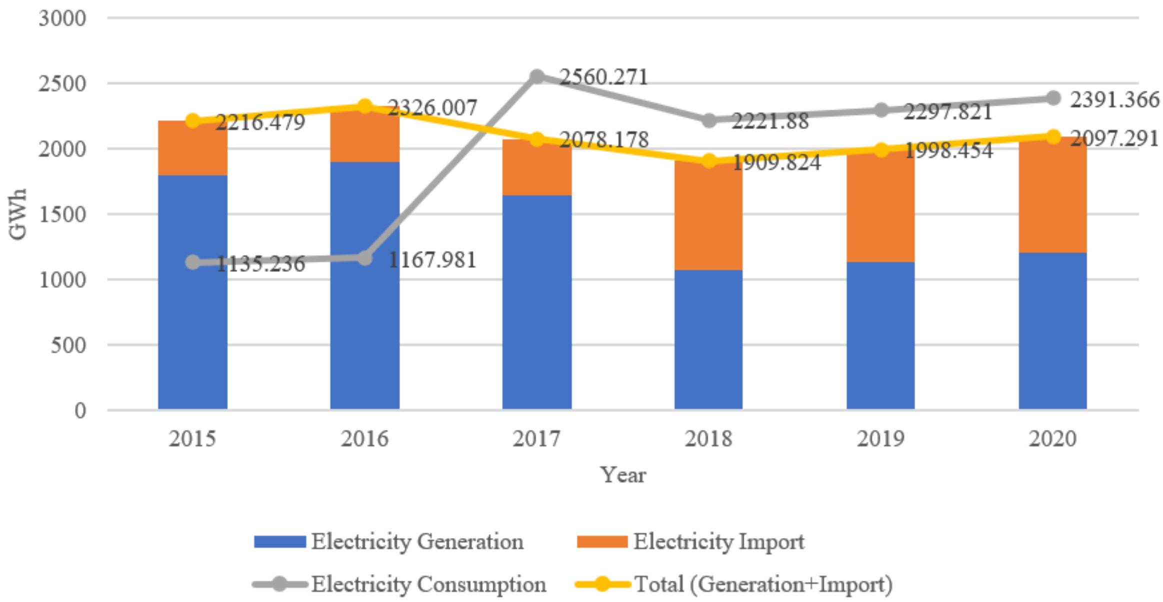

Figure 5. Electricity consumption, generation & import in Burkina Faso (AEP, 2020a)

Niger

Niger has one of the lowest electrification rates in sub-Sahara Africa. Only one in seven Nigeriens have access to modern electricity services, and just 4% of rural residents have access through the national utility. Without power, there is no viable path for economic growth and development, and few prospects for people living below the poverty line (Power Africa, 2023). Niger has vast renewable energy resources with a potential that comprises biomass, solar, hydro, and conventional sources such as coal, oil, uranium, and natural gas (Olivia, 2019).

The total power generation capacity in Niger is estimated to be 182.04 MW in 2018. The existing power capacity are coal power plant (38 MW), light fuel oil power plant (124 MW) and off-grid power plant (20.04 MW) (Allington et al., 2021). Niger aims to reach an installed capacity of 750 MW by 2030 and an electrification rate of 100% by 2035. In the long run, the country plans to fully open its power sector to private investors. Société Nigérienne d'Electricité (NIGELEC) dominates the power sector, its concession for the public service of electricity was extended until 2043. Around 85% of the power supply is imported from Nigeria, representing a high dependency from the neighboring country (Enerdata, 2020).

The increase in imported power is evidence of increasing electricity demand in the country. Niger imports electricity from Nigeria at a low wholesale price of $0.04 per kWh, making it cheaper than the power produced in the country. Niger further sells both imported and locally generated electricity at a tariff of $0.158 per kWh. However, the growing demand in Nigeria and political insecurity undermine the reliability of the system. Another issue is that the existing lines cannot carry the required transmission capacity to Niger, and there is a need to replace current lines with higher voltage lines (Olivia, 2019).

However, due to its limited electricity distribution system, which covers only 54.3% in urban areas and 54% in rural areas, and with most of the population living in rural areas, it can be implied that around 70% of the population has no access to electricity in the country. Niger energy sector is faced with key problems such as limited technical capacity, unreliability of utility companies and security issues. These problems need to be solved with future massive electrification projects, by developing power plants and grid infrastructure (Bhandari et al., 2021).

According to the country's National Renewable Energy Action Plan (2015), renewables (including hydro) were to account for 51% of the installed capacity by 2020 and 58% by 2030. However, the target for 2020 was not reached, with renewables representing only 8% of the capacity in 2020 (Enerdata, 2020). Fig. 6 and Fig. 7 below shows the population with access to electricity, and the electricity consumption, generation and import respectively in Niger.

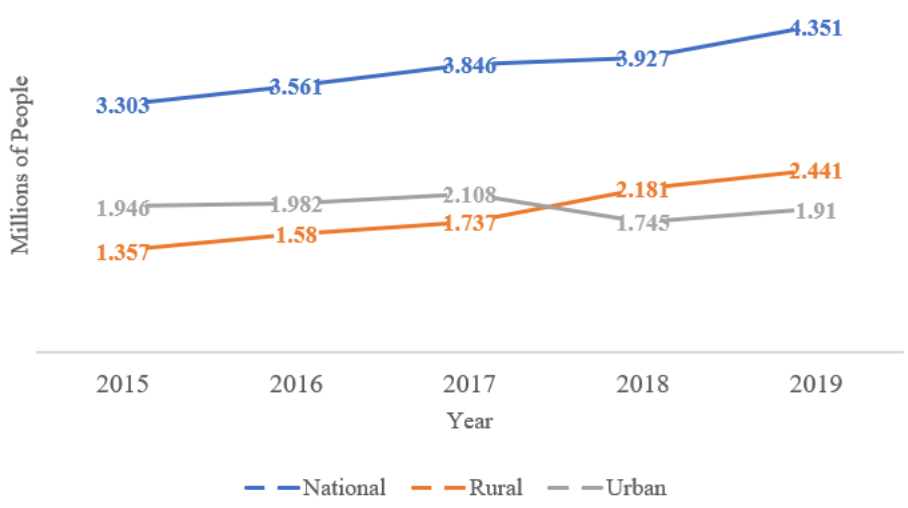

Figure 6. Population with access to electricity in Niger (AEP, 2020b)

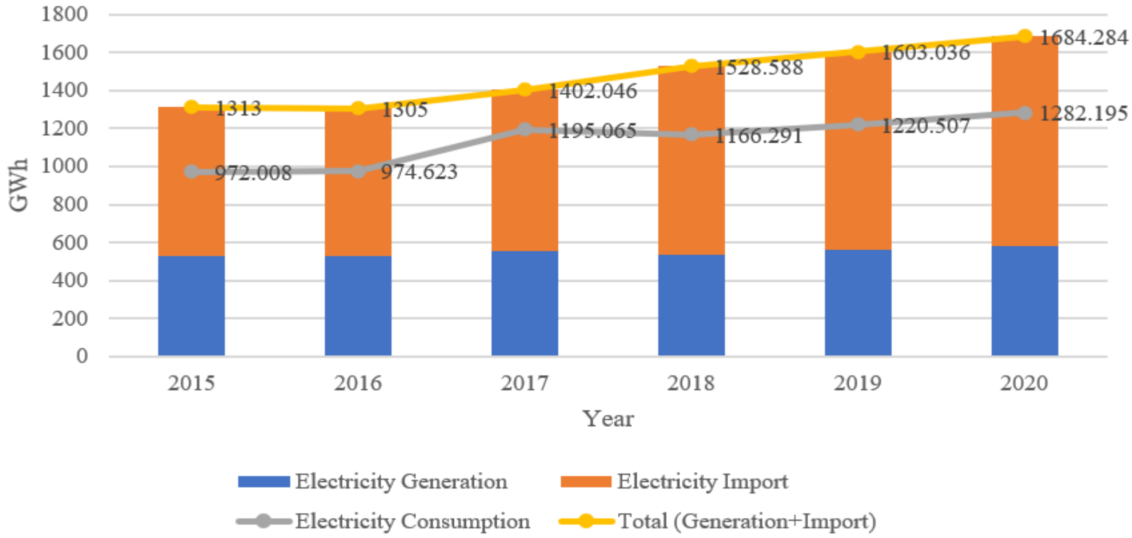

Figure 7. Electricity consumption, generation & import in Niger (AEP, 2020b)

Germany

Over the last four decades, Germany's energy supply has shifted from a clear dominance of coal and oil to a more diversified system. Nuclear energy, first introduced in the 1970s, is being replaced by more renewables. However, electricity generation in Germany still relies heavily on fossil fuels. Coal, natural gas and oil together accounted for 52% of the total power generated in 2018, though oil accounted for a very small share. The electricity generation is 644 TWh (coal 37.5%, nuclear 11.8%, natural gas 13.2%, wind 17.3%, bioenergy and waste 9.1%, solar 7.4%, hydro 2.8%, oil 0.8%, geothermal 0.03%) in 2018 (IEA, 2020a).

Germany is facing an energy crisis as Russia cut off gas supplies to Europe amid the tensions over Ukraine. Gas prices has soared, putting pressure on hundreds of local utilities and energy firms. Germany relies heavily on Russian gas, and have few alternatives or domestic resources. The country has been trying to phase out coal and nuclear power as part of its clean energy transition, but has now temporarily authorized the reopening of some coal-fired plants and may consider keeping some nuclear plants open. The government has announced lending support to energy firms and consumers, while the European Commission has proposed targets to cut electricity consumption and a revenue cap for non-gas plants (Kraemer & Steitz, 2022).

