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MASTER'S DISSERTATION

Submitted in partial fulfillment of the
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ENERGY POLICY

Presented by

Hillary Elegeonye

TECHNO-ECONOMIC OPTIMIZATION AND ENERGY SCENARIO ANALYSIS OF ISOLATED MINI-GRID SYSTEMS IN NIGERIA

Defended on the 24th of November 2021 before the following committee,

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Université Tlemcen

PAN AFRICAN UNIVERSITY FOR WATER AND ENERGY SCIENCES (including climate change)

Techno-Economic Optimization and Energy Scenario Analysis of Isolated Mini-Grid Systems in Nigeria

A master thesis submitted to the Pan Afrrican University For Water And Energy Sciences (Including Climate Change) in partial fulfilment of the requirements for the award of Masters of science degree in energy sciences (policy option).

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DISSERTATION APPROVAL PAGE

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DEDICATION

Dedicated to my unborn children who will do greater exploits both in academia and beyond.

STATEMENT OF THE AUTHOR

I, Hillary Elegeonye, declare that this dissertation titled, Techno-economic optimization and energy scenario analysis of Isolated Mini-grid systems in Nigeria has never been submitted to any institution of higher education. I have followed all Pan African University (PAU) Scholarship regulations and recognized scholarly matters through proper citation and references. I affirm that I have made every effort within my means to avoid plagiarism.

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BIOGRAPHICAL SKETCH

Hillary Elegeonye is a Nigerian who studied Energy Policy at the Pan African University Institutee for water and energy Science in Algeria. He received the award of a fully-funded scholarship from the Pan African University under the African Union Commission. He was born and spent the early years of his life in Imo state, where he finished his Secondary school in 2012 before proceeding to the University of Nigeria Nsukka. He would eventually bag his first degree in Economics from the first indigenous university in Nigeria.

After his one year of national service where he worked as an economics teacher in Niger state Nigeria, he secured a job with Africa's Global bank (United Bank for Africa) as a graduate trainee, where he worked as a customer service and funds Transfer officer for almost two years before heading to Algeria for his Master's degree. He later did a three-month online internship with the West African Science Center for Climate Change and Adapted Land Use (WASCAL) based in Ouagadougou, Burkina Faso. From May 2021 to October 2021, Hillary interned at the Energy Commission of Nigeria in Abuja, where he worked with the Energy Planning and Policy Analysis department. He is passionate and determined to make valuable contributions to the world's energy sector.

He is currently working on building a renewable energy start-up in Nigeria where he currently resides while pursuing more advanced studies in sustainable developement. He believes that he has gathered relevant knowledge in the field of energy and is ready to give back to society.

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Abstract

This paper presents a feasibility analysis of the technical, environmental, and economic sustainability of an existing mini-grid system in Nigeria by investigating the cost as well as other operational parameters. The mini-grid studied is the Gbamu-Gbamu solar-battery-diesel hybrid mini-grid in Ijebu East Local Government area of Ogun state, found within the Owo forest in South-West Nigeria. The target is to assess how the system has helped reduce the effect of global warming caused by the burning of wood and also, enhance the sustainable technological development of the country's rural communities, especially by increasing energy access through renewable sources. The RETScreen Expert software is used to validate the techno-economic and environmental sustainability of the installed mini-grid solar battery-diesel system in the region. Climatic data were accessed from the National Aeronautics and Space Administration (NASA). Results show that the system is both economically feasible and environmentally viable given the positive NPV value and the average monthly irradiance of 4.78kW/h/m^2. The system also showed a 92.9% reduction in GHG emissions, a reasonable payback period of 4 years and yearly electricity export of 203MWh.

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1. INTRODUCTION

1.1 Background

Energy poverty has remained a serious impediment to socio-economic development in sub-Saharan Africa. This is visible in the poor electricity access among the countries in this region. The situation in Nigeria is not an exception. Over 90 million Nigerians live in rural areas, and only about 26% of the rural population has access to electricity. In most cases, those who do have access, pay the most exorbitant prices globally (Worldbank, 2018). This poor access to electricity has impeded the development of both social and economic livelihoods of the overall population of rural dwellers. Across the board, national development is highly affected due to a lack of access to electricity (Adejumobi A, 2013). With advances in technology and the increasing desire to make life easier, electricity has become fundamental for the effective delivery of basic day-to-day services such as water, healthcare, food, telecommunication, agriculture, education, as well as industrial processes. These amenities contribute immensely to poverty alleviation and the general quality of life in any community (Oyedepo, 2012).

The Nigerian energy sector is currently a work in progress, with a lot of work to be done in the development of both generation and transmission infrastructure; if energy access must be improved. According to the Nigerian Electricity Regulatory Commission (NERC), the energy generation sub-sector of the country comprises 23 grid-connected generating plants in operation with a total installed capacity of 10,396 MW (with a total available capacity of 6,056 MW); installed thermal-based generation capacity of 8,457.6MW (with available capacity of 4,996 MW), and 1,938.4 MW of total installed hydropower capacity with an available capacity of 1,060 MW (NERC, 2021). This translates to an energy mix that is dominated by thermal (75%) and hydro (25%) power generating sources. The contribution of other renewable energy sources such and solar PV in Nigeria is currently very infinitesimal, hanging at less than 1% of total grid-connected energy generated and consumed.

Besides the problem of poor access to energy, carbon-emitting non-renewable energy sources contribute a lot to electricity generation in Nigeria. In 2020, gas-fired power plants constituted roughly 70% of grid electricity in Nigeria (AELEX, 2020). The implication is the absence of an eco-friendly environment which results in adverse climatic effects, leading to climate change. The threat of climate change is a global call for action; it has necessitated the development of more environmentally friendly renewable energy sources such as Hydro Power, Solar, and Wind

Energies; The goal, which is to reduce GHG emissions while generating energy sustainably. To this effect, the Nigerian Rural Electrification Agency (REA) is engaged in massive rural electrification programs in Nigeria which are based mainly on clean renewable energy (REA, 2021).

As an effort to increase renewable energy contributions to the energy mix, The Nigerian Government signed a Power Purchase Agreement (PPA) in 2016 with 14 solar firms for solar power plants across the country. As one of its strategies, this agreement is expected to add about 1.1 GW of power to the grid when the projects under it are completed (ITA, 2021). The International Trade Administration (ITA) also notes that there are concerns about the capacity of the current transmission infrastructure in the country, to accommodate the additional power generation. From the foregoing, it is believed that decentralized off-grid options such as smaller solar plants are more viable for rural communities, this is as a result of the poor transmission infrastructure of the national grid as identified by ITA, (2021). The situation, therefore, makes mini-grid solutions the breakthrough alternative for off-grid rural communities in a bid to increase energy access.

To overcome the dual challenge of poor energy access and climate change, the future energy supply in Nigeria must be designed to be technically affordable; economically feasible; socially acceptable, and environmentally sustainable - while increasing energy access, especially in rural areas. Evidence from Owolabi et al., (2019) from a RETscreen analysis shows that a grid-connected solar photovoltaic (PV) system is a viable and dependable electricity source in Nigeria; given the solar irradiance of 5.96 $kWh/m^2/d$ in some regions. The research shows that PV systems have a capacity factor of 21.7% leading to very high energy output exported to the grid, a reasonable payback period of 13.6 years, and a reduction in GHG emission equivalent to 501.5 ha of forest absorbing carbon. This research shows both the technical and economic feasibility of Photovoltaics in Nigeria, Given the high solar irradiance, especially in northern Nigeria.

The International Energy Agency (IEA) estimates that about 42% of the additional electricity generation capacity to reach universal access can most economically be achieved through mini-grids, cited in (Peters et al., 2018). With the increasing demand for electricity, which is a result of the rapidly rising population and expanding economic activities, this study aims to propose an optimized renewable-energy-based mini-grid system that meets the load demand of a selected rural community in Gbamu-Gbamu, Ogun State, Nigeria, through technical and economic feasibility analyses using Homer Pro and RETscreen Expert.

1.2 Demography of Nigeria

Nigeria is geographically located on the West African coast of the Atlantic Ocean, within the Gulf of Guinea - latitude of 9.0820° N and a longitude of 8.6753° E. It spans across over 920 square kilometers of landmass, km (356,669 sq mi), extending 1,127 km (700 mi) E–W and 1,046 km (650 mi) N–S and existing as a sovereign nation (Encyclopedia, 2021). This is shown in Figure 1.1. Its huge geographical dominance makes it one of the biggest countries in the West African sub-region. Nigeria has a population of approximately 206 million people (Worldbank, 2020), accounting for almost about half of the population of West Africa, being the most populous African country (Table 1.1). Nigeria stands as the 7th most populated country in the world, behind China, India, the USA, Indonesia, Pakistan, and Brazil, and one of the most youthful countries globally.

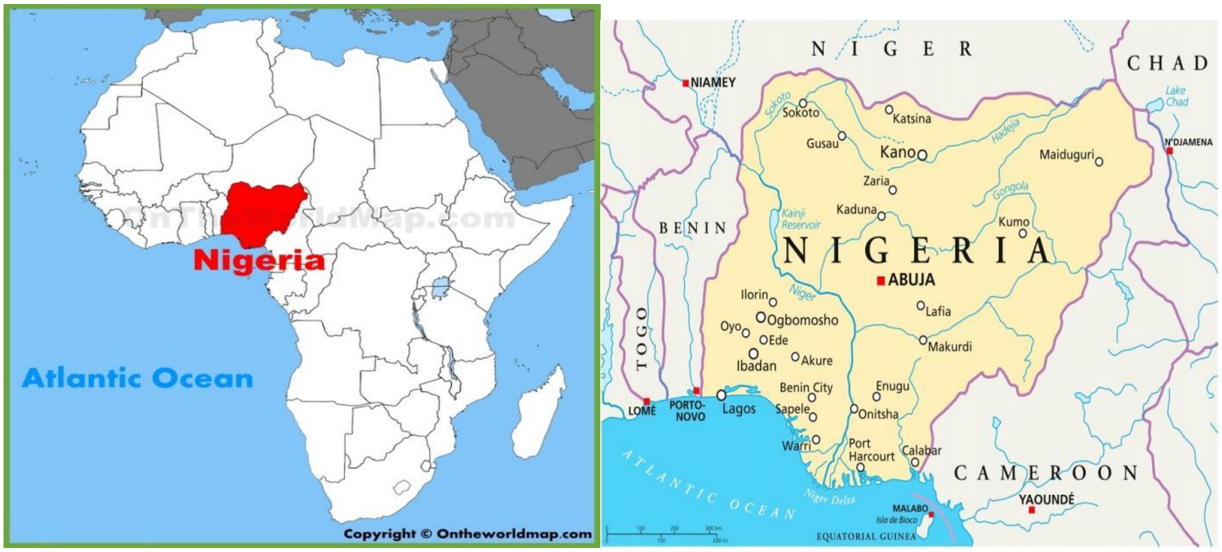


Figure 1.1: Maps of Nigeria

On the borders of Nigeria are Niger, Chad, Cameroon, the Atlantic Ocean, and Benin in the North, North-East, East, South, and West respectively. Below the vast landmass of Nigeria is buried by nature, millions of tons of unexploited natural energy resources including, bitumen, coal, petroleum, natural gas, among others. Nigeria accounts for a very huge proportion of Africa's oil export and has an estimated 37 billion barrels of oil reserve which is equivalent to

30% of Africa's total oil reserves and the largest oil exporter in Africa (World, 2021). It is also a known fact that she is a big player in the production and exportation of natural gas, the first in Africa, and Algeria coming just below - both ranking 9th and 11th respectively in global ranking (AfDB, 2010)

Table 1.1: Country Profile of Nigeria

Country	*Federal Republic of Nigeria*	
Continent	Africa	-
Population	206 milion	(Worldbank, 2020)
Land Mass	920 square km	(Worldbank, 2018)
GDP	422 billion	(Worldbank, 2020)
Life expectancy	54.68	(Worldbank, 2019)
HDI	0.539 (rank - 161)	(Conceição, 2020)
GDP per capita	5186.72 USD	(Worldbank, 2020)
Energy access	55.4%	(Worldbank, 2019)
Rural Energy Access	25.55%	(Worldbank, 2019)
Urban Energy Access	83.9%	(Worldbank, 2019)
Per Capita Energy Access	144.525 kWh	(Worldbank, 2014)
Total installed Energy Generation capacity	12,522 mW	(USAID, 2021)
Final Electricity consumption	30.84 tWh	(IEA, 2018)
Total CO2 emission	104.27 mt	(IEA, 2018)

1.3 Problem Statement

The importance of energy in today's daily life cannot be overemphasized. The above claim stands because every other thing done on daily basis depends on energy availability, accessibility, cost, and sustainability. Following the poor energy access in Nigerian rural areas (Worldbank, 2018), there is a need for the rapid development of alternative energy sources. Several renewable energy options have been identified, such as solar, wind, small hydro, tidal among others. However, a lot of challenges such as high payment default rates, regulatory issues, low electricity demand due to low productive activities in rural areas, and over-optimistic demand projections (Peters J., et al, 2018) abide in the rural areas. These have largely impeded the development of mini-grid systems in rural areas globally.

Other challenges identified include financial factors such as the high initial cost of installation, Operation, and Maintenance (O&M) cost, as well as technical factors such as optimal sizing, identification of base, and peak loads, and technical expertise which have impeded the penetration of mini-grid systems in Nigeria adversely (Dioha & Kumar, 2018). The identified problems, therefore, lies in the inability of the centralized grid electricity to sufficiently supply energy to most rural areas, the failure of some mini-grid projects as well as the environmental impacts of the energy supplied under the high carbon-emitting business as usual energy scenario.

The failure of many mini-grid programs hinges on socio-economic or regulatory reasons. This makes it important to not only consider regulation and technology, but rather to look at the economic incentives for building mini-grids, and the efficiency as well as the effectiveness of policies that would strengthen those incentives (Sovacool, 2012). The optimization of mini-grid systems to tackle the identified challenges applies to both commercially operated schemes that involve a private operator, and community-based schemes (Peters J., et al, 2018).

In this research, we take cognizance of the availability of reasonable solar irradiance in most parts of Nigeria; identified by Dioha & Kumar, (2018) to be most abundant in Kano and least in Portharcourt in the Northern and Southern parts of Nigeria respectively. With good knowledge of the market conditions, we ascertain the economic feasibility of an isolated photovoltaic mini-grid system stationed in Gbamu-Gbamu, Ogun State state, Nigeria. While HOMER pro will be employed to ascertain the optimal sizing of the mini-grid system, RETscreen Expert will be used to carry out the techno-economic analysis (Economic and Technical feasibility)

1.4 Research Aim and Objectives

1.4.1 Aim

This study aims to propose a technically and economically feasible renewable-energy-based microgrid system to meet the load demand of the Gbamu-Gbamu community in Ogun State, Nigeria, by running a technical and economic feasibility analysis as well as an environmental assessment. While the technical and economic analysis will ascertain the feasibility and applicability of the project, the environmental assessment will help to establish the extent to which the project would reduce carbon emission; using the Business as Usual (BAU) scenario as a base case.

1.4.2 Specific Objectives

To achieve this aim, the specific objectives are to:

i. Evaluate the techno-economic analysis and environmental sustainability of the existing system.
ii. Conduct detailed cost, financial, sensitivity, risk, and emission analyses of the optimal system.
iii. Make policy recommendations on isolated mini-grid adoption based on the findings.

1.5 Research Questions

i. How environmentally sustainable is the existing system in Gbamu-Gbamu, Ogun State, Nigeria?
ii. Is the system economically and environmentally feasible?
iii. What are the likely policy implications of adopting isolated mini-grid systems in Nigeria?

1.6 Significance of the Study

A review of existing literature shows that the topic, “techno-economic optimization and energy scenario analysis of Isolated Mini-grid systems in Nigeria” poses some fresh ideas in the energy field for Nigeria. Scholars have carried out studies like sustainable energy technologies and assessments in Nigeria, (Owolabi, et al., 2019); Decentralized Renewable Hybrid Mini-Grids for Rural Communities, (Ugwoke et al., 2020); Optimized Solution for Increasing Electricity Access with Mini-Grid Technology in Nigeria, (Azimoh & Mbohwa, 2019). These scholarly researches, among others, lay a foundation for further exploration of the aforementioned topic.

The topic further stretches into energy scenario analysis, beyond techno-economic optimization. By optimizing PV mini-grids together with an energy scenario analysis, this study will review the context of Nigeria in the business-as-usual scenario and show the potentials to transform into energy saving, efficiency, and renewable energy integration through isolated PV mini-grid systems. The findings of this research will be instrumental in the design of energy systems for remote rural communities where energy access is at the barest minimum and serve as empirical literature for further studies in this area. Due to the intensified emissions of GHG across the globe, this research is positioned to provide an environmentally friendly sustainable energy solution while helping to solve the energy access problem in the selected rural area.

1.7 Scope of the Study

Sequel to the objectives of this study, which is mainly to ascertain the technical and economic feasibility of a renewable energy-based microgrid system and its environmental sustainability in a rural community. The research objectives are focused on a rural community in Gbamu-Gbamu, Ogun State state, in Southwestern Nigeria.

The technical parameters to be optimized include the sizing, load, system operation (see Fioriti D., et al 2017), and the identification of the best tracking angle or slope. For economic feasibility (Owolabi, Nsafon, et al., 2019) estimated the Payback Period and the Net Present Value of a Solar PV system in Nigeria; we will include the risk and sensitivity analysis of all the essential parameters of the study as well as the return on equity and internal rate of return. RETscreen expert will be essential for the estimation of major parameters of the study, including the carbon emission that would be saved from the implementation of an optimized clean energy system. All estimations involved in this study are within the purview of HOMER pro and RETscreen Expert.

1.8 Organization of Thesis

Chapter 1: Introduction (Problem Statement, Objectives, Research Questions, scope, etc.)

Chapter 2: Literature review (Theoretical framework and Empirical Literature)

Chapter 3: Methodology (Data presentation and Validation, Mathematical and Technical details)

Chapter 4: Result Presentation

Chapter 5: Discussions and recommendations

2. LITERATURE REVIEW

2.1 Introduction

The International Renewable Energy Agency (IRENA, 2016) defined Mini-grid as an integrated energy infrastructure with energy resources and loads. Its major functions include energy generation, storage, energy conversion, control, measure, and management. Since its inception, mini-grids have had low penetration in the SSA region, following its high generation costs. However, recent projections show that there will be a significant decline in the cost of generation by 2025 and also a further decrease by 2035 due to improvements in technology according to the report by IRENA. Mini-grids will serve in the best interest of energy access improvement in Nigeria by reducing the stress on the overloaded utility grid, given the unreliable nature of the grid system due to its intermittent nature. Curbing the proliferation of substandard diesel/petrol-engine which has for long contributed to air, noise, and environmental pollution(Azimoh & Mbohwa, 2019). The high solar irradiance in Nigeria as well as the availability of other renewable energy alternatives makes mini-grids viable for supplying energy to the millions of off-grid rural population segment yet to be electrified. A review of the current situation in SSA (Azimoh & Mbohwa, 2019) shows that grid-connected mini-grids are not common, and the existing mini-grids are mostly localized with no interaction with the utility grid.

In this chapter, we will review the literature on the sources of energy in Nigeria, the institutional framework of the energy sector, solar systems, hybrid renewable energy systems as well as renewable energy modeling software (HOMER and RETScreen).

2.2 Energy Resources in Nigeria

Nigeria is endowed with a lot of energy resources. These energy resources include conventional energy resources and renewable energy resources. Conventional energy resources have long been explored whereas renewable energy resources are still in their earliest stages of exploitation. Conventional energy resources have contributed immensely to energy generation in Nigeria over the years. This can be found in the gas-fired power plants as well as petrol and diesel engine generators which have generated a great deal of electricity in Nigeria. Renewable energy sources have been identified as clean and sustainable means of energy generation which would help to increase energy access in the country, especially in rural areas. Below we discussed in detail the conventional energy sources and renewable energy sources as found in Nigeria.

2.2.1 Conventional Energy Resources

Conventional Energy Resources in Nigeria mainly consist of the fundamental fossil fuel resources – including Petroleum, natural gas, and coal (Table 2.1). The Organization of the Petroleum Exporting Countries (OPEC), has described Nigeria as Africa’s largest oil producer and with approximately 37 billion barrels of oil reserves and 187 trillion standard cubic feet (tscf) of natural gas reserves (OPEC, 2021). Nigeria has stood on average daily production of approximately 2 million barrels of oil for about one decade. Nigeria was therefore ranked as the seventh-largest crude oil producer and exporter among all OPEC members between 2009 and 2013, (quoted in GIZ 2014).

Table 1.1: Overview of Conventional Energy Resources in Nigeria

Items	**Oil**	**Gas**	**Coal (total recoverable)**
Reserves	37.2 billion barrels	5.2 trillion cubic metres	209.4 (million short tons) (2008)
Production	2417 thousand barrels per day	43.2 billion cubic meters per year	n/a
Years of extraction remaining	42 years	120 years	n/a

The US Department of Energy (DOE) states that Nigeria accounted for more than 8% of global export of liquefied natural Gas – with this, Nigeria ranks as the 4th largest producer and exporter of natural Gas worldwide as of 2012 (US DOE, 2014). Nigeria’s natural gas is highly associated with petroleum, which is a primary cause of the flaring of gas in Nigeria. By the year 2000, Nigeria's total gas flaring was roughly about 55% of all the gas explored out of the ground. The amount of energy wasted by this flaring was enough to power Belgium, (Ogunleye, Banks, & Legarreta, 2019). The authors further stated that Nigeria has significantly reduced its total gas flaring by 70% over two decades. Figure 2.1 obtained from the Center for Clean Air Policy shows the trend of Gas flaring in Nigeria. Besides natural Gas and Petroleum, there are huge coal deposits in Kogi and Enugu states that have not yet been mined on a large scale (GIZ, 2014)

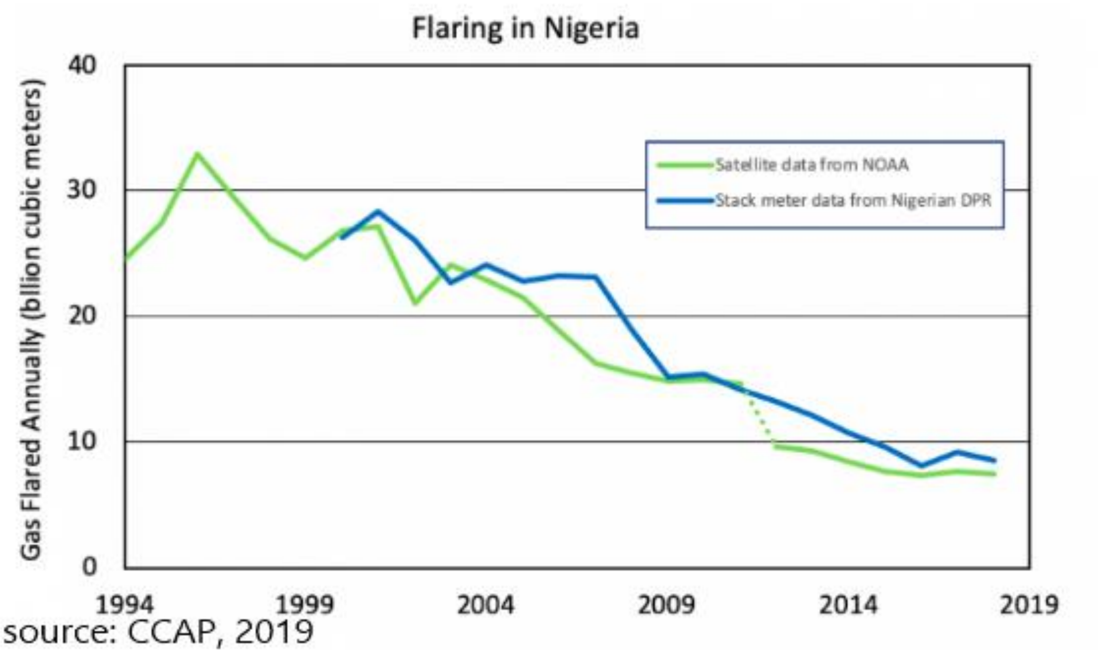


Figure 2.1: Gas Flaring in Nigeria

The total financial loss accruing from gas flaring globally is approximately US$20billion in 2018 The Nigerian Economy, on the other hand, lost a whopping sum of **NGN** 233 billion (US 761 million) to gas flaring. This amount is equivalent to 3.8% of the total amount of gas flared globally. Notwithstanding that gas flaring in Nigeria has reduced significantly since 2002 and stands at 10% in 2018, Nigeria still ranks among the top 10 gas flaring countries globally (PWC, 2019).

Data from the Energy Commission of Nigeria (2018) have shown that coal exists in two forms in Nigeria; the sub-bituminous and the bituminous grades. The sub-bituminous grade has proven to occur in about 33 coal fields spread across 16 States of the country. The coal reserves in the country so far are about 650 million tonnes while the inferred reserves are about 2.75 billion tonnes. The composition of Nigeria’s coal deposit is estimated at approximately 39% bituminous, 49% sub-bituminous, and 12% lignitic coals. The status of conventional energy sources is shown in Table 2.2.

Table 2.2: Status of Conventional Energy Sources (OPEC, 2019)

Value of petroleum exports (million $)	45,106
Proven crude oil reserves (million barrels)	36,890
Proven natural gas reserves (billion cu. m.)	5,761
Crude oil production (1,000 b/d)	1,737.4
Marketed production of natural gas (million cu. m.)	47,827.9
Refinery capacity (1,000 b/cd)	446.0
Output of petroleum products (1,000 b/d)	8.2
Oil demand (1,000 b/d)	469.8
Crude oil exports (1,000 b/d)	2,008.2
Exports of petroleum products (1,000 b/d)	20.1
Natural gas exports (million cu. m.)	35,953.1

b/d (barrels per day), cu. m. (cubic meters), b/cd (barrels per calendar day)

2.2.2 Renewable Energy Resources

Renewable energy is mainly described as energy derived from sources that regenerate over time, mostly a relatively short period through natural processes. In other words, they are not expected to deplete anytime soon, given that normal natural circumstances persist. Nigeria has an enormous renewable energy resources base. The prevalent renewable energy sources in the country include hydro, solar, wind, and others (tidal, geothermal and ocean waves, hydrogen, etc.). Table 2.3 shows the renewable energy potential in Nigeria.

The sources of renewable energy in Nigeria include mainly, large hydro, small hydro, solar, biomass (fuelwood, animal wastes, agricultural residues, energy crops), and wind. Tidal and ocean waves are also among as well as geothermal, which is one of the sources of electricity in the country today. Over-dependence on oil and gas which are generally exhaustible, while giving little or no attention to the inexhaustible renewable energy is indeed abysmal. Nigeria is endowed with renewable energy resources that can generate enough electricity, significantly solar energy, biomass and wind small and large hydropower. The country also has good potentials for geothermal energy, ocean wave, tidal energy and hydrogen fuel. The yearly average of solar radiation ranges from 3.5 kWh/m2-day in the coastal belt of the south to 7.0

kWh/m^2-day in the northern arid regions on daily basis (Figure 2.2), while the daily sunshine hours have an annual average of 4 to 9 hours, increasing from south to north (ECN, 2018).

In recent years, renewable energy has gained unprecedented attention globally without an exception to Nigeria. Huge sums of money have been invested in the development of several renewable energy sources. International donor agencies and other interested organizations have made deliberate efforts to bolster the drive for energy transition, especially as it affects carbon emission and climate change mitigation. with the myriad of renewable energy sources Nigeria is endowed with, the federal government had set a target to expand the market for renewable electricity by at least 5% in the country, coupled with a minimum power generation of 5TWh by 2016 (FMP, 2006).

Nigeria's Federal Government, through the Power Sector Reform Roadmap of (2013), set an ambitious target to increase installed capacities of renewables to 1000 MW, thermal to over 20,000 MW, and hydro to 5,690 MW by 2020. The target was to diversify the energy mix of Nigeria to reduce its dependence on natural gas and other fossil fuel (ECN, 2013).

Table 2.3: Renewable Energy Potential in Nigeria

Energy Resources	**Estimated Reserve**
Large Hydropower	11,250 MW
Small Hydropower (<30 MW)	3500 MW
Fuel Wood	11 million hectares of forest and woodland
Municipal Waste	30 million tonnes/year
Animal Wastes	245 million assorted animals in 2001
Energy Crops and Agricultural Residue	72 million hectares of agricultural land
Solar Radiation	3.5-7.0 kW h/m2/day
Wind	2-4 m/s at 10 m height Wind speeds in Nigeria range from a low 1.4 to 3.0m/s in the Southern areas, except for the coastal line, and 4.0 to 5.1m/s in the North. The Plateau area is particularly interesting.