Nonetheless, to date, the electricity sector has been shouldering a sizeable share of the Energiewende's cost and progress. The Energiewende (energy transition) continues to be the defining feature of Germany's energy policy landscape. Undoubtably, Germany's population has 100% access to electricity. The government focuses its efforts to achieve stronger emission reductions in other sectors, notably transport and heating. The Climate Protection Programme 2030 recently adopted by the German government, including a carbon price in the transport and heating sectors, is an important step in the right direction. The plan is mindful of the distributional impact of climate policies and aims to ensure a level playing field across sectors and stakeholders. Both policy and regulatory reforms can help Germany achieve a cost-efficient, equitable and sustainable pathway to meeting its highly ambitious energy transition goals (IEA, 2020a). Fig. 8 and Fig. 9 below shows the installed net power generation capacity, and share of energy sources respectively of Germany.

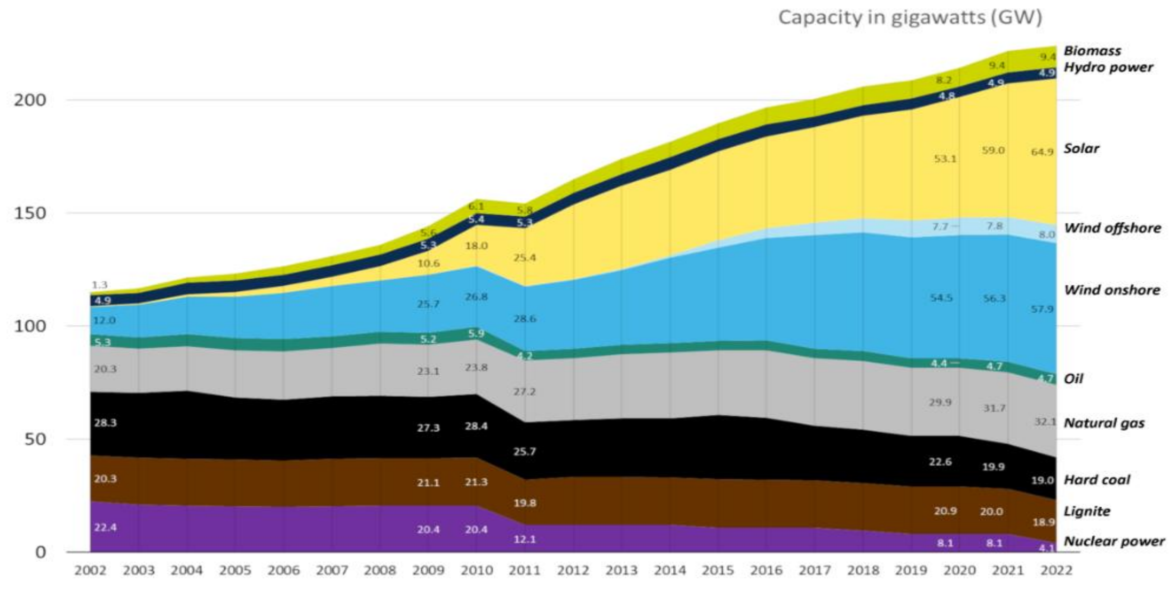

Figure 8. Installed net power generation capacity in Germany (Appunn et al., 2023)

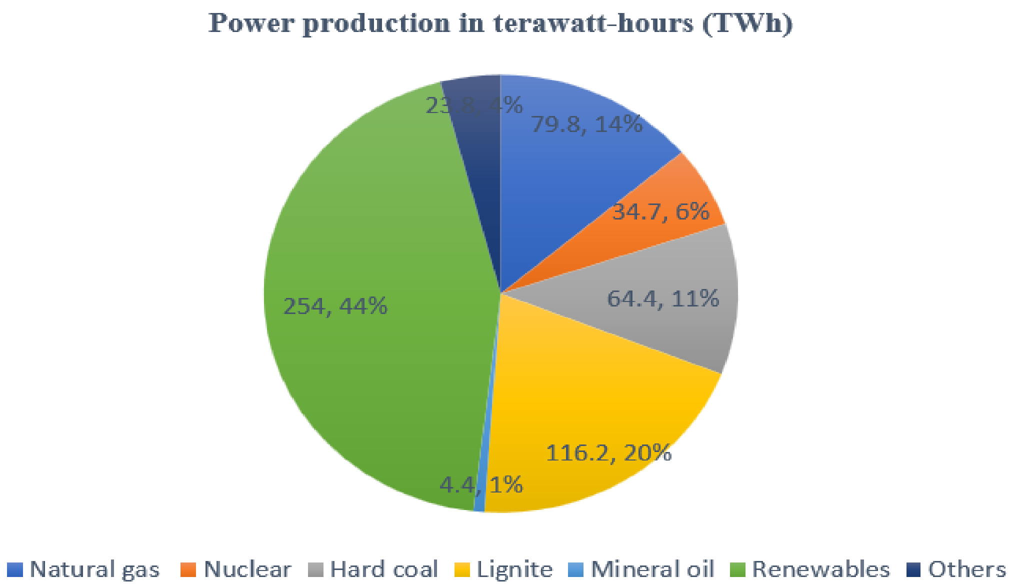

Figure 9. Share of energy sources in 2022 in Germany (Appunn et al., 2023)

2.5. Cost Drivers of Electricity in West Africa and Germany

The cost of electricity in West Africa is relatively high compared to Germany. Electricity access remains a challenge in West Africa where many countries are dependent on expensive imported fossil fuels. Access to electricity in West Africa is at 52%, with shortages of up to 80 hours per month, and yet electricity in the region remains among the costliest in the world, at $0.25 per kWh, more than twice the global average (World Bank, 2018). On the other hand, cost of electricity in Germany is rising, as the country is facing an energy crisis due to the attack of Russia's invasion of Ukraine (Kraemer & Steitz, 2022). Thus, this section identifies the key cost drivers of electricity of the countries under study.

Sierra Leone

Electricity usage is growing rapidly and so is the cost, the cost of electricity in Sierra Leone is relatively high compared to other countries in West Africa. This high cost is attributed to several factors including (EDSA Top Up, 2023):

1. Power generation capacity: Sierra Leone's power generation capacity is relatively low, and the country relies heavily on imported fuel to generate electricity. The reliance on imported fuel makes electricity more expensive, as fuel prices can fluctuate, and transportation cost can add to the overall price.

2. Limited investment in infrastructure: It also contribute to high cost of electricity, many power generation and distribution facilities are outdated and are in of repair or replacement, which can lead to inefficiencies and higher operating cost.
3. Inefficient power generation and distribution: Power outages and load shedding are common, and the system is often unable to meet demand, resulting in higher costs for those who can afford to pay for electricity.

Burkina Faso

Despite the high level of government yearly subsidy, electricity prices in Burkina Faso are one of the highest in West Africa (0.21 €/kWh) (Moner-Girona et al., 2017). The major drivers of high cost of electricity includes (USAID, 2021):

1. No legal or regulatory framework for independent power producers (IPP) and limited experience with IPPs.
2. National utility SONABEL is not a creditworthy off-taker. SONABEL lacks the financial stability and dependence on subsidies.
3. High cost of new on-grid connections and nascent off-grid sector.

Niger

Niger has one of the lowest electricity access rates in sub-Saharan Africa, with majority of its population facing widespread lack of access to electricity. Some of the challenges that hinders the provision of low-cost electricity includes (Tilahun et al., 2019):

1. Dependence of imported electricity: Niger heavily rely on imported electricity from Nigeria, which poses serious energy security issues in the country.
2. Absence of an energy mix in the power grid: The domination of inefficient fossil power generation is another challenge to the provision of low-cost and reliable energy in Niger. Moreover, many of NIGELEC's diesel power plants are close to the decommissioning phase but continue to operate with high generation costs.
3. Limited technical capacity in the sector: The inadequate understanding of the underlying relation among energy demand and its influencing factors (population growth, industrialization, and urban progress) for balancing supply and demand in developing countries such as Niger.

Germany

Research has shown that cost of electricity in Germany is one of the highest in the world. Since the turn of the millennium, the price of electricity in Germany has more than doubled. (Nehra, 2020). The following factors are basic drivers for cost of electricity in Germany:

1. Energy transition: The high cost of electricity in Germany is as result of the country's transition from fossil fuels and atomic energy to renewables. This change comes with a steep price, which is funded by levies and taxes on Germany's citizens and companies (Röckel, 2017).
2. Value added tax (VAT) and CO_2 pricing: There was a temporary reduction in VAT from 19% to 16% in the second half of 2020. However, on January, 2021 that went back to its previous rate. In addition, the CO_2 tax introduced by the previous government resulted in higher energy prices (Kohlmann, 2021).

2.6. Energy System Transition in West Africa and Germany

In recent years, the transition towards sustainable energy systems has gathered momentum. Yet, despite the substantial progress around the world, the energy transition continues to pose significant technological, commercial and political challenges. However, considering climate change and its consequences from the usage of conventional energy sources around the world, the transition to a sustainable renewable energy system is eminent. Thus, this section will give an overview of the energy system transition in the different case studies in terms of achievements, challenges and future plans.

Sierra Leone

Sierra Leone is endowed with huge renewable energy potential which is grossly untapped and underutilized due to lack of government policy direction, lack of financial resources and inadequate research and development of renewable energy technologies. The high dependency on fossil fuels for electricity generation and transport is causing a huge burden on the national budget, coupled with climate change, other adverse environmental impact and the effect of greenhouse gas emissions (Ministry of Energy, 2015).

The government of Sierra Leone is committed to expanding access to affordable, reliable and clean energy to improve people's livelihoods and deliver on its nationally determined contributions under the Paris Agreement. Increasing renewable energy capacity is essential and central to the government's energy, climate and development plans, with a target to achieve 85% renewable energy capacity by 2030. The continued growth of off-grid and mini-grid sector will be key to achieving this target, as will the development from low-cost power from hydro (SEforALL, 2021).

Sierra Leone Renewable Energy Association (REASL) was established in 2016 to spearhead the country's energy evolution. The association was born from the desire to ensure that renewable energy is included on the National Renewable Electrification Plan for Sierra Leone. REASL is dedicated to the development of a thriving renewable market and accelerate the adoption of renewable energy to achieve universal energy access and economic empowerment in Sierra Leone (Harper & Canlas, 2021).