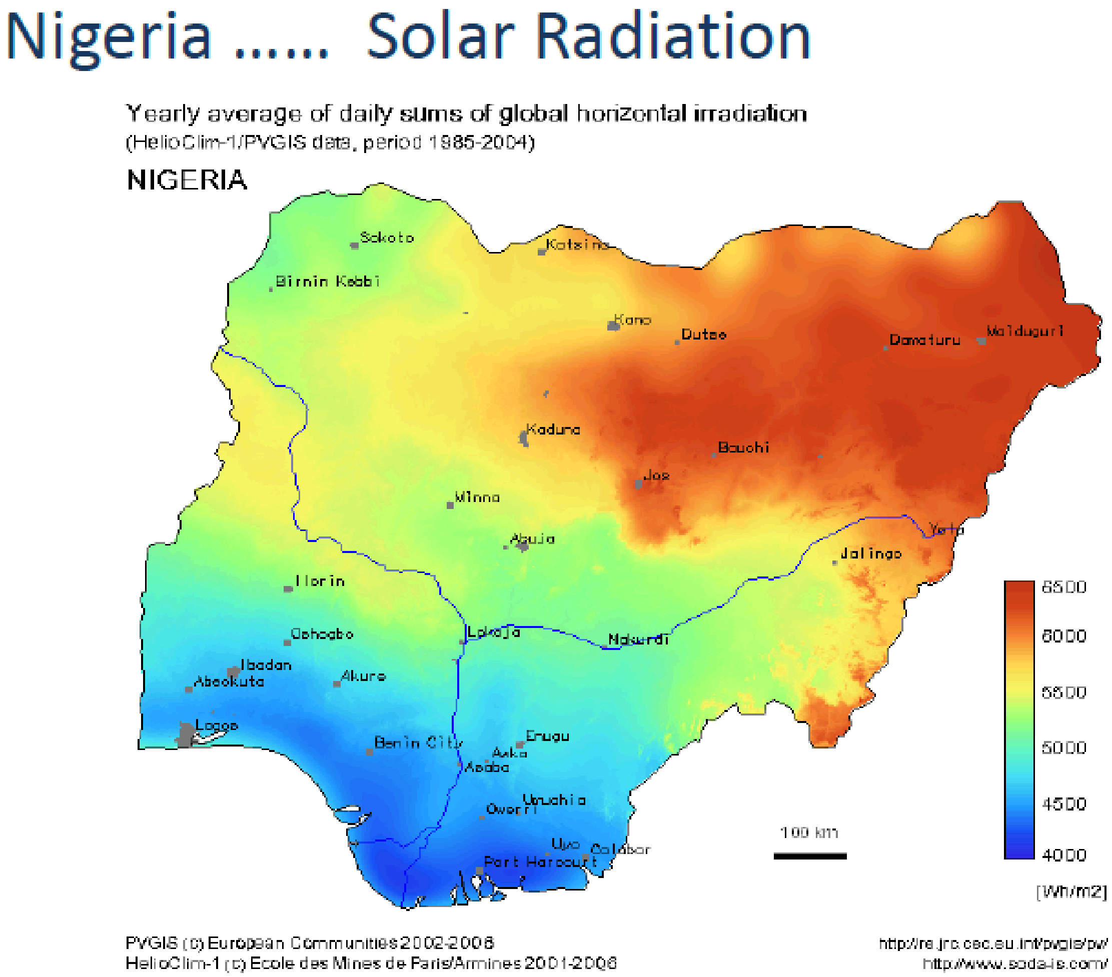


Figure 2.2: Solar Radiation of Nigeria

2.3 The Policies and Institutional Framework of Nigeria’s Power Sector

The energy sector of Nigeria is a well-structured sector with different public departments overseeing the generation, policy, regulation, and distribution. The players have been identified to act in the capacity of some specific ministries of the federal government. Among the myriad of stakeholders lies the two forerunners; the federal ministry of power and the Energy Commission of Nigeria. The hierarchy of the energy sector players, and structure of the power sector are as shown in Figures 2.3 and 2.4 respectively.

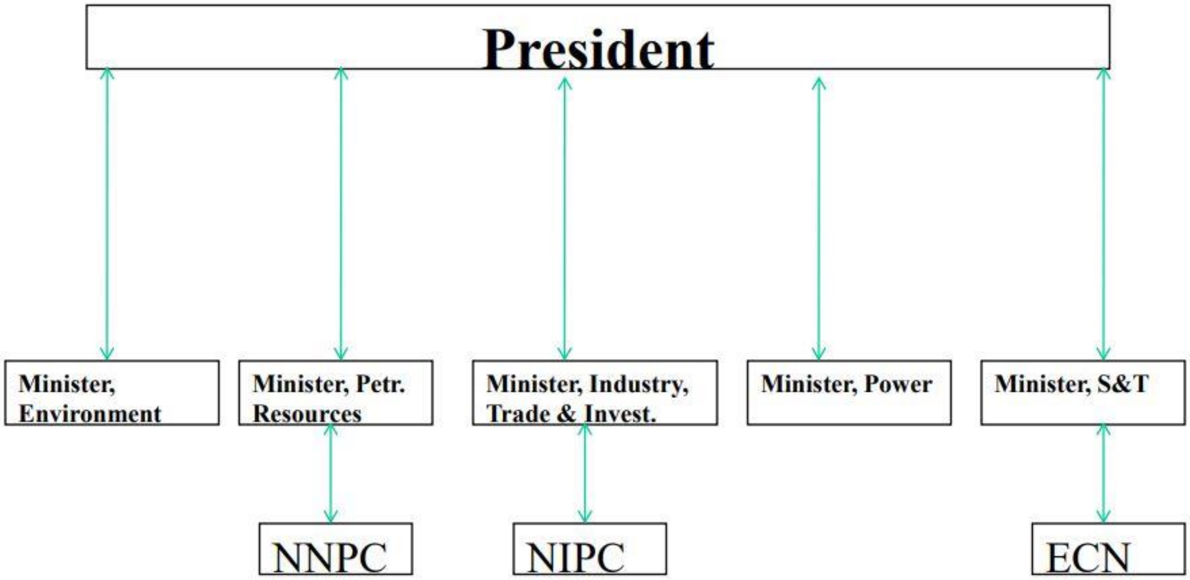


Figure 2.3: Hierarchy of Energy Sector Players

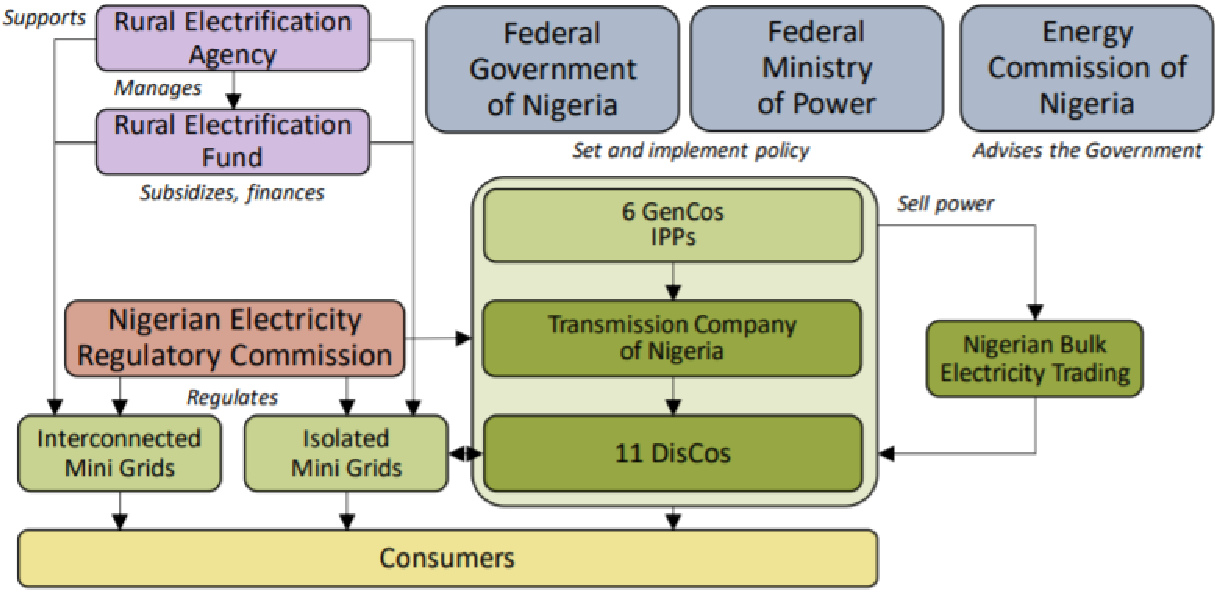


Figure 2.4: Structure of the Nigerian Power Sector (ESMAP, 2017)

2.3.1 Energy Commission of Nigeria

The Energy Commission of Nigeria (ECN) was established through the enabling Act No. 62 of 1979, through the mandate issued by the Energy commission act, the ECN has been statutorily made the apex body in the drafting of Energy policy, planning of the energy sector, implementation of the energy policy, diversification and overall development of clean and renewable energy, ensuring optimal utilization and combination of the various energy sources. The Energy Commission of Nigeria is currently operating under the federal ministry of science and technology.

Just like any other ministry or parastatal of the federal government of Nigeria, the Energy Commission is also stratified into levels of authority for the execution of different responsibilities. The commission is designed to work with several other independent government agencies and ministries, including but not limited to the Ministry of Power, Ministry of Agriculture and Rural Development, Ministry of Petroleum Resources, Ministry of Environment, Ministry of Science and Technology, and Ministry of Water Resources.

2.3.2 The Federal Ministry of Power

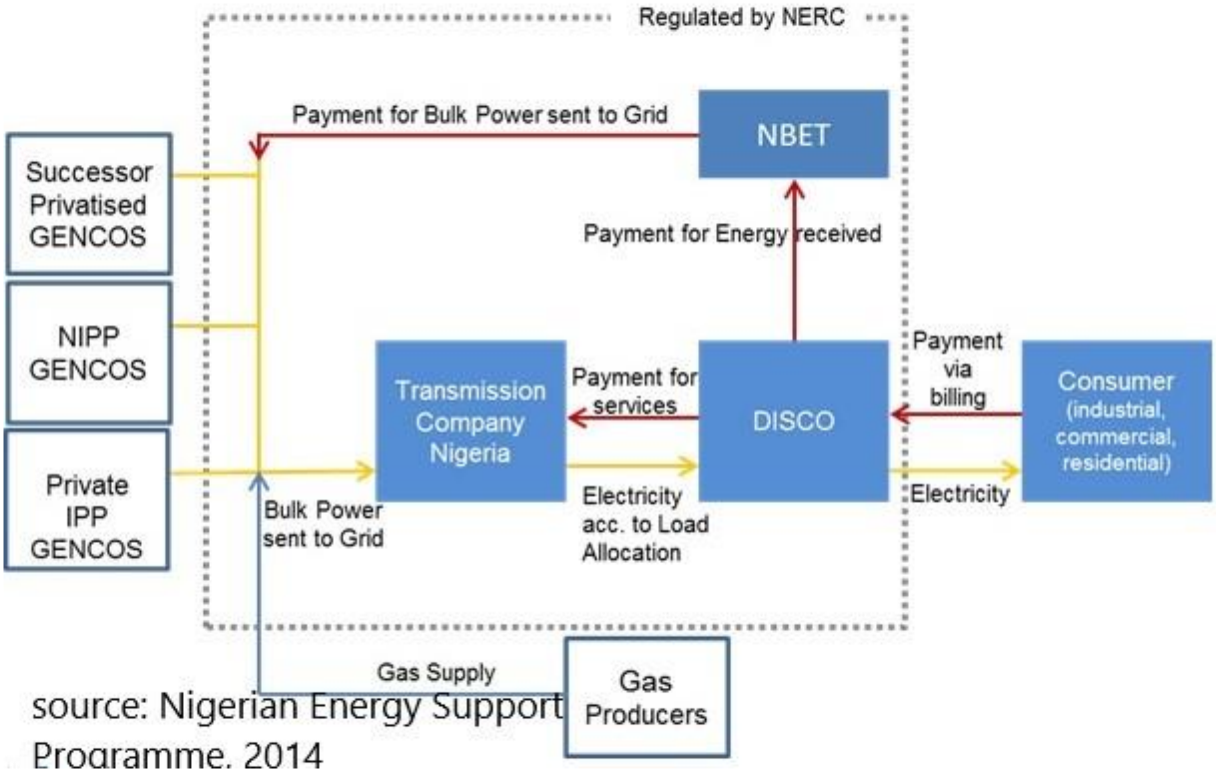
The Federal ministry of power (FMP) in Nigeria is primarily armed with the responsibility of policymaking with regards to the production and distribution of power in the country, using the available resources. With the liberalization of the power sector of Nigeria in 2005, the structure and responsibilities of the federal ministry of power have faced a paradigm shift. Following the situation, the FMP has gone through a series of restructuring to enable it to adapt to its changing needs. The FMP's primary responsibility has remained over time, the establishment of a guaranteed and robust sector that works in line with the overall goals of the nation and its dynamic energy needs. The post-privatization structure of the Nigerian power sector is shown in Figure 2.5.

The responsibilities of the FMP include the following:

- **a.** Broad policy formulation on the development of the power sector
- **b.** Managing concessions on the power sector of the economy
- **c.** All power sector activities coordination
- **d.** Overseeing research and development in the power sector.
- **e.** Coordinating activities of all agencies and parastatals under its supervision.

The FMP is surrounded by several other commissions, agencies, companies, institutes, and ministries working in tandem - towards achieving the same goals, they include:

- **a.** Nigerian Electricity Regulatory Commission (NERC)
- **b.** Rural Electrification Agency of Nigeria (REA)
- **c.** Federal Ministry of Science and Technology (FMST)
- **d.** Federal Ministry of Water Resources (FMWR)
- **e.** Presidential Taskforce on Power (PTFP)
- **f.** Federal Ministry of Environment (FMENV)



source: Nigerian Energy Support Programme. 2014

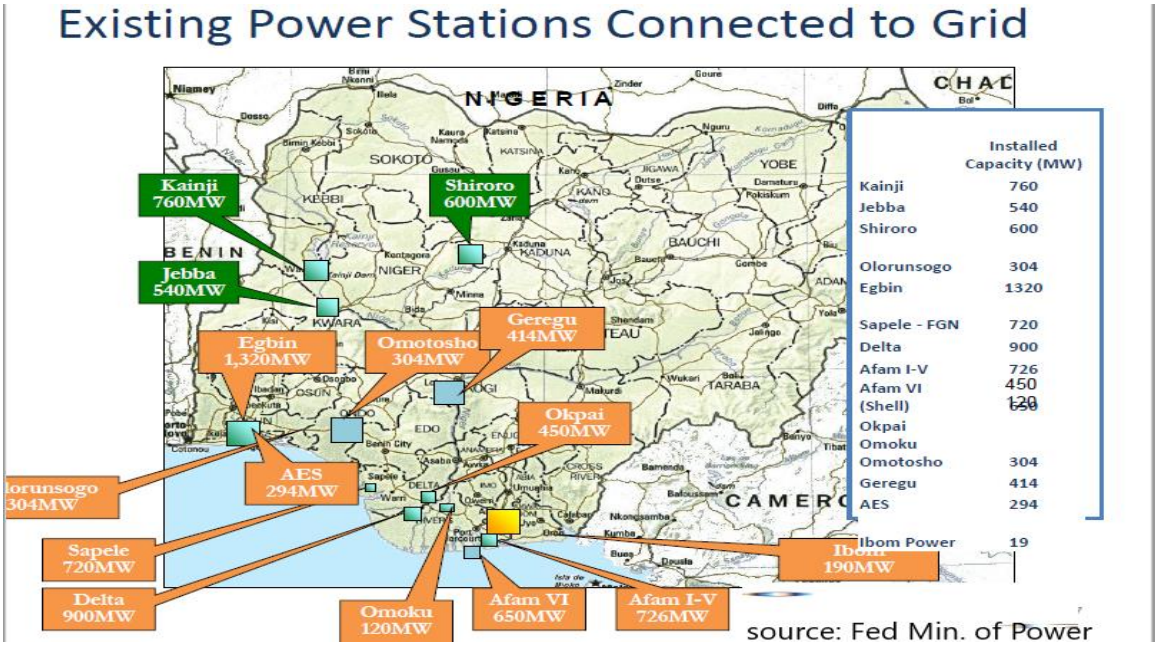
Figure 2.5: Post-Privatization Structure of the Nigerian Power Sector

2.3.3 Nigerian Electricity Regulatory Commission (NERC)

The commission, which was founded in 2005, is an independent regulatory agency with the key responsibility of monitoring and regulating the industry providing electricity in the country. Ensuring that market rules and operating guidelines are appropriately observed. NERC is also solely responsible for the application and assessment of licenses for the operation of independent power plants with a capacity exceeding 1 MW. Figure 2.6 shows the major power stations connected to the grid in Nigeria. Their responsibility also includes consumer protection and the development of customer service standards (GIZ 2015).

2.3.4 Rural Electrification Agency of Nigeria (REA)

In 2006 the REA was established to proceed with the national rural electrification program of 1981, which aimed to connect all local governments of the federation to the national grid. The major responsibility of the REA is the coordination of all rural electrification in the country alongside the activities of the involved stakeholders. The REA conducts research and survey on the people's willingness to pay for power before they take off on any program of electrification (GIZ 2015). According to Montgomery 2012, the agency's (REA) scope has been recently broadened to consist of the redeployment of off-grid renewable energy systems to boost the pace of energy access improvement.