Sierra Leone developed various policies and strategies to accelerate the energy transition, in particular to promote and develop renewables. The country developed the National Renewable Energy policy in 2016 which was updated in 2020, the Energy Efficiency Policy in 2016, the National Clean Cooking Strategy and Action Plan in 2020, and the Off-Grid Solar Energy Strategy in 2020. The country is working to promote energy efficiency, enhance management and expansion of the energy mix through the uptake of renewable energy sources (solar, wind, hydro, biomass) particularly in rural areas of Sierra Leone, as well as promoting the use of clean and renewable energy in the extractive and manufacturing sector. The government's goal is to improve energy efficiency and increase access to grid connections by 42% in 2025, and off-grid mini-grid and solar stand-alone systems by 27% and 10% respectively in 2030 (AfDB, 2022). Fig. 10 below shows the renewable energy generation of Sierra Leone from 2015 to 2020.

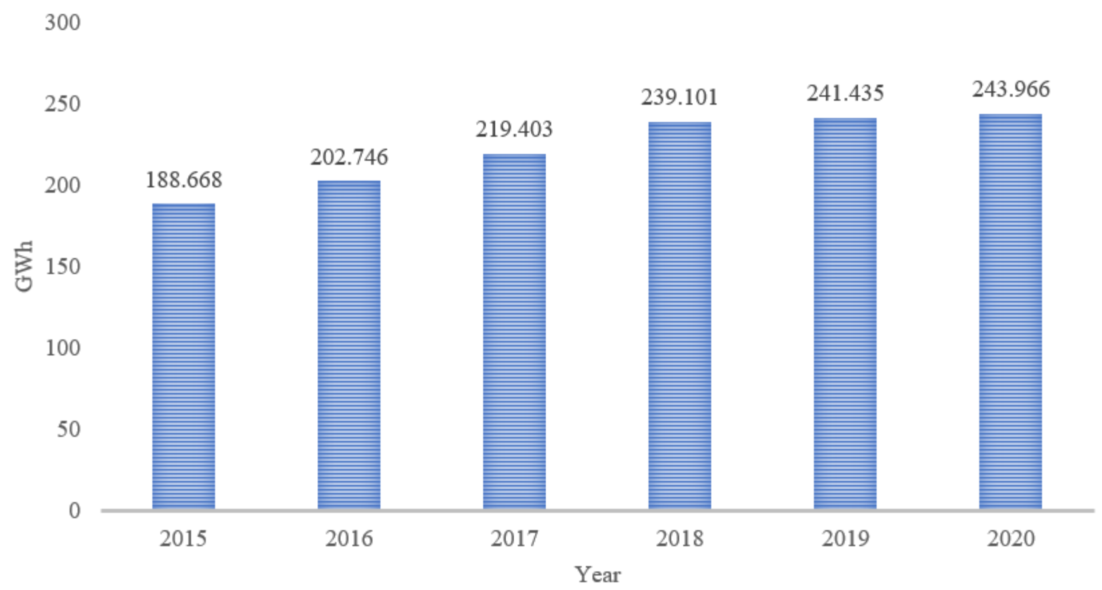

Figure 10. Renewable energy generation mix in Sierra Leone (AEP, 2020c)

Burkina Faso

Burkina Faso aims, in accordance with the commitments made at COP 26 in Paris, to succeed in its transition to solar energy. Since 2016, Burkina Faso started its energy transition by taking advantage of the country's strong solar potential. Several homes and public administrations have abandoned thermal energy for photovoltaic energy to reduce not only consumption cost, but especially greenhouse gas emission. Nonetheless, the energy crisis in the country is not new. For several years the country has lived at a rate of incessant blackouts that extend over several hours, especially during the hottest period (April to July). However, since the liberalization of the energy sector in 2017, businesses and households have found solar energy as a solution (Kinda, 2021).

Currently, less than 25% of the population has access to electricity and the majority of those with access live in the urban areas. In cities, the electricity access rate averages 65%, dropping to 3% in rural areas. The country aims to reach 95% electricity access, with 50% in rural areas and universal access to clean cooking solutions in urban areas, with 65% in rural areas by 2030, up to 9% in 2020. The utilization of Burkina Faso's renewable resource potential will enable the country to reduce its heavy reliance on thermal generation and energy imports. The country could also move to attain 50% renewable energy generation targets stipulated in the 2014 Energy Sector Policy and the 2017 law on the regulation of the energy sector (IRENA, 2021).

The country recently implemented an auctions policy such as import tax incentives and value-added tax (VAT) intended to increase solar projects in rural areas. Burkina Faso has one of the largest solar power plant in West Africa, the Zagtouli solar power plant is a 33 MW on-grid photovoltaic plant. It has been operational since late 2017, it produces electricity for Burkina Faso's public energy company, SONABEL. The Zagtouli solar power plant is unique in terms of its capacity and it's part of the ambitious national plan for renewable electricity production (Cantoni et al., 2021).

In 2023, Burkina Faso launched the Africa Mini-grids Program (AMP) to expand energy access to rural communities. The program will focus on enabling innovation and technology transfers in decentralized renewable energy distribution and storage solutions. Burkina Faso's National AMP project aims to increase access to clean energy by improving the financial viability and promoting large-scale commercial investment in solar mini-grids in the country (UNDP, 2023). Fig. 11. Below shows the renewable energy generation mix of Burkina Faso from 2015 to 2020.

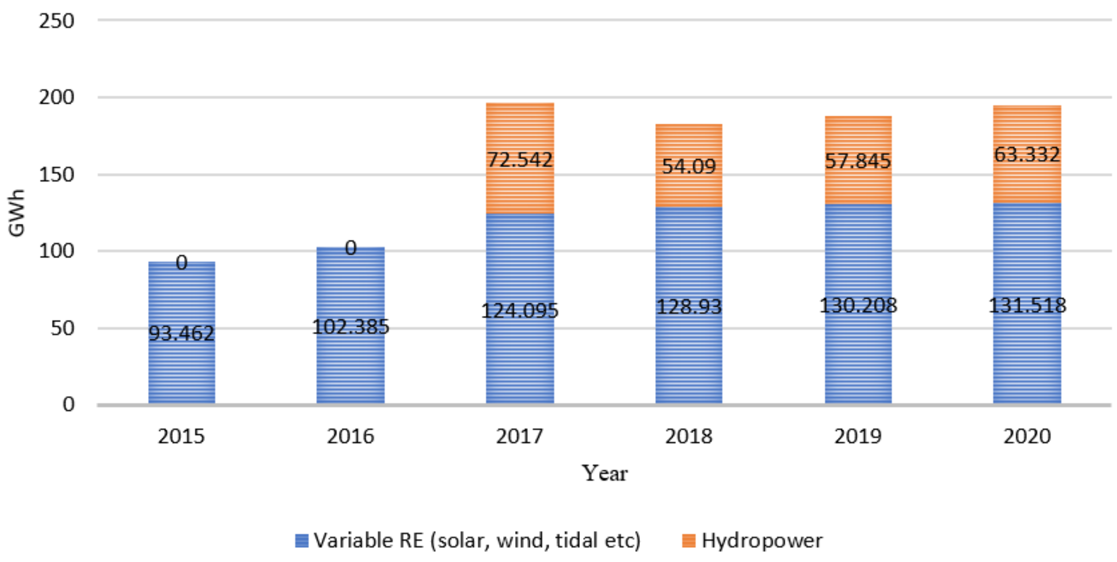

Figure 11. Renewable energy generation mix in Burkina Faso (AEP, 2020a)

Niger

The majority of Niger's population faces a widespread of lack of electricity. Although the country lies in the Sahara belt, exploitation of solar energy is so far minimal. Due to the ongoing fossil fuel exploration in the country, this fuel might dominate the future electricity supply. Currently, Niger imports most of its electricity from Nigeria. There is a need to expand electricity generation and supply infrastructure in Niger (Bhandari et al., 2021). The country envisions 100% access to energy in 2030, with rural access at 30% and overall access at 65%, increase the share of renewables in the generation of electricity to 57% by 2030 excluding the imported electric power and also reduce the percentage of traditional biomass in the energy mix by 2020 from 87% to 67% (Olivia, 2019).

Niger offers the possibility of producing green hydrogen due to its high solar energy potential. Due to the still growing domestic oil and coal industry, the use of green hydrogen in the country currently seems unlikely at higher cost of hydrogen as an energy vector. However, the export of green hydrogen to industrialized countries could be an option. In 2020, a hydrogen partnership has been established between Germany and Niger. The potential import of green hydrogen represents an option for Germany and other European countries to decarbonize domestic energy supply. Currently, there are no known projects for the electrolytic production of green hydrogen in Niger (Bhandari, 2022).

Niger is a member of the Economic Community of West African States (ECOWAS). Every member of this organization has adopted its renewable energy policy (National Energy Action Plan Renewables (PANER)) under the guidance of Regional Center for Renewable Energy and Energy Efficiency (ECREEE). The implementation period of this policy is from 2015 to 2030, with the aim of increasing the access to energy in a sustainable manner to achieve energy dependence. This policy also supports the fight against climate change as the Sahel region is vulnerable to impacts of climate change even though their share to global greenhouse gases emission is minor (Bhandari, 2022). Fig. 12 below shows renewable energy generation mix of Niger from 2015 to 2020.

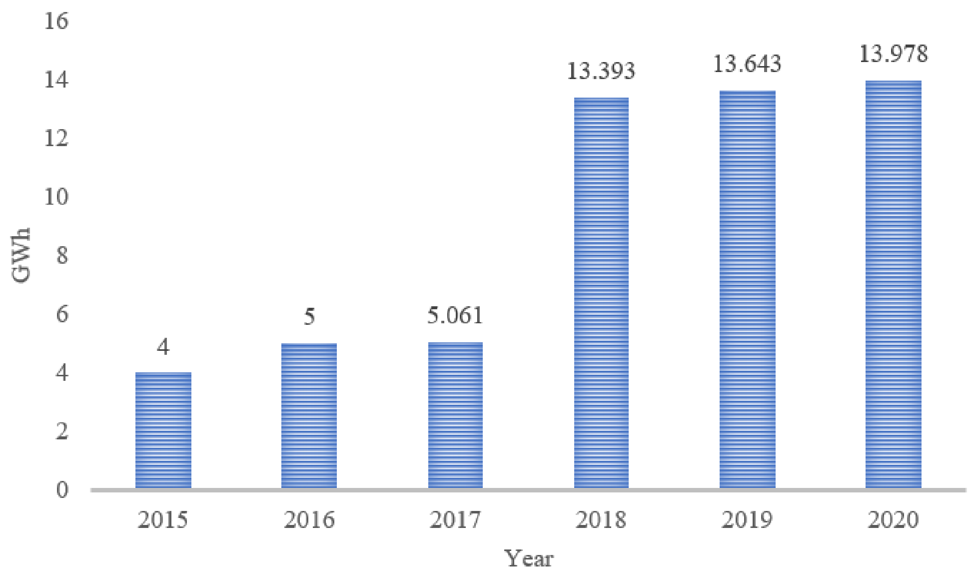

Figure 12. Renewable energy generation mix in Niger (AEP, 2020b)

Germany

The energy transformation, in Germany widely known as the "Energiewende", is the country's planned transition to a low-carbon, and nuclear-free economy. However, there is much more to it than phasing out nuclear power and expanding renewable energies in the power sector. The German's electricity sector is in a period of transition, spurred by the German's government endeavor to maintain a sustainable, secure, climate-friendly and affordable energy supply system. The most important aspect of this Energiewende is to phase out of nuclear energy, promotion of renewable energy technologies, and reduction of greenhouse gas (GHG) emissions. As a consequence, huge investment in power generation systems and infrastructure are needed. Wind and solar photovoltaics (PV) are important renewable energy sources for achieving the goals, but power generation depends on spatial and meteorological conditions on site. Due to the decreasing unit investment costs and increasing capacity, solar PV and wind power are becoming increasingly competitive against conventional power generation. Hence, efforts are needed to enhance and optimize the grid integration of wind energy and PV and to maintain the long-term security of electricity supply during the transition process (Weida et al., 2016).

To date, Germany's Energiewende is clearly visible in electricity generation, where it has been effective in increasing renewable electricity generation. While coal (mainly lignite) remains the largest source of electricity, renewables have mainly replaced a large share of nuclear over the last decade. In 2017, wind power surpassed both nuclear and natural gas to become the second-largest source of electricity generation. Continued growth in renewables in line with Germany's energy and climate targets will require a number of measures for advancing electrification and system integration of renewables, including improvements to taxation and market regulation, and expansion of the transmission and distribution infrastructure, including improving its functionality (IEA, 2020a). Fig. 13 below shows the renewable energy generation mix of Germany in 2020.

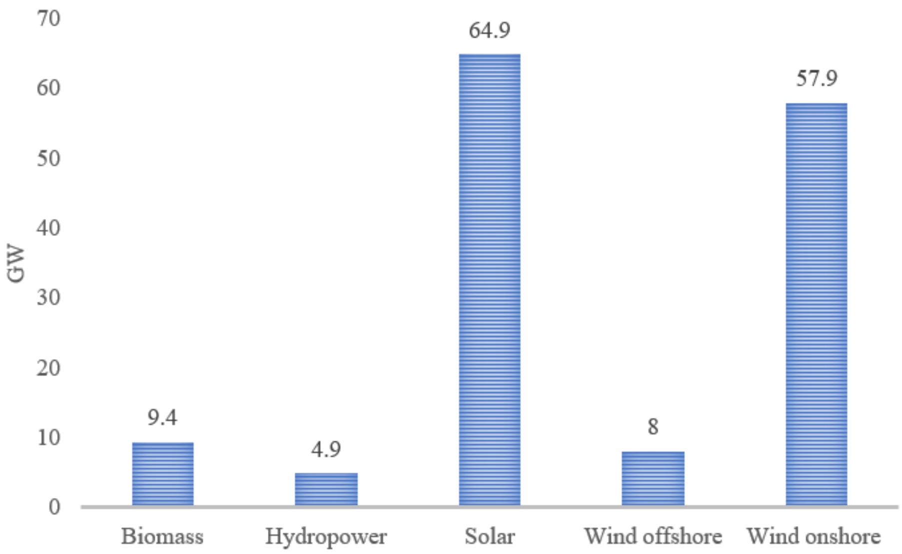

Figure 13. Renewable energy generation in 2020 in Germany (Appunn et al., 2023)

3. METHODOLOGY

The methodology adopted in this thesis is divided into four major components, as shown in the research methodology framework presented in Fig. 14. The research framework is intended for order and ease of adaptation of the research methodology. The research framework is fashioned to promote input-output relationship as the outputs from a phase form the inputs of the subsequent phases. Boundary and assessment of the current PV penetration in the different case studies are presented. The LCOE calculation formulae describes the methodology use to derive the capital expenditure (CAPEX), operational expenditure (OPEX), and amount of electricity generated over the lifetime of the project. This section further describes the parameters, assumptions and data used in the calculations. The contribution of the chosen research methodology enables one to assess the energy project's applicability, cost effectiveness, and economic soundness.

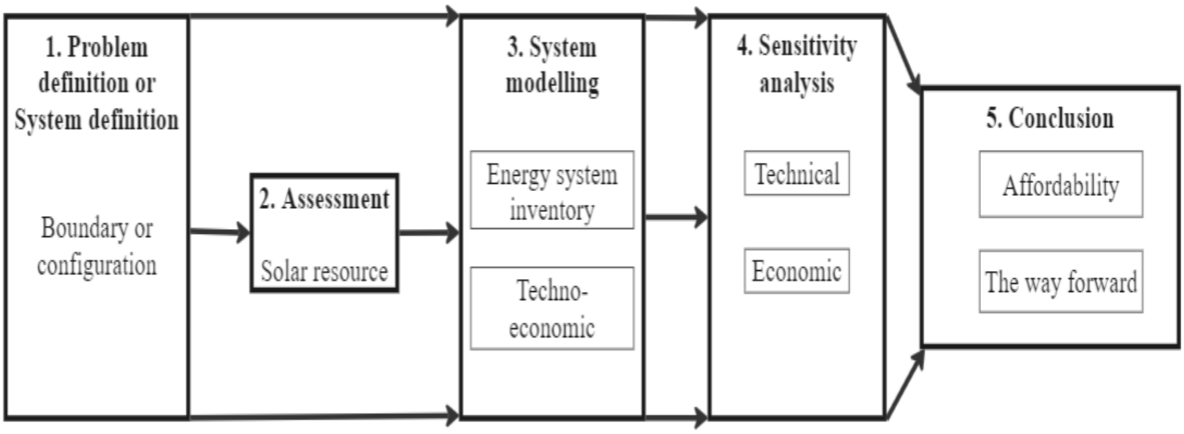

Figure 14. Research Methodology Framework (Own Illustration)

3.1. Boundary and Assessment of Solar PV Penetration

Photovoltaic (PV) refers to the direct conversion of sunlight to electrical energy. However, this thesis is restricted to crystalline silicon panels, grid-connected, and ground-mounted systems as a baseline since the costs are to a large part similar on an international scale (Fraunhofer ISE, 2015). Fig. 15 below shows an overview of the solar PV grid system. The solar PV panels convert the sun's energy to direct current (DC) electricity, which is transferred to the inverter for conversion into alternating current (AC). The inverter also houses the DC/AC disconnect, the converted AC electricity is transferred to the AC service panel, which in turn transfers the AC electricity to the AC utility meter. Additionally, the AC electricity is step-up from low voltage (LV) to medium voltage (MV) by a transformer, which finally transfers the AC electricity to the grid for usage by different power sectors.

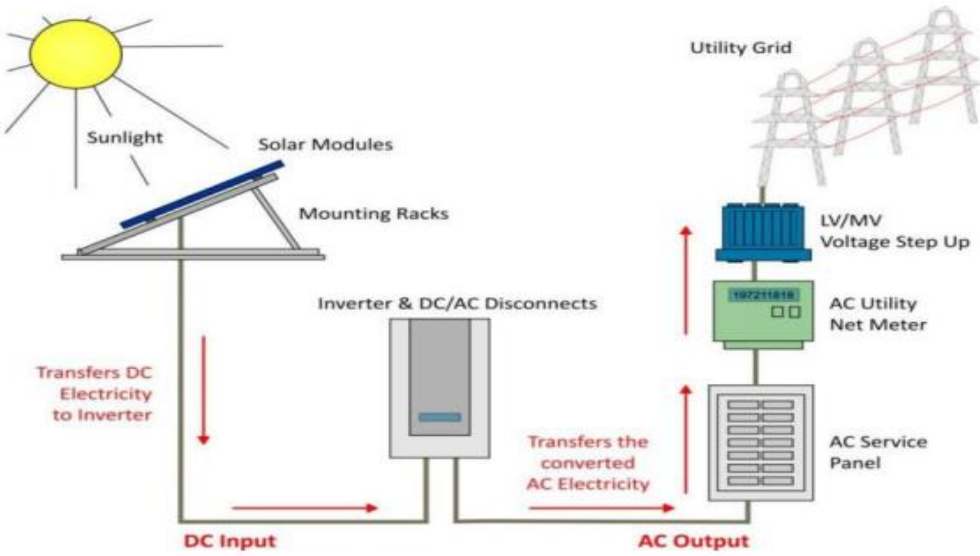

Figure 15. Overview of solar PV system boundary (Hindocha & Shah, 2020)

In relation relation to climatic data, this thesis uses RETScreen software, which is a Clean Energy Project Analysis Software developed by the Ministry of Natural Resources, Canada. As part of its analysis tool, RETScreen uses NASA's global climate data (NASA, 2023). In this thesis, NASA Surface meteorological as well as Solar Energy (SSE) data sets from RETScreen have been used to obtain the climatic data of each case study. Table 2 below shows the location, elevation and annual solar radiation-horizontal of the selected case studies. Fig. 16 and Fig. 17 below shows the daily solar radiation-horizontal and the air temperature of the selected locations respectively. It is observed from Fig. 16 that West Africa has high potential of solar resource for producing electrical energy through solar PV systems. Also, it can be deduced from Fig. 17 that West Africa air temperature almost doubles Germany's air temperature and solar PV panels efficiency decrease at higher temperatures.