Existing Power Stations Connected to Grid

	Installed Capacity (MW)
Kainji	760
Jebba	540
Shiroro	600
Olorunsogo	304
Egbin	1320
Sapele - FGN	720
Delta	900
Afam I-V	726
Afam VI	450
(Shell)	120 650
Okpai	
Omoku	
Omotosho	304
Geregu	414
AES	294
Ibom Power	19

source: Fed Min. of Power

Figure 2.6: Major Power Stations Connected to the Grid in Nigeria

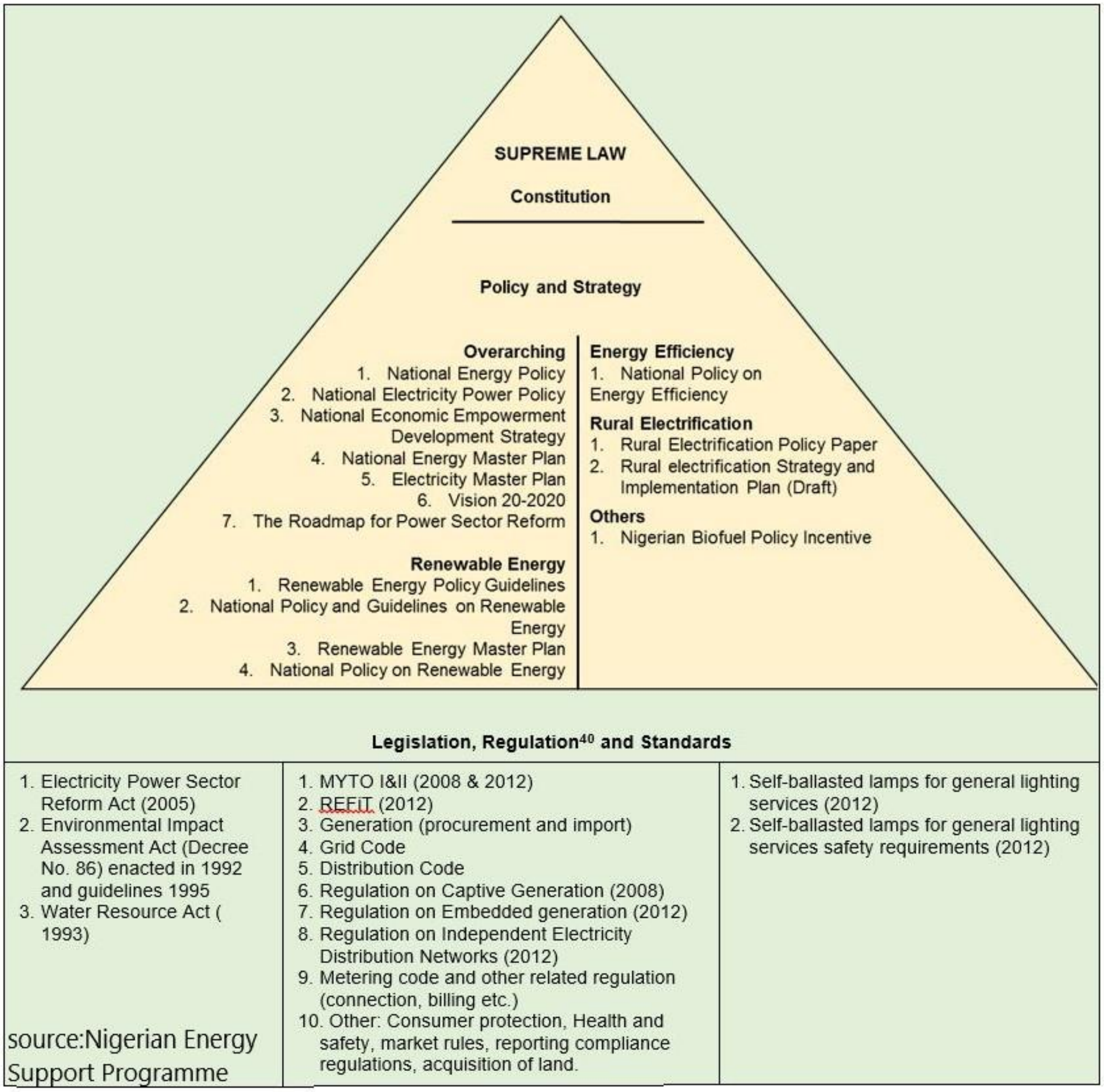
2.3.5 Federal Ministry of Water Resources (FMWR)

Water resources have proven over time to be a fundamental source of renewable energy. Many countries have developed their hydroelectric systems to a very robust level whereby it supplies a significant amount of their energy. Nigeria in this case is not an exception. Today, Nigeria has developed about 277 small hydro sites with a cumulative potential of approximately 3500 MW and Large Hydropower sites with a cumulative potential of approximately 11,250 MW (Nigerian Energy support program 2014)

The FMWR is not only charged with overseeing water resources. Its creation in 2010 gave it the mandate to as well oversee the management of water resources for basic human needs, agricultural irrigation, and hydropower for the promotion of life and economy. Its involvement in hydropower projects is overseen by the department of Dams and reservoir operations. However, the FMP has an overriding power to oversee all power-generating aspects of the FMWR by working together.

2.3.6 Nigeria Energy Policy and Regulations

Every economy is concerned with the level of energy utilization and the efficiency with which energy resources are converted to useful energy. This is a direct indicator of the level of development of the country's economy. In a bid to ensure optimal, reliable, and security of energy supply as well as its efficient utilization in the country, it, therefore, becomes essential to put in place a coordinated and comprehensive energy policy to guide the energy sectors of the economy. The policy framework serves as a pathway for the desired sustainable development, optimal supply, and efficient utilization of energy resources within the economy – as well as to trade such resources and foster international cooperation. Figure 2.7 shows the regulation of the Nigerian energy sector.



source:Nigerian Energy Support Programme

Figure 2.7: Regulation of the Nigerian Energy Sector

2.3.6.1 National Energy Policy

The Nigeria energy policy consists mainly of the development, supervision, and regulation of the petroleum and electricity industry of the economy which is pivotal in driving the activities of several other sectors of the economy. Both petroleum and electricity sub-sectors have over time been characterized by large government influence through its several Ministries, Departments, and Agencies (MDAs) that were in charge of a large part of the activities of the sectors, but have gone through immense changes in recent years especially with the drive for a move towards privatization and liberalization (ECN, 2018).

The Nigerian energy policy is structured into sub-sectoral policies in the energy sub-sectors, particularly; electricity, oil and gas and solid minerals, etc. There are energy-related policies in some other sectors, which work very closely with those in the energy sector. These include but are not limited to agriculture, science, and technology, climate change, transportation, environment, among others. The sub-sectoral policies, however, are made to reflect the individual perspectives of the sub-sectors. It is therefore important to have a concise, comprehensive, and integrated energy policy, which provides a guide into the current situation and insight for future energy-related sub-sectoral developments. The structure of the policy into sub-sectors is designed that way to avoid policy conflicts ad confusion that may arise (GIZ, 2014).

2.3.6.2 Petroleum Policy

In 1956, Crude oil was first discovered in commercial quantities in Nigeria. However, oil production started in 1958. The oil reserve of the nation had been proven to be an estimate of about 37 billion barrels. The distinct characteristic of the Nigerian oil is its predominance of low Sulphur light crude of different variants based on the location of drilling as of December 2018 (ECN, 2019). Nigeria has four indigenous refineries located in Kaduna, Warri, and two in Port-Harcourt with a total installed capacity of approximately 445,000 barrels per day. However, the capacity utilization is below local demand. Hence, domestic consumption of petroleum products is fully met by supplementing local production by imports. The nation’s current overt dependence on crude oil for foreign exchange is seen in its contribution, which currently is over 80%; hence, the economy is vulnerable to the unstable nature of the international oil market.

2.3.6.2.1 Policies

“The national energy policy, in a nutshell, intends to engage in extensive exploration and production of crude oil and associated liquid petroleum: attain self-sufficiency in processing and export of petroleum products; encourage the inclusive participation of indigenous as well as foreign companies in upstream and downstream activities; adopt environmentally-friendly oil exploration; complete deregulation and privatization of the nation’s oil industry; pursue research and development studies and human capacity development to derive maximum economic benefit from its oil resources” (ECN, 2018).

2.3.6.2.2 Objectives

The policy outlined above is a gross overview of the general petroleum policy in Nigeria. The objectives of the policy are outlined below in line with the long term macroeconomic objectives of the country - increasing the overall reserves and the national production capacity; to obtain maximum economic benefits derivable from the nation's petroleum resources; to achieve refining to local consumption ratio greater than or at least equal to one (1); to boost the process of technology acquisition in the oil industry; to increase private sector capital inflow to the oil industry; integrate climate change adoption in upstream and downstream activities of the oil industry; among others (ECN, 2018).

The energy commission of Nigeria suggests that strategies have been designed and put in place to ensure the smooth implementation of the petroleum policy. They include but are not limited to; Investing in and intensifying crude oil exploration and production in all Nigerian sedimentary basins and ensuring that acreages put up for bidding rounds are properly pre-estimated with minimal speculations and. Investing in exploration, production, and refining activities in other countries to promote national development and energy security.

2.3.6.3 Renewable Energy Policy

Table 2.4 shows the energy policies by Energy Source. The National Energy Policy (NEP) 2003 identifies the level of energy utilization in the economy coupled with the efficiency of the conversion of energy resources is vital for the development of the economy without substantial quantitative targets being set. However, it made provision for all forms of energy, including renewable energy sources, and how they can be effectively utilized (GIZ, 2014).

The government of Nigeria has made several efforts to develop renewable energy in the country; one of which was the establishment of two Renewable Energy centers in the year 1983, namely, the Sokoto Energy Research Center (SERC) at the Usman Danfodio University, Sokoto, and the one at the University of Nigeria, Nsukka the National Center for Energy Research and Development (NCERD), a recent one was also developed at the University of Ilorin which are funded through the Energy Commission of Nigeria. Their activities, together with those of tertiary and other research institutions, have led to the development of many solar thermal, biomass, and biogas devices and improved woodstoves technologies that are ready for commercial production and adoption into the national economy. These are in line with the general Renewable energy policy of the country.

With the expected population explosion of Nigeria's which is expected to double, and resultantly increase aggregate energy demand threefold. Conventional energy sources will not be able to meet the challenges of an increasing population at least, at an affordable cost and in a flexible manner. For this anticipated hike in demand for energy and the glaring challenges posed by climate change, there has been a conscious effort to increasingly include renewable energy in the nation's energy mix to a substantial amount. Renewable energy has the potential to create jobs, improve livelihoods and open up the market in rural areas. The needs of increasing small and micro enterprises are driving the market for solar PVs already. This trend is driving small hydro and wind power plants which is what the renewable energy policy intends to achieve through the regulatory structures that have been put in place.

The national renewable energy policy is broken down according to the energy sources, their technical and regulatory requirements as published by the Energy Commission of Nigeria in 2018.

Table 2.4: National Energy Policy by Energy Source

Source	Key Policy	Objective	Strategy
Hydropower	i fully harness the hydropower ii Exploit hydropower resources with environmental sustainability. iii promote private sector participation iv Research and Development	i. increase the contribution of hydropower ii. extend electricity to rural and remote areas, iii. attract private sector investments	i. Promoting research and development ii. Organizing sensitization iii. tax reductions, soft loans, grants iv. use of power purchase agreement
Solar	i. Integration of solar energy into the energy mix. ii. Updated with technological developments iii. Encourage individual and corporate bodies	i. Develop the nation's capacity. ii. Develop the market for solar energy iii. Develop the market for solar energy iv. Encourage research and	i. Intensifying research and development ii. Human and institutional capacity building iii. Fiscal incentives iv. Aggressive mass campaign and advocacy.

	iv. Research and development.	development.	
Wind	i. Develop wind energy resource ii. Harnessed at sustainable costs iii. Apply global best practices iv. Encourage the utilization of wind energy	i. Develop wind energy ii. develop local capability iii. Encourage the utilization of wind energy for agricultural purpose.	i. Encouraging research and development ii. Developing skilled manpower iii. Intensifying work in wind data acquisition
Other Renewables	i. The nation shall maintain an interest in other sources of renewable energy.	i. Keep abreast of trends in global energy technology development.	i. Research and development in the technologies of the exploitation of these emerging energy resources.

2.3.6.4 Power Sector Reform

The National Power Sector Reform Act of 2005 saw the deregulation of the Nigerian power sector (EPSRA, 2005). This Act is subsequent upon the National Electric Power Policy adopted in 2001, National Power Sector Reform Act of 2005 which made provision for a new legal and regulatory framework for the sector. The fundamental change was the privatization of the government-owned electricity company, a process that saw a completely liberalized market for power. Provision was made for the vertical and horizontal unbundling of the electricity company into separate and competitive entities, seeing to the development of a competitive electricity market. The reform further set up a legal/regulatory framework for the sector, including a framework for rural electrification, another framework for the enforcement of consumer rights and obligations: establishment of performance standards. It resulted in the transfer of the previously public power company, NEPA, into a Holding Company, the Power Holding Company of Nigeria (PHCN) - called “Successor Company” in the legal text (GIZ, 2014).

The reform act generally saw to the following, including the privatization of the NEPA, transfer of its assets to the holding company PHCN and its subsequent restructuring by privatization and transfer into 18 different generation, distribution, and transmission companies at regional levels a competitive electricity market was Developed by the creation and operation of a wholesale electricity market in Nigeria. It was this process that saw the birth of the Nigerian Electricity Regulatory Commission (NERC) as a national regulatory body to oversee the market and administer licenses. The NERC ensures the use of guiding standards and codes as guidelines and requirements for activities in the sector, followed y the establishment of a Rural Electrification Agency to expand access to electricity to the rural areas, the planning and financing of its activities (ECN, 2014).

In a nutshell, the reform Act reshaped the whole energy landscape of the country affecting all the different players for generation, transmission, and distribution. The intention was to significantly increase efficiency and competition in the sector by establishing a Wholesale Electricity Market (WEM) and promoting the participation of private companies in the generation as Independent Power Producers (IPP).

2.4 Solar Energy Terminologies

2.4.1 The Sun

The Sun has been described as the central star of the solar system. It consists of hydrogen and helium, which are its major components. The Sun is so large that it makes up about 99.68% of the total mass of the solar system (Figure 2.8). In the center of the Sun, the pressure-temperature conditions are such that nuclear fusion can take place (Table 2.5) (Oliveti et al., 2014). The Sun is the primary source of most renewable energy sources, directly or indirectly. Its energy delivery per hour exceeds global annual energy consumption. The sun is free from pollutants and greenhouse gases and devoid of geopolitical constraints and conflicts (Ohunakin et al., 2014).