Table 2. Location, elevation and annual solar radiation-horizontal of the selected locations

Location	**Latitude (ºN)**	**Longitude (ºE)**	**Elevation (m)**	**Annual Solar Radiation-Horizontal ($kWh/m^2/d$)**
Sierra Leone	8.7	-11.9	222	4.74
Burkina Faso	12.4	-1.5	306	5.55
Niger	17.1	7.8	510	6.54
Germany	51.4	10.3	356	2.82

Source: (NASA, 2023)

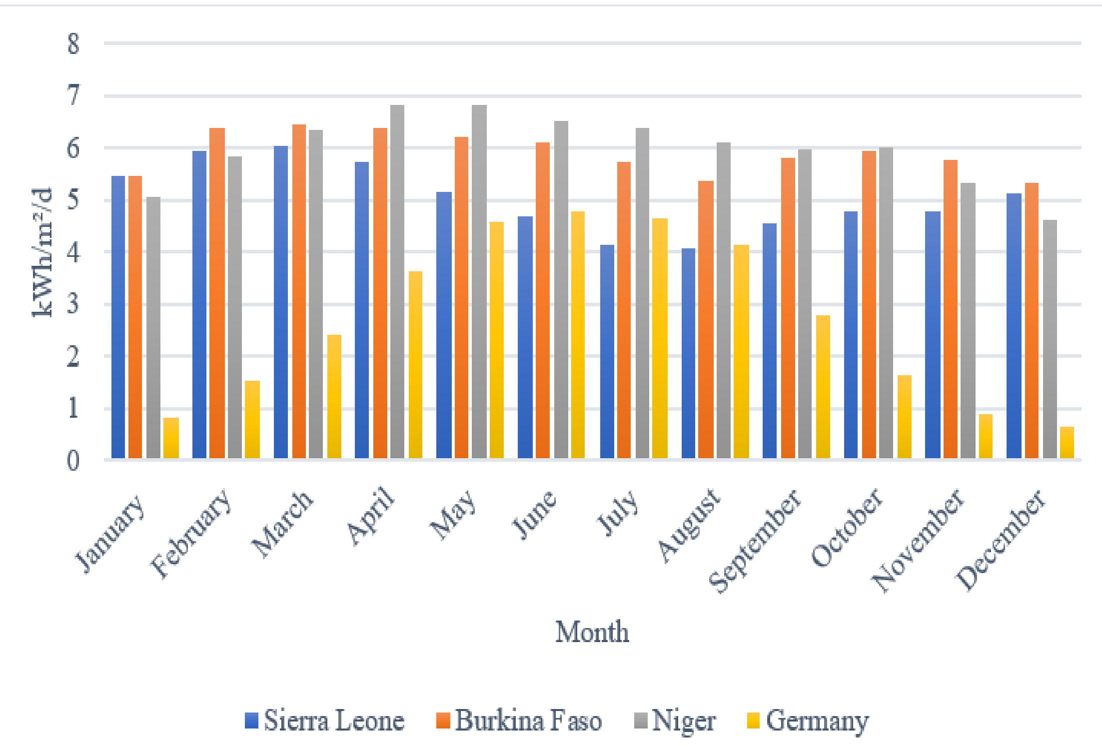

Figure 16. Daily solar radiation-horizontal (NASA, 2023)

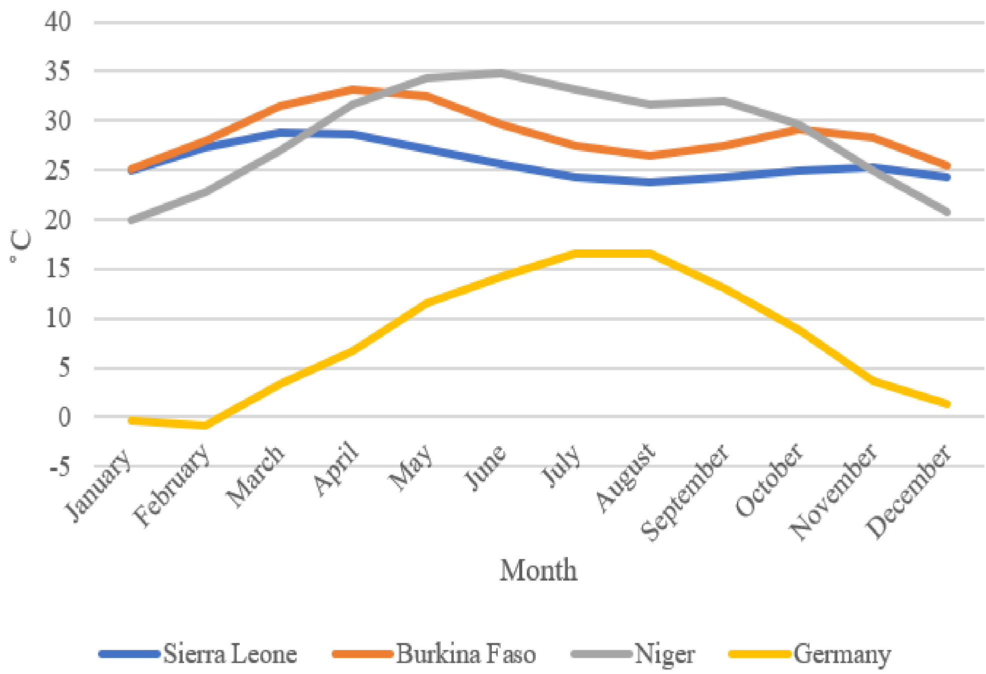

Figure 17. Air temperature (NASA, 2023)

3.2. LCOE Calculation Formulae

The levelized cost of electricity (LCOE) is an economic assessment of the total cost to building and operating a solar PV installation over its lifetime divided by the total energy output of the asset over that lifetime. It can also be regarded as the minimum cost at which electricity must be sold in order to achieve break-even over the lifetime of the project. It is expressed in currency per kilowatt-hours (kWh). The LCOE is a fundamental calculation used in the preliminary assessment of an energy-producing project. The significance of the LCOE is that it can be used to determine whether to move forward with a project or as a means to compare different energy-producing projects. LCOE calculations mainly depend on the CAPEX and the OPEX of the systems, the CAPEX is the fixed cost (capital cost) and the OPEX is the variable cost (operation, maintenance, and replacement costs). The LCOE calculations also strongly depends on the electricity generated by the solar PV system over its lifetime. This section describes the methodology used to derive the CAPEX, OPEX, and amount of electricity generated over the project lifetime. The LCOE is simply expressed as:

$$\text{LCOE} = \frac{\text{Life cycle cost (LCC)}}{\text{Lifetime energy production (kWh)}} \quad (1)$$

Alternatively,

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (2)$$

Where C_t is the total cost; E_t is the total energy generated from the solar PV system; and n is the project lifetime. Equation 2 which represents the LCOE is the sum of all discounted costs incurred during the project lifetime divided by the units of discounted energy produced from the system. While calculating, all CAPEX of the project occurs at n=0 year and should not be discounted. Hence, the CAPEX needs to be separated from equation 2 and all other parameters in equation 2 should be discounted starting from year 1. Annual costs are incurred over the project lifetime and hence required discounting.

Next, we considered the energy generated from the solar PV system over its lifetime. The energy produced from PV systems is related to the available solar resource, i.e., solar irradiation (S), the solar PV performance factor (PF), and solar PV annual degradation factor (d), and installed PV peak power (P_p). Hence, the energy generated (E_n) annually can be illustrated as:

$$E_n = P_p \times PF \times (1 - d) \times S \times 365 \quad (3)$$

However, both the energy generated (E_n) and the costs must be calculated in kWh per watt and € per watt, respectively, to derive the LCOE in €/kWh. Thus, combining and rearranging equations 2 and 3, the LCOE can finally be derived as:

$$\text{LCOE} = \frac{\text{CAPEX} + \sum_{n=1}^{N} \frac{\text{OPEX}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{P_p \times PF \times (1-d)^n \times S \times 365}{(1+r)^n}} \quad (4)$$

Where r is the discount rate; S is the solar irradiation ($kWh/m^2/day$); PF is the performance factor of the solar PV system (%); P_p is the installed PV peak power (W_p); d is the annual degradation of the PV module (%); n is the project lifetime, i.e., 25 years; CAPEX is the capital expenditure (€); and OPEX is the operational expenditure (€).

3.3. Used Parameters

3.3.1. Capital Expenditure (CAPEX)

The capital expenditure also known as the capital cost of the solar PV system is a vital catalyst for influencing the outcome of the LCOE model. Most of the existing studies considered the capital cost of the solar PV system as a whole (Owolabi et al, 2015; Fraunhofer ISE, 2018, 2021), while other studies considered the PV module cost, inverter and balance of system (BOS) separately (Vartiainen et al, 2019). Moreover, previous research works used the global average data.

Table 3. CAPEX subcategories of previous studies

Cost factor	Paper
PV module	Vartiainen et al. (2019) Al Matin et al. (2019) Mohamed A.S.A. & Maghrabie H.M. (2022) Abbood et al. (2018) Fathi et al. (2017) Akpahou et al. (2023)
Inverter	Vartiainen et al. (2019) Al Matin et al. (2019) Mohamed A.S.A. & Maghrabie H.M. (2022) Abbood et al. (2018) Fathi et al. (2017)
BOS	Vartiainen et al. (2019) Al Matin et al. (2019) Akpahou et al. (2023)
Miscellaneous	Akpahou et al. (2023)

Feasibility study, development and engineering	Abbood et al. (2018) Akpahou et al. (2023)
Land	Ouedraogo & Yamegueu (2019) Al Matin et al. (2019)
Mounting structure	Al Matin et al. (2019) Mohamed A.S.A. & Maghrabie H.M. (2022) Abbood et al. (2018) Fathi et al. (2017)
Installation	Mohamed A.S.A. & Maghrabie H.M. (2022) Abbood et al. (2018)
DC and AC cables	Mohamed A.S.A. & Maghrabie H.M. (2022) Abbood et al. (2018) Fathi et al. (2017)
Transportation	Mohamed A.S.A. & Maghrabie H.M. (2022)
Transformer	Abbood et al. (2018) Fathi et al. (2017)
Monitoring and control	Fathi et al. (2017)

This thesis work has segregated PV system costs (CAPEX) into three categories: hardware cost, installation cost, and soft cost. Also, these categories have been separated in subcategories to give a detailed information of the constituents of the CAPEX. This approach has provided a better understanding of the implication of individual subsystem cost on the LCOE outcome.

Table 4. Major cost categories

Categories	Subcategories
Hardware costs	PV module Inverter Racking and mounting Cable/wiring Monitoring and control Security and safety Transformer
Installation costs	Electrical installation Mechanical installation Civil installation
Soft costs	Feasibility study, development and engineering Permits, inspections and connections Land

3.3.2. Land Cost

Calculating the land cost is one of the most challenging aspect, as it varies greatly from one geographical region to another. Solar PV plants require 10-50 km^2/GW, a land cost of 30 $/kW was employed in a study (Takeda, 2019). Also, another study used a land cost of 20 $/$m^2$ (Ouedraogo & Yamegueu, 2019), thus, a land cost of 27.62 €/kW for West Africa and 5 €/kW for Germany are employed in this thesis.

3.3.3. Operational Expenditure (OPEX)

The operational expenditure also known as the annual cost is very pivotal for the smooth and successful running of a solar PV plant. The operational expenditure for large-scale PV plants is probably the lowest for any power generation source. Its simple technology for producing power without mechanical moving parts is a key factor in reducing this cost. The operational expenditure mainly composes of operation, maintenance and replacement costs. However, the OPEX employed in this thesis comprises of insurance, dust clearing, land clearing, repairing and replacement costs. Most existing literatures use 1-2 % of the capital cost as the operational expenditure.

3.3.4. Degradation Factor

The performance of a solar PV modules gradually degrades over the operational lifetime of the system as a result of exposure to extreme temperatures. The amount of solar radiation converted to electrical energy defines the efficiency of the module. It reduces with time and this phenomenon is called degradation of the solar modules. A conservative value of 0.5% per year is used for properly installed PV systems (Vartiainen et al., 2019). Fig. 18 below shows modes of degradation in PV modules.

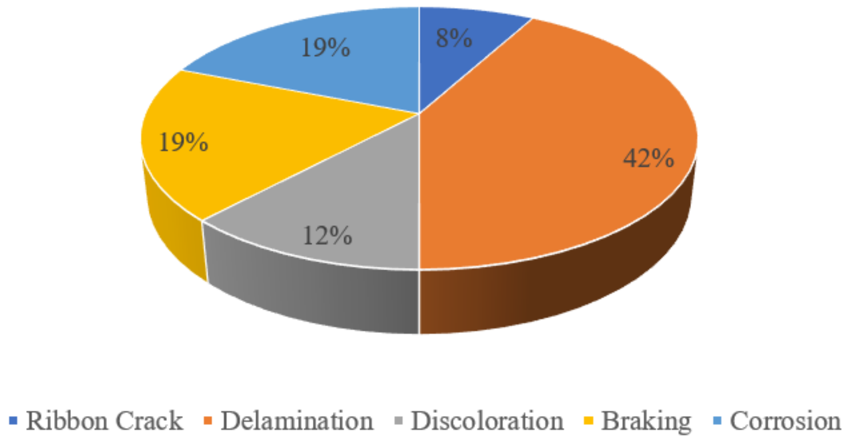

Figure 18. Parameters of degradation in PV modules (Nagar & Gidwani, 2018)

3.3.5. Discount Rate

In financial terms, the discount rate is one of the most essential parameters influencing the outcome of the LCOE calculations. Discount rates are used to attribute a value of future cash flow. The discount rate not only takes into account the inflation rate but also the technology risk. However, high discount rates make energy efficiency measures and supporting policies less attractive. According to the Expert Group on Projected Costs of Generating Electricity (EGC Expert Group), a 3% discount rate (corresponding approximately to the social cost of capital), a 7% discount rate (corresponding approximately to the cost of capital of a large utility in a deregulated or restructured market), and a 10% discount rate (corresponding approximately to the cost of capital in an environment with relatively higher risks) (IEA, 2020b). Thus, a discount rate of 7% is employed for all case studies in this thesis.

3.3.6. Performance Factor

As given in equation 3, the energy generated from the solar PV system can be expressed as:

$$E_n = P_p \times PF \times (1 - d) \times S \times 365 \quad (3)$$

However, the actual output of a solar PV reduces due to various factors and losses. Since the power generated from the solar PV is direct current (DC), it must be converted to alternating current (AC) before evacuating to the grid for transmission. Performance factor is important to monitor the efficiency of the solar PV and has a major influence in the energy generated. A performance factor of 75% was used in a study (Ouedraogo & Yamegueu, 2019).

3.3.7. Solar Resource

The solar resource is the average annual energy per unit area (kWh/m^2/day) based on the location of the country where the solar PV systems will be installed. Solar PV systems use both direct and diffuse radiation for their power generation (Takeda, 2019). The output of a solar PV system greatly depends on the solar resource of the location. The higher average annual energy per unit area and longer hours of sunshine, the higher the energy generated by the solar PV system. Thus, based on the solar resource data collected from RETScreen (NASA, 2023), the power generated by the fixed-structure tilted solar PV for different countries is compiled in Fig. 16 above.

3.4 Data Collection

This section presents in details the data collection methods and the tool used for analysis of the collected data during the study. Firstly, a literature study was carried out to understand the energy situation of the different case studies. Some of the documents that were reviewed include reports from different agencies of the government in the energy sector. Through these reports, a clear picture was concluded regarding electricity access in the different case studies and also the recent developments in the countries to improve their energy infrastructures.

Published articles and journals were also studied to get an in-depth understanding of the subject of study. In addition, books and a critical summary of work that has been realized in the area of research were used to understand the information that needs to be collected for designing the system for different case studies.

3.4.1. Technical Indices

In this thesis, the technical performance of the solar PV systems is evaluated by determining the energy output, performance factor, and capacity factor. These parameters provide information about the overall performance of the installations with respect to the available solar resource and other environmental variables.

The energy generated from the solar PV system has been indicated in equation 3. The performance ratio (PR) measures the overall effects of losses on the rated output of the system due to site's environmental conditions, installed components efficiencies and system's installation angles (such as tilt angle and orientation angle). The PR indicates how close a solar PV performance approaches ideal situation during real life operation (Oloya et al., 2021). Mathematically, it is expressed as:

$$PR = \frac{E_{AC}}{GII \times PV_{capacity}} \quad (5)$$

Where E_{AC} (kWh) is the usable energy at user end, GII (kWh/m^2/year) is the global inclined irradiation, and $PV_{capacity}$ (kW_p) is the PV module installed capacity.

The capacity factor of the solar PV installation is defined as the ratio of the final energy produced by the installation over a given period to the energy output that would have been generated if the system was operated at full capacity for the entire period (Oloya et al., 2021). It is given as:

$$C_f = \frac{E_{AC}}{PV_{capacity} \times H_{op}} \quad (6)$$

Where H_{op} is the total expected number of hours of operation in a given period, commonly taken as a year (for a regular year, which consists of 365 days, H_{op} = 8760 h).

Table 5 and Table 6 below shows the performance indicators for the selected grid-connected solar PV system and selected technical specifications for PV modules respectively.

Table 5. Performance indicators for selected grid-connected solar PV system

Location	Installed capacity (MW)	PV generation (MWh/yr)	GII ($kWh/m^2/yr$)	Capacity factor (%)	Performance ratio (%)
Sierra Leone	5	6839.25	1880.7	15.6	72.7
Burkina Faso	10	16017.75	2081.5	18.3	76.9
Niger	20	37748.89	2264.0	21.5	83.4
Germany	30	22813.65	1095.0	8.7	69.4

Table 6. Selected technical specifications for PV modules

PV Specification	West Africa	Germany
Module type	JKM560N-72HL4	TSM-430 DE09R.08
Maximum Power (P_{max})	560Wp	430Wp
Maximum Power Voltage (V_{mp})	41.95V	42.3V
Maximum Power Current (I_{mp})	13.35A	10.17A
Open-circuit Voltage (V_{oc})	50.67V	50.3V
Short-circuit Current (I_{sc})	14.13A	10.64A
Module Efficiency STC (η)	0.2168	0.215
Weight	32kg	21.8kg
Dimension	2278×1134×30 mm	1762×1134×30 mm
Normal operating cell temperature (NOCT)	45±2ºC	43ºC(±2K)
Temperature coefficient (P_{max})	-0.30%/ºC	-0.34%/K
Temperature coefficient (V_{oc})	-0.25%/ ºC	-0.25%/K
Temperature coefficient (I_{sc})	0.046%/ ºC	0.04%/K

3.4.2. Financial Analysis

The financial cost is divided into two parts and they are the initial project cost and further financial parameters. A comprehensive literature review was done, and the relevant data were collected for the LCOE modelling. Apart from this, various assumptions were made to complete the research work. Details of the assumed parameters and financial input parameters used in the thesis are in Table 7 and Table 8.