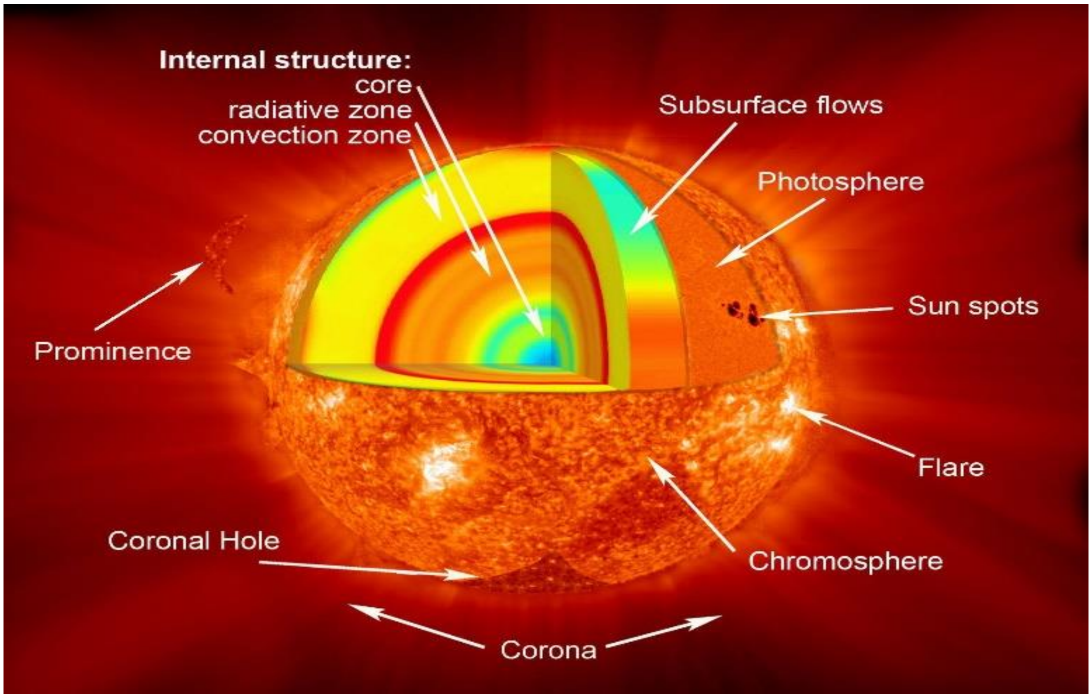


Figure 2.8: The Sun with its layer structure depicted (NASA/Goddard, 2012)

The core is the central region of the sun where nuclear reactions consume hydrogen to form helium. During this reaction, the energy that is released ultimately leaves the surface as visible light. ***The radiative zone*** extends outward from the outer edge of the core to the base of the convection zone, characterized by the method of energy transport – radiation. ***The convection zone*** refers to the outer-most layer of the solar interior extending from about 200,000 km depth up to the visible surface where its motion is seen as granules and super-granules (NASA/Goddard, 2012).

Table 2.5: Facts about the Sun (Oliveti et al., 2014)

Mean distance from the Earth	149 600 000 km (the astronomic unit, AU)
Diameter	1 392 000 km (109 × that of the Earth)
Volume	1 300 000 × that of the Earth
Mass	1.993 × 1027 kg (332 000 times that of the Earth)
Density	(at its center): >105 kg m−3(over 100 times that of water)
Pressure	(at its center): over 1 billion atmospheres
Temperature	(at its center): about 15 000 000 K
Temperature	(at the surface): 6 000 K
Energy radiation	3.8 × 1026 W
The Earth receives	1.7 × 1018 W

Over 100,000 TW of solar energy reaches the Earth's surface hourly (Yerramilli & Tuluri, 2012), compared to the total global primary energy consumption of 154,000 TWh in 2020. The sun, therefore, generates more energy than the world would require if solar energy is harnessed effectively. It is therefore not out of place to say that the global annual energy consumption can be supplied by solar energy about 6000 times the total annual energy consumption (BP Statistical, 2013). The sun remains to date the most abundant permanent energy source in the world. It shows different appearances depending on the topography of the earth’s surface (Zekai, 2008).

2.4.2 Solar Photovoltaic Cell

Photovoltaic (PV) is a term used to describe the method of converting solar energy (direct sunlight) into direct current electricity using semiconductors that exhibit the photovoltaic effect, This phenomenon is studied mainly in physics, photochemistry, and electrochemistry (Yadav & Kumar, 2015). A photovoltaic system, therefore, uses solar panels which are usually made up of several solar cells to supply power in a usable form. The process of photovoltaic solar conversion comprises both physical and chemical properties; the first step of the process involves the photoelectric effect which triggers the electrochemical process to take place in the presence of ionizing crystallized atoms in a series, generating an electric current (Yadav & Kumar, 2015).

In 1839, the first-ever solar Photovoltaic (PV) effect was observed by Alexandre-Edmond Becquerel. It was not until 1946 that the invention of the first modern solar cell was made using silicon, an invention by Russel Ohl (Yadav & Kumar, 2015). Before the invention, thin silicon wafers were the available photovoltaic solar cells that transform sunlight energy into electrical power (Sharma, Jain, & Sharma, 2015). More recent solar cell technologies are based on the principle of electron-hole creation in each cell composed of two different layers of a semiconductor material described in (Sharma, Jain, & Sharma, 2015) as p-type and n-type materials. (Srinivas, Balaji, Nagendra Babu, & Reddy, 2015) further described the arrangement of the structure as; “when a photon of sufficient energy impinges on the p-type and n-type junction, an electron is ejected by gaining energy from the striking photon and moves from one layer to another; this creates an electron and a hole in the process and by this process, electrical power is generated”.

Several materials are used in the application of Photovoltaic solar cells. They exist mainly in the form of silicon (single crystal, multi-crystalline otherwise known as monocrystalline and polycrystalline), amorphous silicon (a-Si), copper-indium-gallium-selenide, cadmium-telluride, and copper-indium-gallium-sulfide. The listed materials are discussed below in section 2.4.3.

2.4.3 Categories of Solar Cells

Solar cells (Figure 2.9), which are also referred to as photovoltaic cells, are any devices that directly convert the energy of light, from the sun into electrical energy through the photovoltaic effect (Fonash, Ashok, & Joseph, 2020). Light goes into the solar cell device through an optical coating also known as an antireflection layer, which minimizes the loss of light by reflection; it effectively traps the light falling on the solar cell by promoting its transmission to the energy-conversion layers below. The said antireflection layer usually is made of an oxide of silicon, tantalum, or titanium (Fonash, Ashok, & Joseph, 2020). Solar cells are generally classified into four generations depending on time and categories of materials that are used for their fabrication. In the work of Bagher et al., (2015). The materials used in the manufacture of solar cells must have sunlight absorbing characteristics. They further stated that while some cells are designed to handle sunlight that reaches the Earth's surface, some others are optimized for use in space. Solar cells can be made of a single layer of light-absorbing material only, known as single-junction; or use multiple physical configurations, known as multi-junction to take advantage of various absorption and charge separation mechanisms. Solar cells can be classified into first, second, and third-generation cells. In Figure 2.10, we found the most common solar cells available in the market to be the first-generation solar cells which comprise single and multi-crystalline silicon (Mono-crystalline silicon solar cells and Polycrystalline silicon solar cells) (Sharma, Jain, & Sharma, 2015).

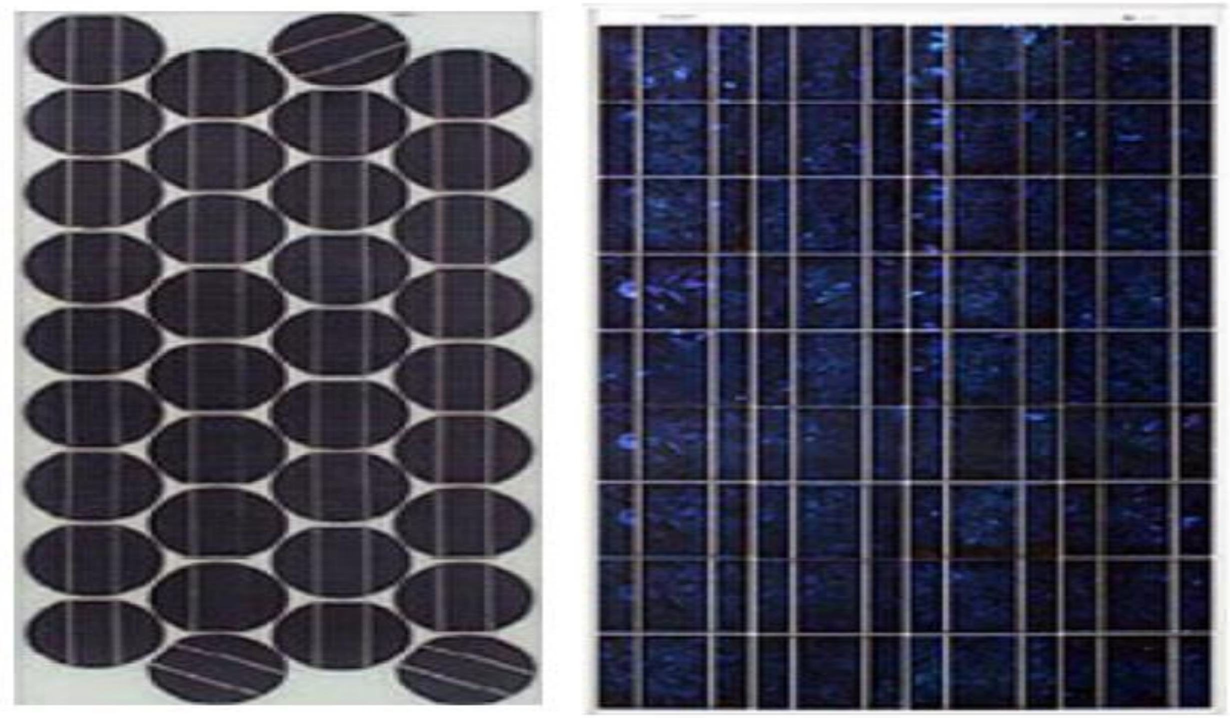


Figure 2.9: A schematic of monocrystalline (left) and polycrystalline (right) solar cells

The first generation cells—also called conventional, traditional wafer-based cells—are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon (Bagher et al., 2015). Second-generation solar cells were introduced as a response to the high material usage and cost of silicon solar cells (Sharma, Jain, & Sharma, 2015). They are usually thin-film solar cells, that include amorphous silicon (a-Si), copper indium gallium selenide solar (CIGS), and Cadmium telluride (CdTe) cells and are commercially significant in utility-scale photovoltaic power stations, building-integrated photovoltaics and in small standalone power systems. The third generation of solar cells includes many thin-film technologies often described as emerging photovoltaics—most of them have not yet been commercially applied and are still in the research or development phase (Bagher et al., 2015).

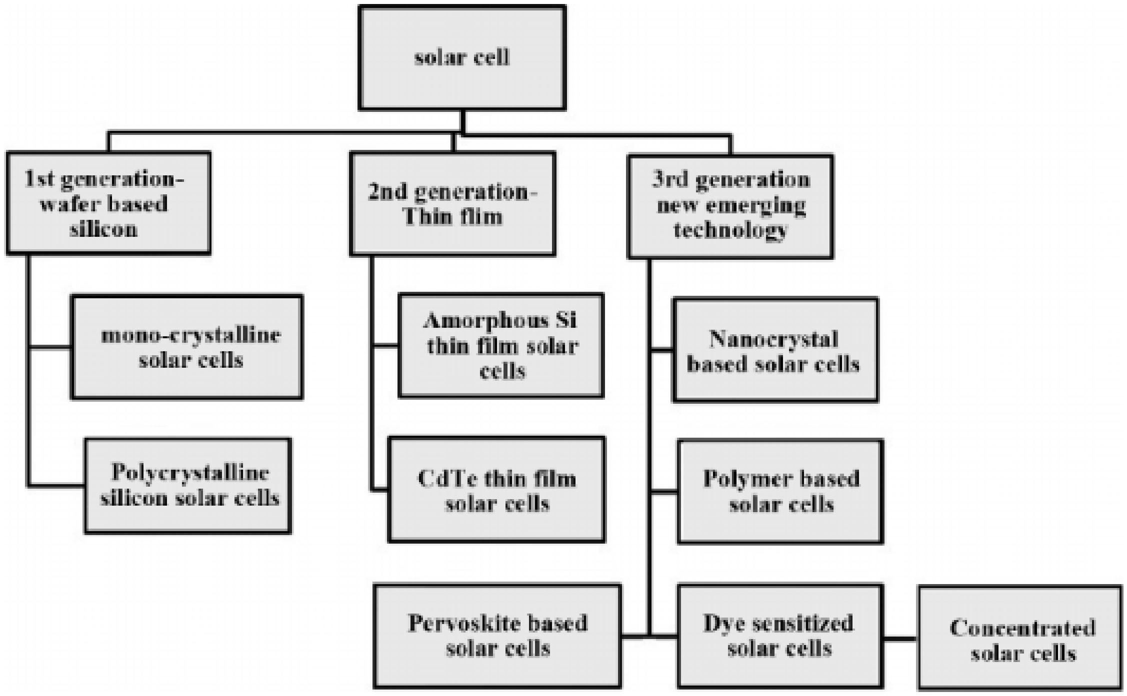


Figure 2.10: Solar Cells Categorization (Sharma, Jain, & Sharma, 2015)

2.4.5 Solar PV Model

The solar PV systems can be presented in the form of a very simple model, consisting of only a PV module and load. This can be found in the direct powering of a water pump motor, whereby there is a need to operate the system only when there is sunlight; there is no energy storage system. However, to power a residential building, the solar system has to be operated both during the day and at night. In which case, both AC and DC loads can be fed as well as a reserve power (or storage battery). The overall system may as well require a backup generator (Jäger, Isabella, Smets, Swaaij, & Zeman, 2016). Solar Photovoltaic systems can be modeled in three different ways. In general terms, they can be classified as either grid-connected or off-grid. However, a broader categorization will include stand-alone, grid-connected, and hybrid solar systems. In each of the models, the basic principles and elements remain the same. However, each model is adapted to meet particular requirements by varying the type and quantity of the basic elements (Jäger, Isabella, Smets, Swaaij, & Zeman, 2016).

2.4.5.1 Components of a solar PV system

The solar panels are the heart of a PV system and as well, are the most visible and popular parts of the system. However, several other components play important roles in ensuring that the system works. These Solar PV system components put together are called the Balance of System (BOS). It is important to note that the components required for each system depend on the model (ie, grid, stand-alone system, or direct connection). Some of the most important components of the BOS are:

Solar Panels: This makes up the array of solar modules usually mounted outside and directed towards the sun.

Energy storage/Batteries: These are very vital for stand-alone systems. It ensures power supply by the system during the night and in periods of bad weather.

DC-DC converters: The purpose of this component is to convert the module output; in the case where there may be a variable voltage depending on the time and weather conditions The module output is therefore converted to a more compatible output voltage that can be used as input for an inverter in a grid-connected system.

Inverters: Used to convert the DC electricity originating from the PV modules into AC electricity that can be fed into the grid or used for other electrical appliances in the house. Many inverters have a DC-DC converter included converting the variable voltage of the PV array to a constant voltage that is the input for the actual DC-AC converter. Also, stand-alone systems may have an inverter that is connected to the batteries. The design of such an inverter differs considerably from that for a grid-connected system.

Charge controllers: Mainly used in stand-alone systems to control charging and discharging of the battery. They prevent the batteries from being overcharged and also from being discharged via the PV array during the night.

Cables: Mainly used to connect the different components of the PV system and to the electrical load. It is important to choose cables of sufficient thickness to reduce resistive losses.