Table 7. Assumed parameters

Parameters	**West Africa**		**Germany**
Project lifetime (years)	25		25
Irradiation (kWh/m2/day)	Sierra Leone	4.74	2.82
	Burkina Faso	5.55	
	Niger	6.54	
Performance factor (%)	87.4		84.8
Degradation factor (%)	0.4		0.55
Discount rate (%)	7		7

Table 8. Financial input parameters

Parameters	**West Africa**	**Germany**	**Sources**
PV module	0.213 €/W [5]	0.247 €/W [5]	[1] Ouedraogo and Yamegueu (2019)
Inverter	65264.5 €/500kW [3]	20 €/kW [6]	[2] Al Matin et al. (2019)
Racking and mounting	93.23 €/kW [3]	38 €/kW [6]	[3] O.R. O et al. (2021)
Cabling/wiring	41.96 €/kW [3]	32 €/kW [6]	[4] Own assumptions based on R. Akpahou et al. (2023)
Monitoring and control	23308.75 € [3]	5 €/kW [6]	[5] Ready Solar (2023)
Transformer	23308.75 € [3]	10 €/kW [6]	[6] Own assumptions based on Fraunhofer ISE (2015)
Security and safety	27.62	5 €/kW [6]	[7] Own assumption based on

	€/kW [3]		A.S.A. Mohamed and H.M. Maghrabie (2022)
Installation (€/Kw)	35 €/kW [7]	30 €/kW [6]	[8] Own assumption based on A. Mandal (2013)
Feasibility study, development and engineering	0.8 % of CAPEX [4]	5 €/kW [6]	
Permits, inspections, and connections	35 €/kW [8]	5 €/kW [6]	
Land cost	27.62 €/kW [2]	5 €/kW [6]	

4. RESULTS AND DISCUSSIONS

This chapter presents the findings of the technical performance of the systems, economic implication and sensitivity analysis performed across the different case studies to test the robustness of the results. Several parameters were considered in the analysis of the economic feasibility of the different solar PV systems. These include total investment cost, and the fixed operating costs of maintenance, repair and use. The final system design to calculate the LCOE is performed using excel spreadsheet. Solar PV systems only vary in their size, capacity, cost and finance structure, but the technology, inclination of the sun, losses and site conditions are assumed to be the same.

4.1. System Performance

This section presents the results of the impact of PV module on design specifications, energy output, performance ratio and capacity factor of the proposed case studies.

Fig. 19 shows various sites' installed capacity and PV generation. Different solar PV systems have been considered regardless of solar resource potential and geographic location. The output of the PV generation greatly depends on the system capacity and solar radiation to a large extent. Germany (30 MW) system capacity is one-third greater than Niger (20 MW), but the PV generation of Niger is vastly greater than Germany due to the increased solar radiation in the locality. Also, considering Germany (30 MW) system capacity with the lowest solar radiation among the different case studies, it is observed that the PV generation of Germany is far way greater than Burkina Faso whose solar radiation is about twice Germany's. However, this indicates how pivotal the system capacity and solar radiation are to the output of the solar PV generation.

Fig. 20 shows various sites' annual performance ratio and capacity factor. The performance ratio, which is equivalent to derate factor or overall system's efficiency relative to available solar radiation arriving on the surface of the solar PV array, is an essential parameter in accessing and evaluating solar PV performance (Oloya et al., 2021). A key observation from Fig. 20 reveals that the annual performance ratio ranges between 69.4% in Germany (lowest) and 83.4% in Niger (highest), with an average of 75.6%. This suggests that the sites' PV installation performance ratios are very comparable. The lower performance ratio is due to losses attributed to the PV system. This comprises losses due to inverter inefficiency, wiring systems, soiling modules, dust accumulation on modules, high ambient temperatures, and low wind speeds. The capacity factor increases with higher electricity generation. Generally, a power plant with a capacity factor of 100% produces electricity continuously. It can be seen that the annual capacity factor varies between 8.7% in Germany (lowest) and 21.5% in Niger (highest), with an average of 16.0%. This infers that capacity factors for the installation sites are very close. Also, the estimated PV capacity factor is nearly comparable to the global average capacity factor of about 17.0% for utility-scale solar PV (Akpahou et al., 2023).

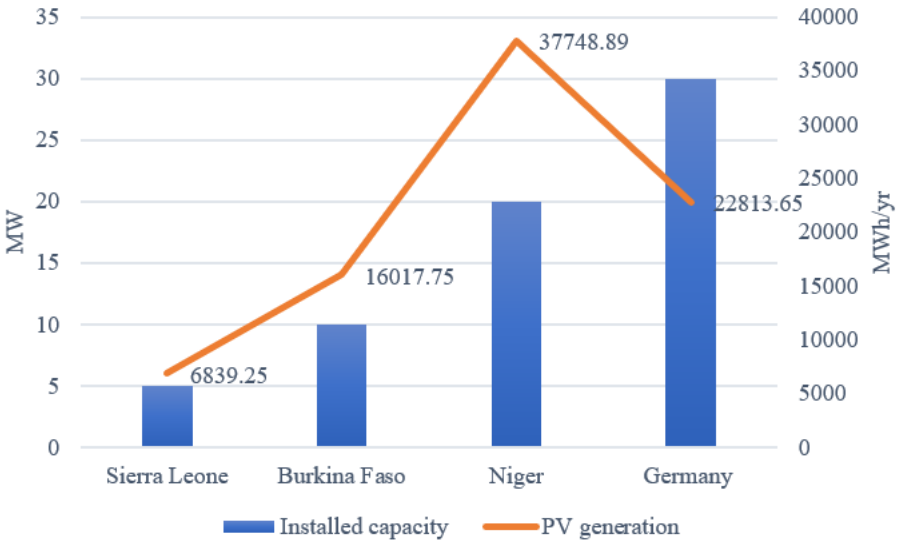

Figure 19. Installed capacities and energy generation of solar PV systems

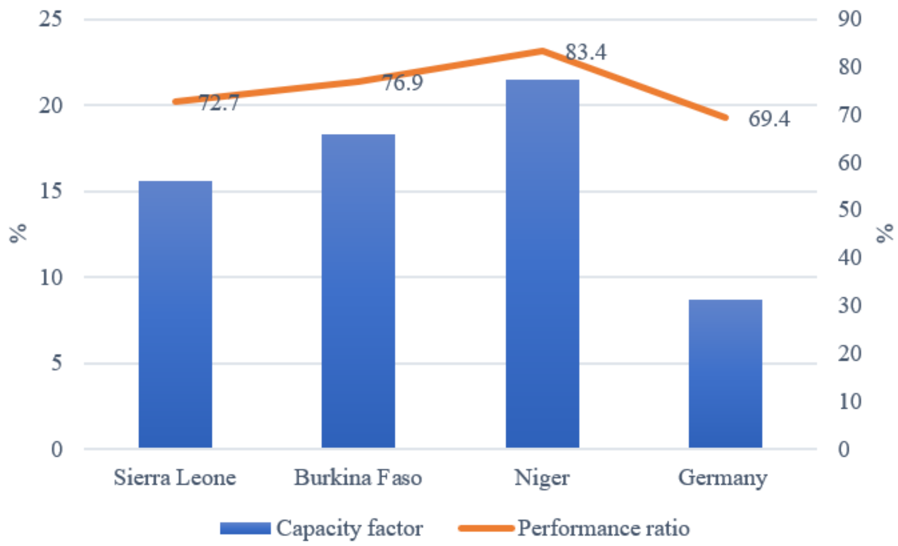

Figure 20. Performance ratio and capacity factor of solar PV systems

4.2. Economic Evaluation

The economic viability of a grid-connected PV system is a function of many factors. These factors include system performance ratio, system component cost, site specific-economic parameters, electricity price, government policy issues and economic life of the system. Accurate and detailed information on these factors is essential for reliable economic assessment of the PV system. The economic feasibility of the different solar PV systems is assessed using LCOE as an economic indicator. It can be gleaned from Table 9 that the cost drivers of the LCOE in West Africa are hardware cost, soft cost and OPEX. The reason for these cost drivers are due to lack of solar PV market and economies of scales in West Africa. However, the cost driver in Germany is the installation cost due high labor cost as compared to West Africa. It can also be deduced that the LCOE for the different case studies in West Africa achieve grid parity. The average cost of electricity in Sierra Leone and Burkina Faso are 0.1410 €/kWh and 0.1883 €/kWh (Global Petrol Prices, 2022). Also, the average cost of electricity in Niger and Germany is 0.145 €/kWh (Enerdata, 2020) and 0.235 €/kWh (FfE, 2023) respectively.

Table 9. Differences in key energy system parameters and financial results

Parameter		Unit	Sierra Leone	Burkina Faso	Niger	Germany
CAPEX	Hardware cost	(million €)	2.58	5.11	10.18	10.71
	Installation		0.17	0.35	0.70	0.90
	Soft cost		0.31	0.63	1.25	0.45
OPEX		(million €)	0.67	1.32	2.64	0.78
Total annual cost		(million €)	3.73	7.41	14.77	12.84
LCOE		(€/kWh)	0.1333	0.1130	0.0956	0.0766
Generation		(MWh)	6839.25	16017.75	37748.89	22813.65
Installed capacity		(MW)	5	10	20	30

4.3. Sensitivity of Inputs

In order to test the robustness of the results, a number of scenarios has been analyzed and a sensitivity analysis has been carried out in this section. The sensitivity analysis provides an estimation of the sensitivity of important financial indicators such as CAPEX in relation to key technical and financial parameters. To assess the sensitivity of the results, one parameter is changed at a time, keeping all other parameters constants. Sensitivity analysis on the LCOE and discount rate is done taking into consideration three different discount rates (3%, 7% and 10%) as proposed by the EGC expert group (IEA, 2020b). Also, sensitivity analysis on the LCOE and total cost is done at a discount rate of 7%, a decrement of 10% CAPEX on interval is assumed in order to have an understanding on how the LCOE varies with change in CAPEX. Table 10 and Table 11 below shows the LCOE for 10% decrement of CAPEX and the LCOE for assumed discount rates respectively.

Table 10. LCOE for 10% decrement of CAPEX

Sierra Leone						
Percentage (%)	0	10	20	30	40	50
CAPEX (€) *	3.06	2.76	2.45	2.14	1.84	1.53
OPEX (€) *	0.67	0.66	0.66	0.66	0.66	0.66
Total Cost (€) *	3.73	3.42	3.11	2.80	2.50	2.19
LCOE (€/kWh)	0.1333	0.1296	0.1260	0.1223	0.1186	0.1149
Burkina Faso						
Percentage (%)	0	10	20	30	40	50
CAPEX (€) *	6.08	5.48	4.87	4.26	3.65	3.04
OPEX (€) *	1.32	1.32	1.31	1.31	1.31	1.31
Total Cost (€) *	7.40	6.80	6.18	5.57	4.96	4.35
LCOE (€/kWh)	0.1130	0.1098	0.1067	0.1036	0.1005	0.0973
Niger						
Percentage (%)	0	10	20	30	40	50
CAPEX (€) *	12.13	10.91	9.70	8.49	7.27	6.06
OPEX (€) *	2.63	2.63	2.63	2.63	2.62	2.62
Total Cost (€) *	14.76	13.54	12.33	11.12	9.89	8.68
LCOE (€/kWh)	0.0956	0.0930	0.0904	0.0877	0.0851	0.0824

Germany						
Percentage (%)	0	10	20	30	40	50
CAPEX (€) *	12.06	10.85	9.64	8.44	7.23	6.03
OPEX (€) *	0.78	0.76	0.75	0.73	0.72	0.70
Total Cost (€) *	12.84	11.61	10.39	9.17	7.95	6.73
LCOE (€/kWh)	0.0766	0.0717	0.0668	0.0619	0.0570	0.0520

* = million Euro

Table 11. LCOE for assumed discount rates

LCOE (€/kWh)				
Discount rate (%)	**Sierra Leone**	**Burkina Faso**	**Niger**	**Germany**
3	0.1224	0.1037	0.0878	0.0637
7	0.1333	0.1130	0.0956	0.0766
10	0.1423	0.1206	0.1021	0.0871

The impact of discount rate on LCOE is shown in Fig. 21. It can be deduced that the LCOE is dependent on the discount rate and increases with increasing discount rate. It can be observed that at a discount rate of 3%, the LCOE is most attractive. Fig. 22 shows the sensitivity analysis on the total cost and percentage decrement of the CAPEX. It is clearly observed that the total cost decreases as the CAPEX decrease, indicating the CAPEX is very essential. Fig 23 shows the impact of the CAPEX on the LCOE, it can be deduced that the LCOE decreases as the CAPEX decrease, however, this indicates that the CAPEX is a major cost driver for the LCOE.

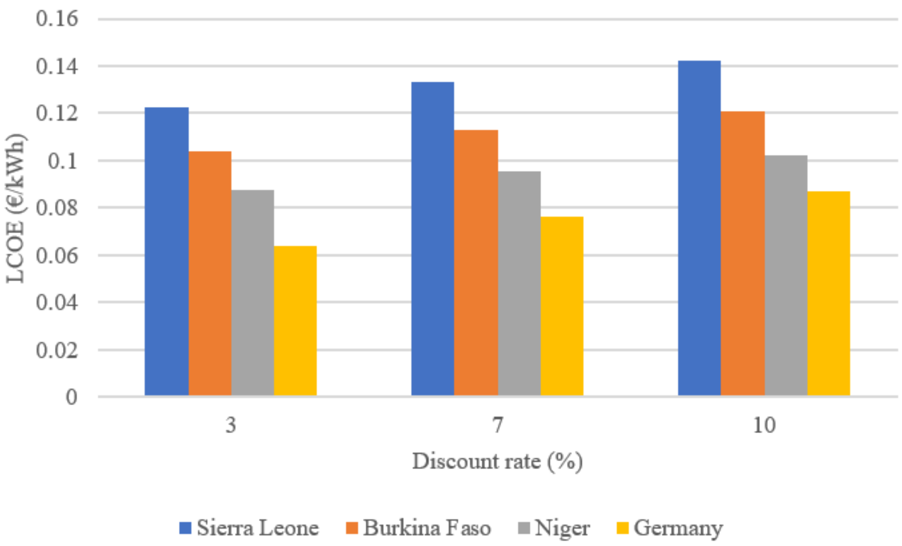

Figure 21. Sensitivity analysis on LCOE and discount rate

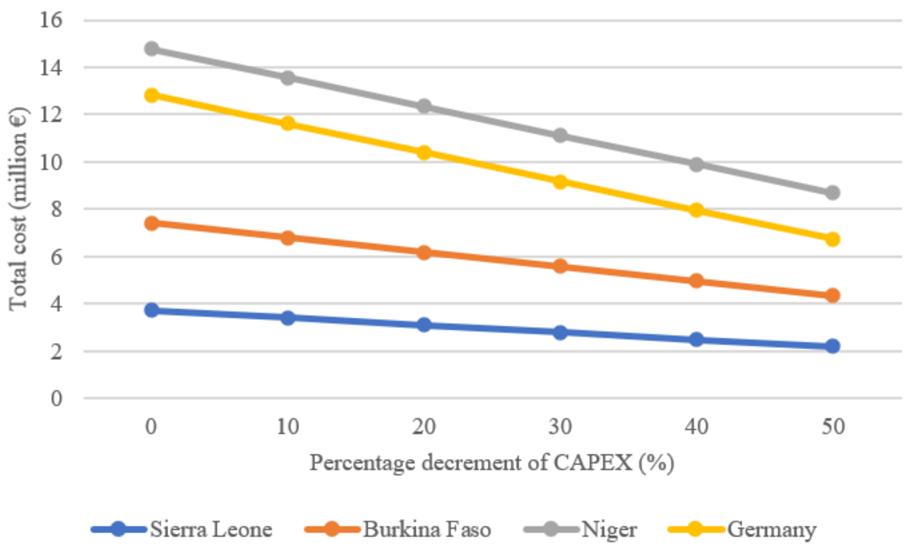

Figure 22. Sensitivity analysis on total cost and CAPEX

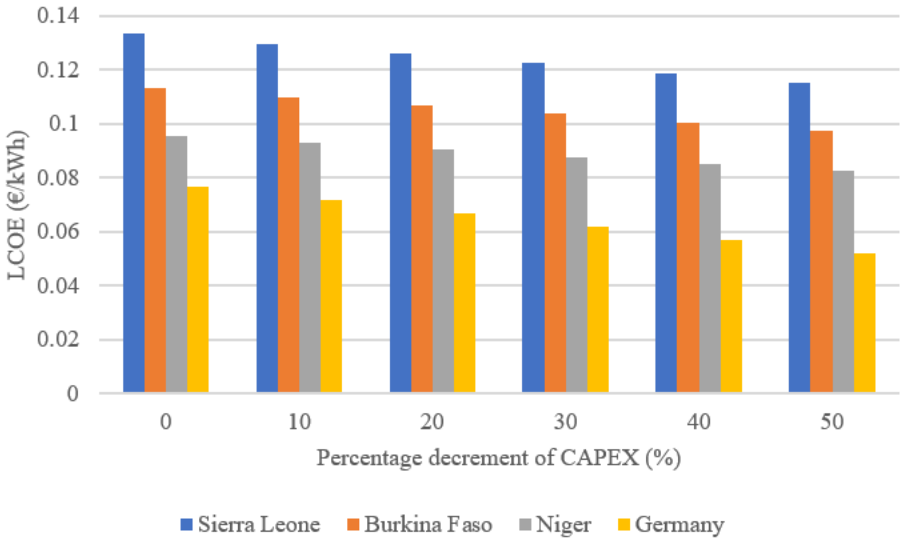

Figure 23. Sensitivity analysis on LCOE and CAPEX

5. CONCLUSION AND RECOMMENDATIONS

The potential of solar PV systems in Germany and West Africa in particular is enormous, but it depends on the acquaintance of users of the advantages of this technology from the technological and financial points of view. The production of electricity from solar PV plants meets two crucial points; clean energy is generated without any kind of emissions and economic benefits are obtained because the price of the energy is cheaper than fossil fuel energy sources and the investment cost can be recovered in a short period of time.

This thesis conducted technical and economic analysis of four different solar PV systems for the different case studies. The thesis' key findings and recommendatios can be summarized as follows:

- The average electricity generation from the four installation sites is about 20.85 GWh/yr.
- The average performance ratio and capacity factor for the solar PV systems at the installation sites are about 75.6% and 16.0% respectively.
- The levelized cost of electricity ranges from 0.0766 €/kWh to 0.1333 €/kWh.
- The cost drivers of electricity in West Africa are hardware cost, soft cost and OPEX, whereas for Germany is the installation cost.
- Considering the electricity crisis in West Africa due to its growing population, the potential of producing green hydrogen in West Africa is very challenging taking into account electricity costs as a factor.
- In the case of West Africa, investing in utility-scale solar PV systems can be more economically viable with government support and infrastructure development. In addition, government support for capacity building in solar PV technologies (from design to production,

utilizing local resources) can expedite the commercialization of solar PV technologies in West Africa.

- West Africa must foster the development of policies that can accelerate the deployment of renewable energy projects and promote the use of new technologies for a cleaner and safer environment.
- The thesis results could guide West Africa and other developing countries willing to implement a utility-scale grid-tied solar PV project. Future studies should use artificial intelligence optimization techniques to enhance the results.

Thesis Limitations

Some of the limitations of this thesis included having primary data for land cost of each case study. It is obvious that land cost varies across different countries and geographic regions. Additionally, having primary data for installation cost for each case study was a barrier considering labor cost for each case study. However, assumptions based on previous literatures were employed.

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