2.4.5.2 Stand-alone Solar Systems

A stand-alone solar Photovoltaic system is also called the off-grid PV system. This model of solar PV depends on solar power alone. These systems can come with only the PV modules and the load, in other instances, they exist with batteries for energy storage. When energy storage is involved, there is a need to include a charge controller which regulates the batteries of the system by disconnecting from the PV when they are fully charged. The charge controller may also disconnect the load to prevent discharging of the batteries below a certain limit. The batteries must be designed to capacity, such that the days of autonomy of the system can carry the loads during the night and in periods of weather fluctuation. Figures 9 and 10 below show the schematics of a stand-alone (Off-Grid solar PV Model).

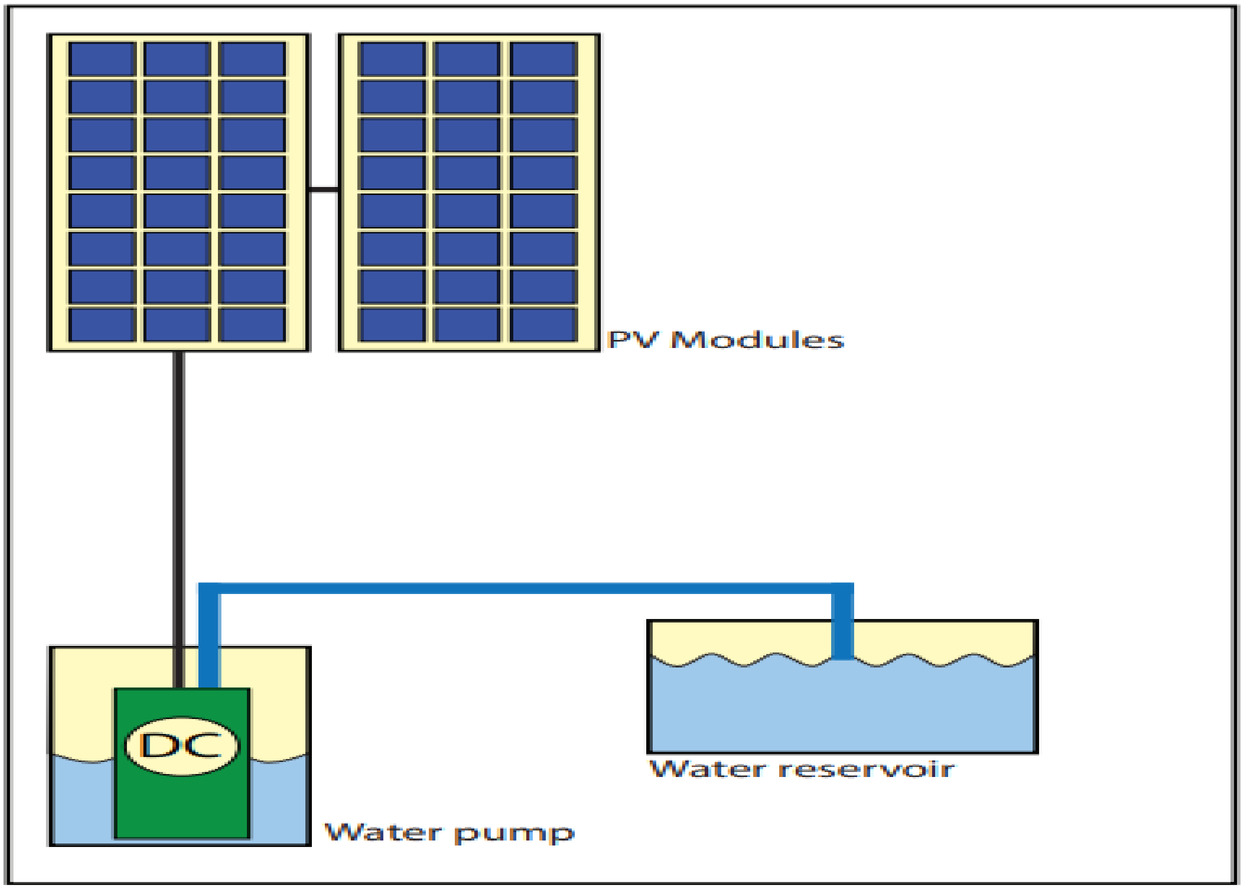


Figure 2.11: A simple solar PV without storage

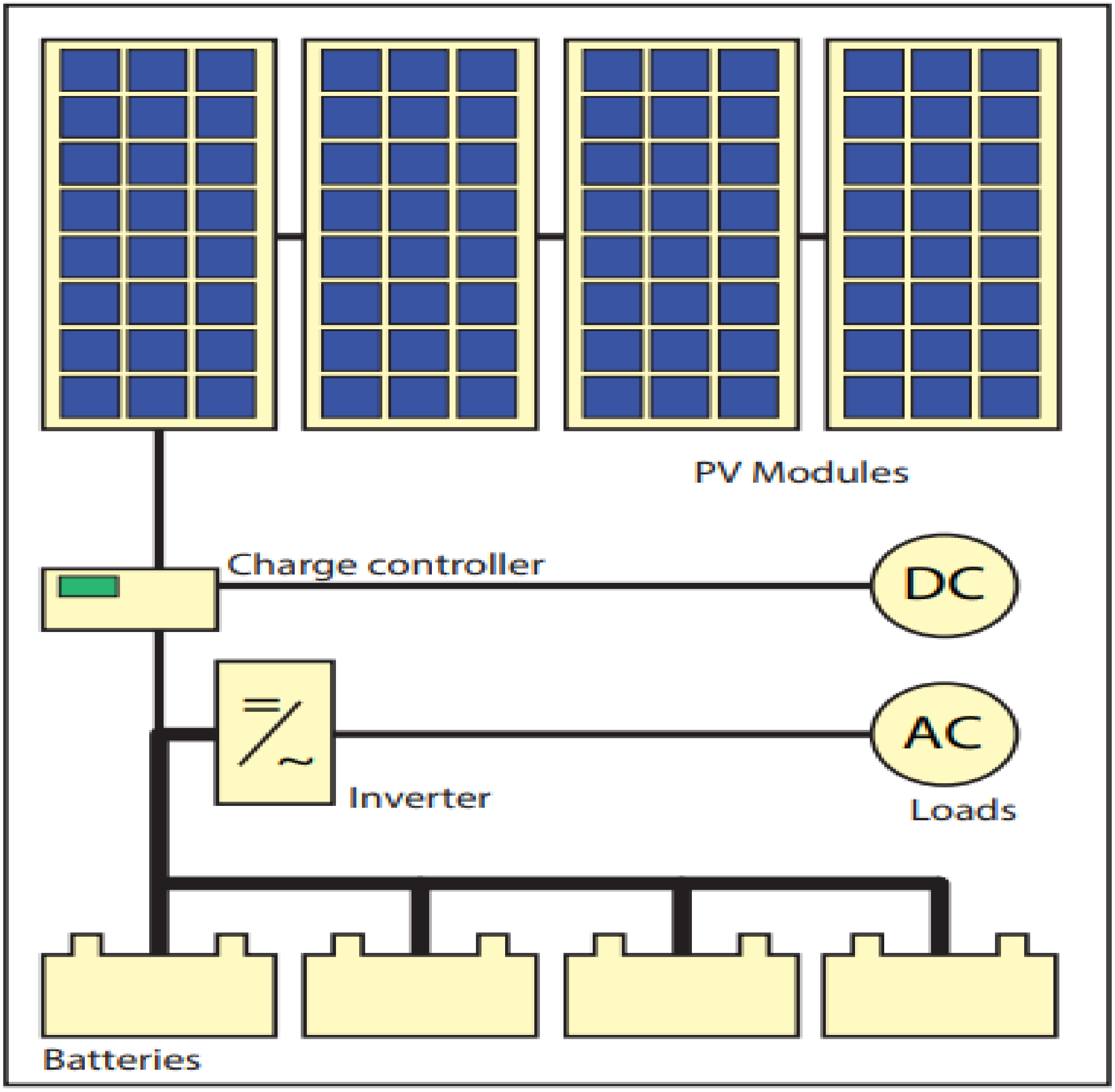


Figure 2.12: A solar PV model with battery storage

2.4.5.3 Grid-Connected Solar Systems

PV systems are increasingly being connected to the grid and have become more popular for applications in built environments (Figure 2.13). Usually, inverters are used to convert the DC to AC electricity before they are connected to the grid. For small solar home systems (SHS) applied in residential homes, a distribution board is used for the connection of the inverter, where the power generated is transferred into the electricity grid or to AC appliances in the building. Since these systems are connected to the grid, In principle they do not require batteries. The generated energy serves as a buffer, whereby excess PV electricity is transported to the grid. The grid in return supplies the house with electricity when PV power generation is insufficient. There are Large PV fields that serve as power stations; all the generated PV electricity is transported directly to the electricity grid. They can reach peak powers of up to several hundreds of MW depending on the installed capacity of the PV modules.

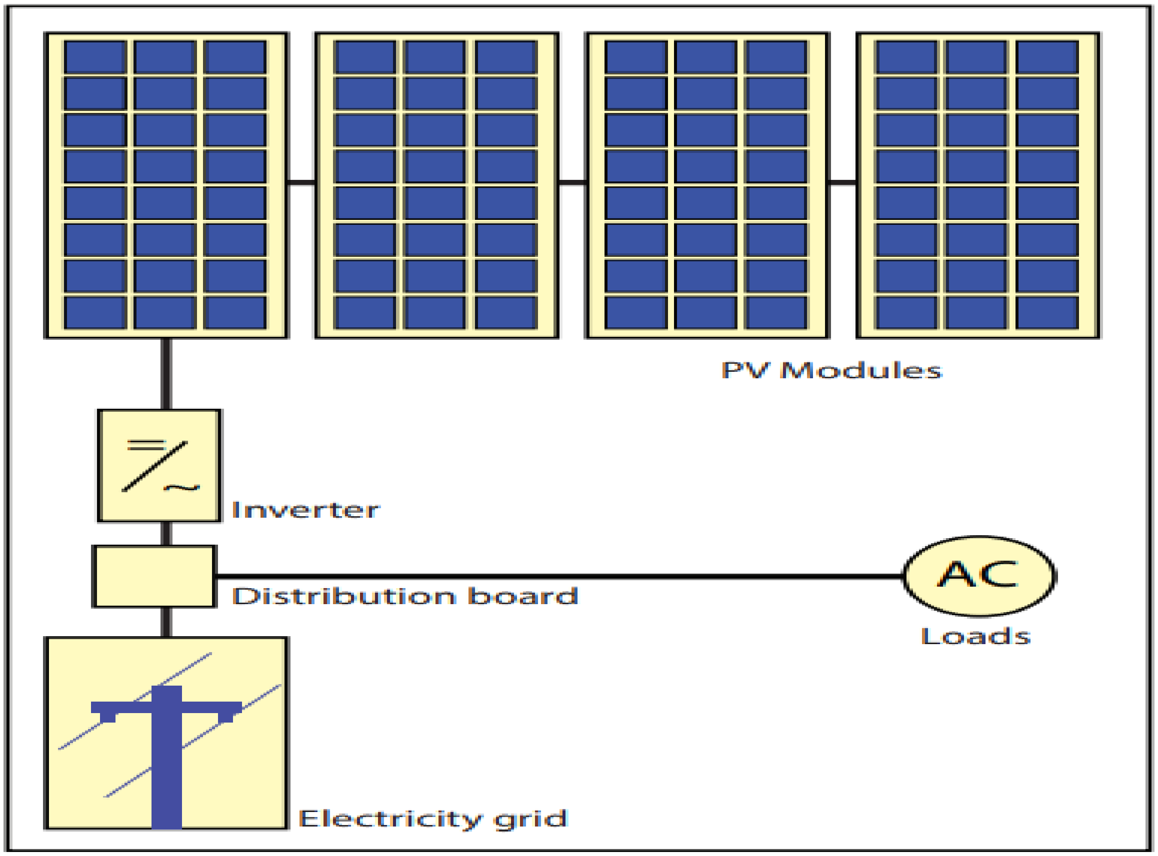


Figure 2.13: Grid-connected PV Model

2.4.5.4 Hybrid Solar Systems

Hybrid Solar PV systems combine PV modules with another source of electricity generation (diesel, gas, or wind generator) to complement energy generation from the PV systems (Figure 2.14). Hybrid systems are usually more sophisticated in design and control than both standalone and grid-connected PV systems to maximally optimize the different methods of electricity generation. In the case of a PV/diesel system, for instance, the diesel engine must be turned on when the minimum battery discharge level is reached should be stopped again when the battery reaches maximum charging state. The backup generator can either be used to recharge batteries only or to supply the load as well.

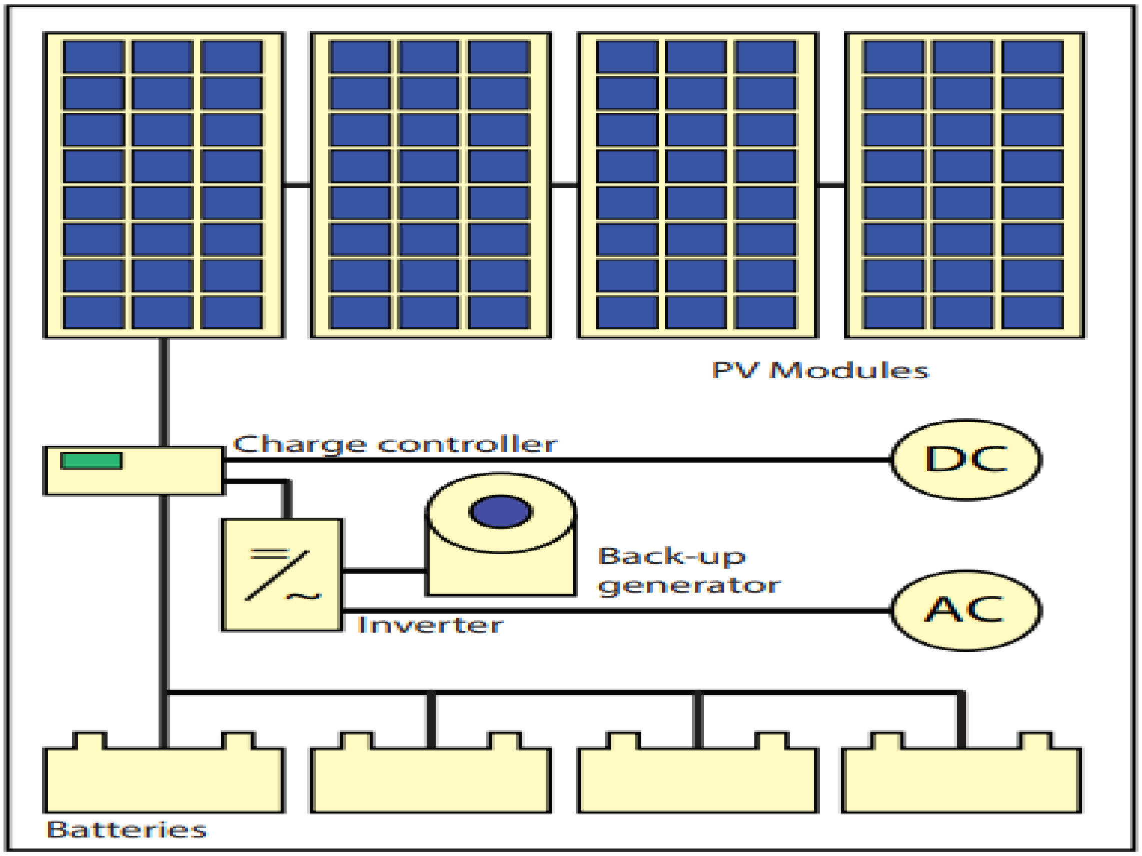


Figure 2.14: A Typical Hybrid PV system

2.4.6 Effects of Temperature and Light Intensity on Solar Cells

The most important parameters that affect the operation of a solar cell are the total irradiance, the spectral distribution of the irradiance, and the temperature (Al-naser et al., 2015). Temperature plays an important role in the performance of PV systems. Dubey et al., (2013) posits that solar cell performance is inversely related to temperature, that is, as temperature increases the performance of the solar cells will reduce. They argued that the relationship fundamentally owes to increased internal carrier recombination rates, caused by increased carrier concentrations. The operating temperature plays a key role in the photovoltaic conversion process. The Electrical efficiency, as well as the power output of photovoltaic (PV) module systems, have a linear dependence on the operating temperature. The electrical performance is primarily influenced by the material of PV used.

PV modules convert between 6-20% of the incident solar radiation into electricity depending on the type of solar cells and climatic conditions. The rest of the incident solar radiation is converted into heat, which significantly increases the temperature of the PV module, thereby reducing the efficiency of the PV module. The efficiency of a crystalline silicon solar cells photo module depends on the sun insulation reaching its surface (Dubey et al., 2013). Solar cells perform differently given temperature variations. The temperature changes will directly affect the power output from the cells; the voltage is highly dependent on the temperature and as temperature increases, the voltage output will decrease (Fesharaki et al., 2011). The evidence from the literature shows that the correlation between temperature and solar cells is negative, hence, higher temperatures are not suitable for solar cells.

A study by Zoungrana et al., (2017) proved that with an increase in the illumination light intensity, silicon solar cell shunt resistances decreases while series resistance, electric power, short circuit current, fill factor, open-circuit voltage, and conversion efficiency increase. This means that there exists a positive relationship between light intensity and the power output of solar cells. From the foregoing pieces of literature, higher light intensity and lower temperatures combined will give the best possible output for silicon solar cells (Li et al., 2021, Zoungrana et al., 2017). The voltage output of a solar PV cell rises sharply as illuminance or light intensity increases, but after some time, it reaches the maximum level. After that point, the rate of change of the voltage with increasing illuminance or intensity adds almost nothing more to the total output(Amajama, 2016). The power output of the solar cell is directly proportional to the output current with change in illuminance, regardless of that of the voltage under similar atmospheric conditions and within the limit of the photovoltaic cell rating (Amajama, 2016).

2.5 Wind Energy Technology

Wind energy technology has been employed in different forms, such as windmills, wind turbines, and others. It stands as one of the oldest forms of energy, generated by applying mechanical controls. These controls convert wind to mechanical energy that either gets used up in its mechanical form or is converted to electric energy by wind turbines(Tong, 2009). The first electrical grids were constructed using mostly low-voltage DC cables that incurred very high energy losses. Due to these high losses and the cost of transmission, electricity had to be generated very close to where it was needed. For instance, small wind turbines were ideal for farms and grain mills that are far away from the grid (Hansen, 2008).

Wind results from the movement of air due to atmospheric pressure gradients. Usually, it flows from regions of higher pressure to regions of lower pressure. Larger atmospheric pressure gradients lead to higher wind speed. Higher wind speeds lead to greater wind power that can be captured from the wind, utilizing wind energy-converting machinery (Tong, 2009). The wind energy available for utilization by wind turbines increases with the cube of wind speed; that is, if wind speed increases by 10%, there will be a 33% increase in available wind energy (Bošnjaković, 2013). Wind speed is usually considered highly unreliable, coupled with the fluctuations in the conversion mechanism, which stand as some of the major challenges of the wind energy solution. Its dynamic nature of energy production, unlike static solar energy production, makes the wind the second next source other than solar technology (Rajkumar & Vaithlingam, 2016).

Rajkumar & Vaithlingam, (2016) believe that the evolution of wind energy technology is expected to continue over the next decades which will lead to improvements in reliability and energy capture as the costs will decrease. This is because, given the tremendous improvements in blade design and materials, innovative rotors, drive systems, towers, and controls will invariably enhance the reduction in the cost and improve the cost-effectiveness of wind technology.

According to the International Renewable Energy Agency (IRENA), the blades of wind turbines convert kinetic energy from the movement of air into rotational energy in the rotor blades; through electromagnetic induction, a generator in the turbine will then convert this rotational energy to electricity. In theory, when the wind speed increases by two, the wind power increases by a factor of eight. The main determining factors of the output power are the wind speed and the length of the blades (IRENA, 2016). Wind turbines have been continuously developed over the years. This led to the average capacity of new grid-connected onshore turbines rising from 0.05 megawatts (MW) in 1985 (EWEA, 2015) to 2.0 MW in 2014 (Broehl et al., 2015 cited in IRENA, 2016).

Three major elements of wind generation form the basis of its classification. They include, according to IRENA (2016); the turbine type (vertical/ horizontal-axis), grid connectivity (connected/stand-alone) and installation characteristic (onshore/offshore). Most large wind turbines are upwind horizontal-axis turbines with three blades. Most small wind turbines are also horizontal-axis. Innovative designs for vertical-axis turbines are being applied in urban environments, particularly in China. The overall generation efficiency of wind turbines is typically 30-40% at wind power facilities with aerodynamic energy loss of about 50-60% at the blade and rotor, mechanical loss of 4% at the gear, and a further 6% electromechanical loss at the generator (IRENA, 2016).

According to Hansen, (2008), wind turbines produce clean electricity, i.e, no CO_2 emissions. Hence, it does not contribute to the greenhouse effect. Wind energy generation is also relatively labour intensive, thereby creating as many jobs as possible. In rural areas or areas with little or no access to the grid, wind energy can be used for charging batteries. It can as well be used in a hybrid energy generation model with a diesel engine to save fuel whenever wind is available. Moreover, wind turbines can be employed for the desalination of water in coastal areas with little poor access to fresh water, for instance, the Middle East and North African region.

2.5.1 Wind Aerodynamics

Aerodynamics is the oldest science in wind energy. Wind turbine aerodynamics has to do with, in concise terms, the modelling and prediction of the forces of aerodynamics on the structures of a wind turbine especially regarding the turbine rotor blades. Aerodynamics is the most important aspect of wind technology for the prediction of performance and loadings on wind turbines (Sørensen et al., 2013). Aerodynamics is mainly interested in the performance of a wind turbine including areas such as power, torque and thrust (Das & Amano, 2014). The aerodynamic model is usually integrated with models for wind conditions and structural dynamics. The integrated aero-elastic model for predicting performance and structural deflections is a prerequisite for the design, development, and optimization of wind turbines. The modelling of aerodynamic may also have to do with the design of specific parts of wind turbines, such as rotor blade geometry, or performance predictions of wind farms (Sørensen et al., 2013).

The standard computational technique for the prediction of power curves of wind turbines is the Blade Element Momentum (BEM) theory; a theory based on the two-dimensional aerodynamic properties of aerofoil blade elements and some corrections accounting for three-dimensional wing aerodynamics (Martínez, Bernabini, Probst, & Rodríguez, 2005). According to them, regardless of the point that most BEM models yield acceptable results for low-wind and pitch-controlled regimes where the local angles of attack are small, there is no generally accepted model up to date that consistently predicts the power curve in the stall regime for a variety of blade properties and operating conditions.

2.5.1.1 Momentum Theory

Momentum theory is used to describe the control volume analysis of the forces at the rotor blade based on the conservation of linear and angular momentum, whereas blade element theory refers to the analysis of forces at a section of the blade, as a function of blade geometry. As mechanical energy can only be extracted from a change in kinetic energy, hence the theory states that the velocity of the wind stream, the wind velocity behind the wind turbine should not be greater than the wind velocity in front of the wind turbine. This would imply an increase in the area since the density change is insignificant (Das & Amano, 2014).

2.5.1.2 Blade Element Momentum (BEM) Theory

Typical wind turbine performance analysis is done based on BEM theory, which is also referred to as Strip theory. The BEM theory is built on the principle that the forces acting on the wind turbine blades are solely responsible for the change in axial momentum of the air passing through the swept area of the blades (Das & Amano, 2014). BEM analysis is a combination of results from blade element theory and momentum theory. Blade element theory refers to the analysis of forces at a section of the blade, as a function of blade geometry. The blade is split into sections or strips along the length of the blade and each section is separately analyzed. The results are combined at the end to provide the total power output for the turbine blade (Das & Amano, 2014).

2.5.2 Wind Turbine Model

Das & Amano, (2014) described a wind turbine as a device, which extracts kinetic energy from the wind and converts it to torque at the shaft. They broadly classified Traditional wind turbines into lift machines and drag machines. In a typical sense, drag machines utilize the drag force produced by the wind to generate power, whereas lift machines make use of lift force to generate torque and hence power.

The structural classification of wind turbines is based on their orientation and axis of rotation. Hence, they can either be Horizontal Axis Wind Turbines (HAWT) or Vertical Axis Wind

Turbines (VAWT) Both models can be installed offshore and onshore(Soriano et al., 2013). HAWT has proven to have higher wind energy conversion efficiency due to the blade design and access to stronger wind. Since they are heavyweight, they require a stronger tower to support the nacelle which increases its installation cost. The VAWT on the other hand has the advantage of lower cost of installation; however, with lower wind energy conversion efficiency following the weaker wind on the lower portion of the blades and limited aerodynamic performance (Soriano et al., 2013).

Another form of classification of wind turbines is by speed control methods and power control methods. Wind energy conversion is divided into fixed and variable speeds (Ofualagba & Ubeku, 2008). The work of Soriano et al., (2013) states that Fixed Speed Wind Turbines (FSWT) rotate at a near-constant speed, determined by the combination of the gear ratio, grid frequency, and the number of poles of the generator; The conversion efficiency can be maximized only at a specific wind speed, and the system efficiency declines at other wind speeds. The wind turbine is protected by aerodynamic control of the blades from possible damage caused by high wind gusts. On the other hand, variable speed wind turbines (VSWT) can achieve maximum energy conversion efficiency over a wide range of wind speeds. This energy conversion efficiency can be maximized at different wind speeds, given that the turbine can continuously adjust its rotational speed according to the wind speed. Soriano et al., (2013) believe that vertical axis wind turbines are mostly found in small wind applications due to their very low starting torque, as well as dynamic stability problems. Conversely, horizontal axis wind turbines are the most common wind turbines and are most commonly used for wind farms, small wind applications, and community wind projects.

The wind turbine works as a result of several components working together. Each component is designed to achieve a certain task. The components according to the Wind Energy Systems Laboratory, (WESL, 2016) include:

a. Yaw Pitch: for tracking incoming wind.
b. Drivetrain: Shift torque and speed characteristic.
c. Generator: Convert energy from mechanical to electrical.
d. Power system interconnection: Interface generator with load or power grid.
e. SCADA: Monitor performance, control set-points, human interface.

Each of the subsystems depends on the one next to it. Hence, the turbine must have a system-wide controller to communicate, synchronize and coordinate control of various turbine components. Information from various sensors triggers the controller to set operating conditions, verify performance metrics, and communicate with external parties, such as the Supervisory Control and Data Acquisition (SCADA) system. The scope of the study is limited to further expansion of the subsystems.

2.6 Energy Storage Systems

Global energy needs are currently being skewed towards renewable energy sources (RESs), such as wind and solar. The concerns about climate and environmental degradation have contributed greatly to this shift. However, RESs suffer the intermittency shortfall, which has necessitated energy storage systems (ESSs) to gain popularity worldwide (Hossain et al., 2020). ESS is the process of converting the electrical energy to another storable form and the eventual conversion of the stored energy to electricity in the time of need. Several ways exist to store up surplus energy obtained from RESs for later utilization, especially during periods of intermittency or shortages. The stored excess energy generated by the RESs helps in the reduction of energy waste and spillage.

In recent times electric vehicles (EVs) are gradually becoming a very important source of transportation. This is made possible through ESS, which is their main source of power. Notable also is the many utility-scale applications where ESS is applied; such as peak shaving, load levelling, backup power, and uninterrupted power supply (UPS) (Poullikkas, 2013).

The classification of Energy storage systems can be based upon their specific function, speed of response, duration of storage, the form of energy stored (Luo et al., 2015). Energy can be stored in the form of mechanical, electrochemical, chemical, or thermal energy, as well as in the form of electric or magnetic fields (Hossain et al., 2020). It is also possible to store energy as a hybrid of two different forms Among the available energy storage systems. However, in this study, we focus on Battery Energy Storage Systems (BESS) which is predominantly a form of electrochemical energy.

2.6.1 Battery Energy Storage Systems (BESS)

BESS is a form of Electrochemical storage which consists of all rechargeable battery energy storage (BES) as well as flow batteries (FB), which store electrical energy in the form of chemical energy (Hossain et al., 2020; Luo et al., 2015). BESS is one of the oldest and most mature technologies available for energy storage where a reversible chemical reaction in the active material through electrolyte is used for producing and/or storing DC power (Nadeem et al., 2019). Electrochemical Storage Systems are the largest group of electrical energy storage systems available with energy densities ranging from 10 Wh/kg up to 13 kW/kg having efficiencies of 70-80% for several available solutions, they have also shown no harmful emissions and require very little maintenance (Divya & Østergaard, 2009).

Batteries are effective for shorter duration storage with backup feasibility of one second to as high as five hours. BESS is commercially successful in grid-scale utility applications, which can be attributed to their availability in various sizes and system mobility features, making them suited for residential and commercial buildings (Akinyele et al., 2017). A comparative overview of large-scale battery systems for electricity storage was presented with a focus on the types, operational characteristics, and applications of battery systems in large-scale solar and wind energies (Poullikkas, 2013).

The Battery Energy Storage system comprises several technologies. They are grouped based on the type of electrodes and electrolytes used in their storage system arrangements (Zakeri & Syri, 2015). It is made up of electrochemical cells that are wired in series; they generate specified voltage electrical energy through an electrochemical process. Each electrochemical cell has two electrodes which are the anode and cathode, and an electrolyte (Luo et al., 2015). Akinyele et al., (2017) conclude that an electrochemical cell can convert energy from electrical to chemical energy and can as well reverse the process, thereby converting chemical energy to electrical energy.

There exist several battery storage technologies currently in large scale use Globally. The following types of batteries have been identified and discussed in several studies (Akinyele et al., 2017; Hossain et al., 2020; Luo et al., 2015; Zakeri & Syri, 2015): Lead-acid batteries, Lithium-ion (Li-ion) batteries, Sodium–sulfur (NaS) batteries, Nickel-cadmium (NiCd) batteries, sodium-nickel chloride (NaNiCl2) also known as ZEBRA, zinc-bromide (Zn-Br), polysulfide bromine (PSB) and vanadium –redox (VRFB). Akinyele et al., (2017) further identified new battery BESS systems such as “advanced valve regulated (VRLA) lead-acid, lead-carbon, metal-air technologies, UltraBattery, battery with current collector improvement, advanced sodium-metal chloride, high-performance sodium-copper chloride and nanostructured energy materials in lithium batteries".

2.6.2 Battery System Modeling

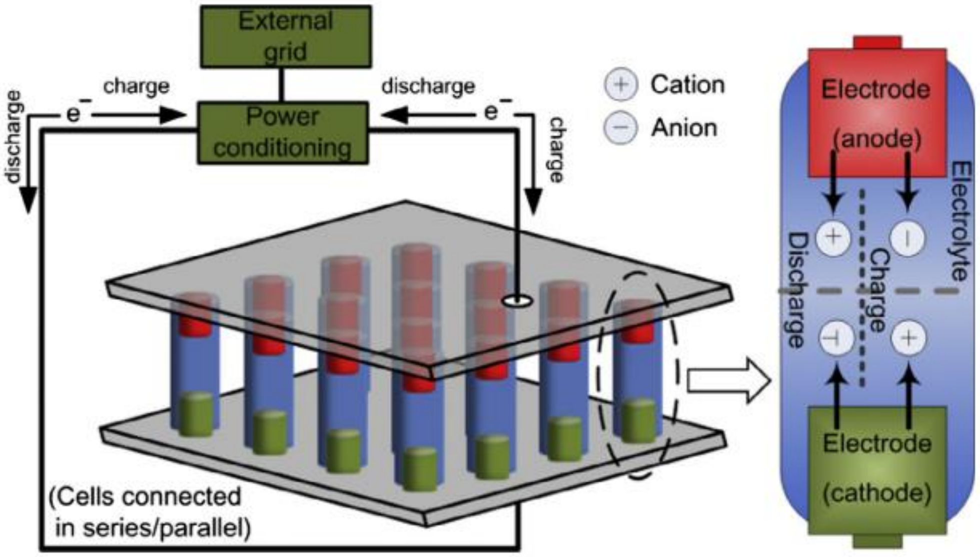


Figure 2.15: Schematic of a Battery Storage System (Luo et al., 2015)

The Schematic of a Battery Storage System is shown in Figure 2.15. Silva & Ferreira De Jesus, (2020) identified batteries as the weakest link in the electric power system chain. Hence, they emphasized the need to implement a model that describes the behavior of a battery storage system. A model is, therefore, necessary to predict the longevity and performance of the BESS and can is also useful in the construction of viable systems for the improvement of the performance of the system and to predict their longevity for different load profiles, thereby creating the possibility to increase their overall efficiency. Models capture battery behavior for specific purposes, from battery design and performance estimation to circuit simulation (Chen & Rincón-Mora, 2006)

To describe a large scale BESS, the model should describe several key behaviors, including (Silva & Ferreira De Jesus, 2020):

- ***Voltage***: The voltage exists as a result of the contributions of several cells.
- ***Current***: The current is usually defined by an external device or connection.
- ***Capacity***: Expressed in terms of the number of active materials in reagent form.

- ***State of charge***: This is defined by the quantity of active materials in reagent form.
- ***Impedance***: Represents the relation between the voltage and current.
- ***Losses***: represent the electrochemical efficiency in energy conversion.

The Major deficiency in battery modeling is that some variables need to be estimated. Among the listed parameters, only the voltage and the current can be explicitly determined. The rest need to be estimated. In addition, these variables are interdependent and as well depend on external factors like temperature and age(Chen & Rincón-Mora, 2006).

Electrochemical models of BESS are mainly used to optimize the physical design aspects of batteries, relate battery design parameters with macroscopic (e.g., battery voltage and current) and microscopic (e.g., concentration distribution) information, and characterize the fundamental mechanisms of power generation(Chen & Rincón-Mora, 2006). However, Dees & Battaglia, (2002) insists that BEES models are complex and time-consuming because they involve a system of coupled, time-variant, spatial, partial differential equations, which requires days of simulation time to reach a solution, complex numerical algorithms, and battery-specific information that is difficult to obtain, due to the proprietary nature of the technology. Some of the most popular BESS models include the Thevenin-Based Electrical Model, the Impedance-Based Electrical Model Impedance-based, and the Runtime-Based Electrical Model. These models, therefore, are beyond the scope of this study and will not be further discussed.

2.7 Hybrid Renewable Energy Systems (HRES)

Hybrid energy systems arise as a result of the combination of two or more forms of energy generation, storage, or end-use technologies, such that they deliver a wide range of advantages when compared with single-source systems. With the increasing energy demand and the intermittency of most renewable energy sources, hybrid energy systems are an ideal solution, given that they can offer substantial performance improvements (Zohuri, 2018).

Similarly, Hybrid Renewable Energy Systems (HRES) consist of two or more energy sources, with at least one of them renewable and integrated with power control equipment and an optional storage system (Martínez & Mart, 2017). They could be a combination of two renewable energy sources such as Solar and Wind, or a renewable energy source and a non-renewable energy source such as solar and Diesel engine generator. HRES can be found in the literature also as other terms which may include (Martínez & Mart, 2017); stand-alone hybrid energy (or power) system, remote, islanded, hybrid system, hybrid energy (or power) system, microgrids, off-grid, mini-grids or autonomous power systems.

Some known combinations for HRES systems include Battery/PV, Grid/Battery/PV, Wind/PV, Hydrogen/Wind/PV, Fuelcell/Wind/PV, Battery/Wind/PV, Diesel/Battery/Wind/PV, Grid/Diesel/Wind/PV, Hydro/PV, Battery/Diesel/PV, Battery/PV/Wind, Water pump/PV/Wind, Battery/Diesel/FC/PV/Wind, Hydro/Diesel/Wind, among others. As seen in these examples and Figure 2.16, the configurations may include renewable or nonrenewable energy sources, electrical and chemical energy storage, as well as fuel cells, which are usually connected via a smart grid. A study has stated that they have both economic and environmental benefits, such that they drastically lower cost and emissions from energy generation and distribution for households but suffer setbacks due to its limitation of individual power generation or storage technologies (Zohuri, 2018).

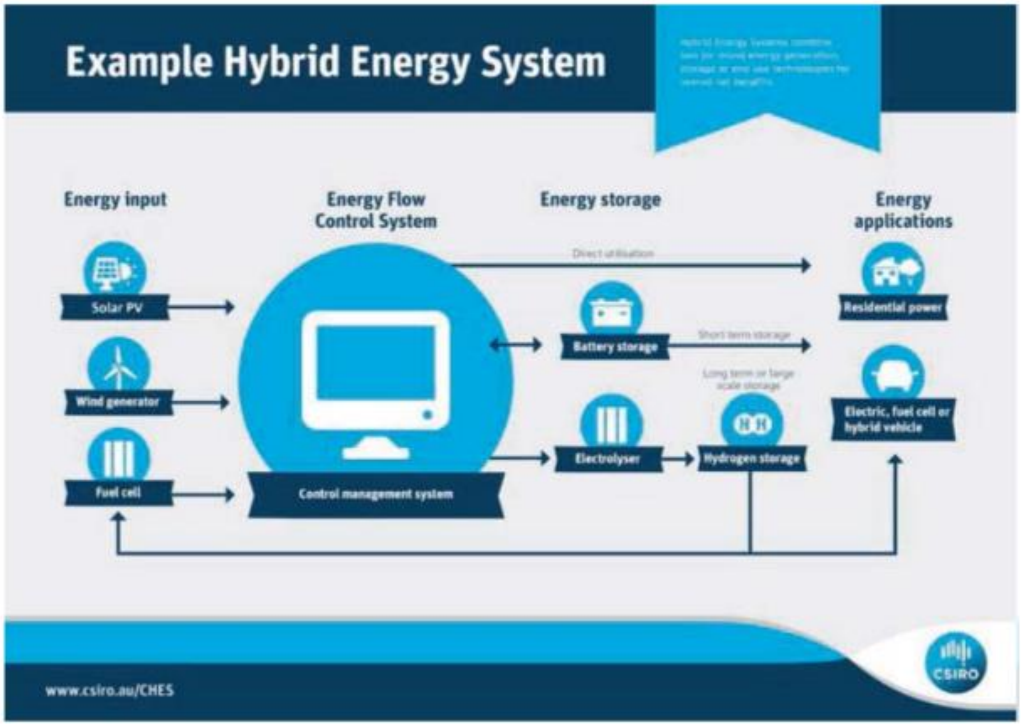


Figure 2.16: Schematic of a Hybrid Energy System (Zohuri, 2018)

2.7.1 Why a Hybrid Mini-Grid?

Research (Wiemann, Rolland, & Glania, 2011) shows that a combination of different energy technologies with different energy sources provides competitive advantages, in comparison to using a single technology. Their research paper stated that the combination of renewable energy sources such as solar or wind with a diesel Genset proved to be the least-cost solution for rural communities as the benefits and advantages of each technology complement each other. Since renewables do not run on fuel, fuel price or supply volatility does not affect their operation. However, renewable systems depend on the availability of specific resources at a specified time, which are subject to natural phenomena, hence they are non-dispatchable. Diesel generators, on the other hand, are dispatchable. Hence, they can deliver electricity when scheduled. A combination of these two sources leads to the coverage of a variety of shifting load profiles. Furthermore, the combination of various renewable sources simply makes sense in many scenarios (Wiemann, Rolland, & Glania, 2011). For instance, we can relate seasonal resource fluctuations with solar PV collectors, whereby wind power is complementing it during the months with less sun. Considering daily fluctuations, solar energy production peaks around midday when the sun is intense, whereas wind power facilities can operate whenever the wind is blowing, including at night. An introduction of storage batteries will add more stability to the system by storing the energy for when there is insufficient production from renewable sources

2.7.2 Mini-grid Systems

The important role electricity plays in human lives today cannot be overemphasized. With the increasing world population and expanding economic activities, the electricity demand is increasingly overwhelming. However, established public utilities have often concentrated more in urban areas while trying to meet the demands of the vocal and economically buoyant class, while at the same time, has failed largely to address the needs of rural villages. As a result of the foregoing, in rural areas around the world, where there is no or poor access to the national grid, numerous individuals and communities have taken it upon themselves to construct their own rudimentary electricity distribution systems supplied by isolated power sources, such as hydropower plants or diesel/petrol generators.

The Energy Management Assistance Program (ESMAP, 2017), notes that eleven private mini-grids were operational in Nigeria as of 2017. These mini-grids serve about 9,100 people, with a cumulated capacity of about 236kW1. Mini-grids hold out the promise of being the lowest-cost means of providing electricity to neighbors or entire communities (Mini Grid Manual, 2000). Over the past two decades, Mini-grid generation in Nigeria has gradually grown from fossil-based generation to renewable sources of energy. From the 1990s until the end of the 2000s, most mini-grids in Nigeria were diesel-fired. Today, all of Nigeria's 11 mini-grids are renewable-based, whereby solar PV is the dominant technology, in combination with batteries. Notable is the 50kW project by GVE in Bisanti (Grampus Heritage and Training Limited, 2020), the Ajima 20kW Farms in Rije which is run on biogas and two others that use hybrid solar PV-diesel systems (Ewepu, 2017).

A (hybrid) mini-grid system usually comprises three key subsystems: (i) production, (ii) distribution, and (iii) demand subsystem as shown in Table 2.6 (Wiemann, Rolland, & Glania, 2011). The availability of energy resources, the desired services to provide, and the user characteristics collectively determine how the subsystem can vary in its architecture and components.

Table 2.6: Sub-systems of a Mini-Grid

Sub-system	Description
Production	This subsystem includes all components of the energy generation (RETs and Genset), storage (batteries), converters (converters, rectifiers, and inverters to convert DC power to AC), and management (energy management systems) components. The production subsystem determines the capacity of the hybrid system to provide electricity and connects all the components through the bus bar (i.e. the electrical wiring connecting the different components) at the required voltage (AC/DC) for the distribution subsystem.
Distribution	This subsystem includes all the necessary distribution equipment. It is in charge of distributing the produced electricity to the users using the mini-grid. The primary issues are whether to use a distribution mini-grid based on DC or AC, and whether to build a single-phase or three-phase grid. This decision will have an impact on the cost of the project and will mainly determine the devices which can be used.
User or application	Here we consider all the equipment on the end-user side of the system,

subsystem or demand subsystem	such as meters, internal wiring, grounding, and the devices which will use the electricity generated by the hybrid power plant.

The mini-grid design directly affects the cost structure of the project. It determines the price of the energy produced and the quality of the services provided to the users. The early assessment phase of any successful design has to analyze the local conditions and the needs of the rural community. This helps to boost community involvement and support in the design considerations. Local involvement which considers the socio-economic cum cultural environment is important to reduce the chances of project failure and any negative image of renewables in the region (Koirala & Limbu, 2013).

2.7.3 Electrification Access Rates and Prices in Nigeria

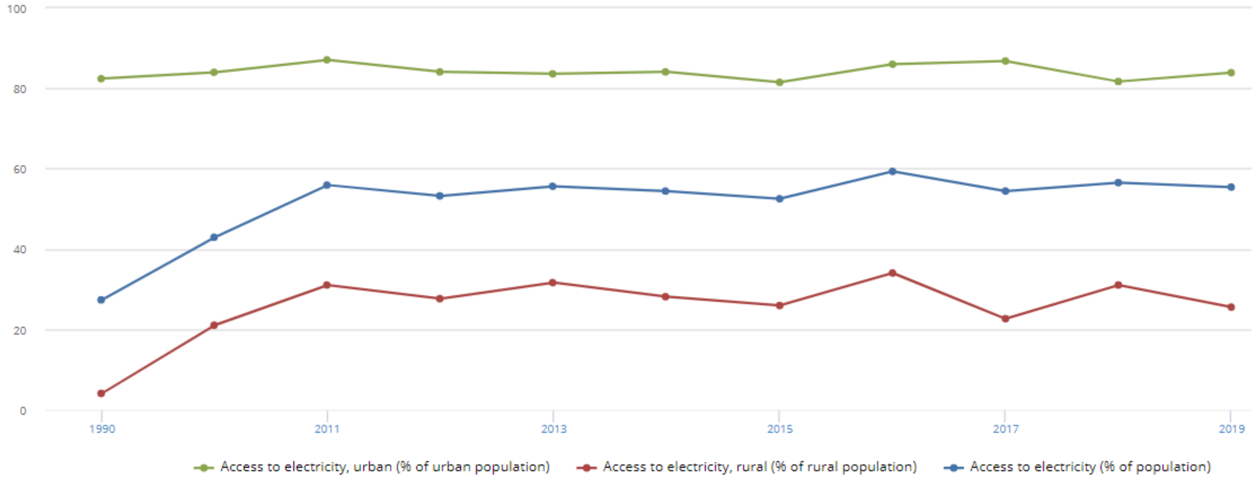


Figure 2.17: Rural, Urban and Total Access to Electricity (% of the total population)

In the past 2 decades, electrification in Nigeria has steadily increased (Figure 2.17). The share of people connected to the main grid increased from 27% in 1990 to 58% in 2014 (IEA, 2016) and 55.4% in 2019 (Worldbank, 2019). This is high when compared with the overall rate of electrification for Sub-Saharan Africa, which stood at 38%. The urban electricity access rate is way above 80% (Worldbank, 2019) while the rural energy access is below 30% (Worldbank, 2019). This goes further to show the need for the adoption of off-grid and mini-grid applications to enhance rural electricity access. This sub-section presents the historical chart of electricity access in Nigeria with the use of figures and tables. Figure 2.18 shows the electricity access rate of Nigeria (in orange line) in comparison with other neighbors such as Cameroon, Ghana, Niger and Gabon. The total access rate o Nigeria stood at 55% at the end of 2019. There exists a discrepancy between connection to the grid and access to electricity in Nigeria. This is because the grid might reach a town, but not all its inhabitants might be connected to it, hence the discrepancy between access and actual connection which has been a result of poor maintenance. By 2016, 43.2 million people receive electricity from the grid, which represented 23% of the population, compared to the connection rate of 58% (ESMAP, 2017).

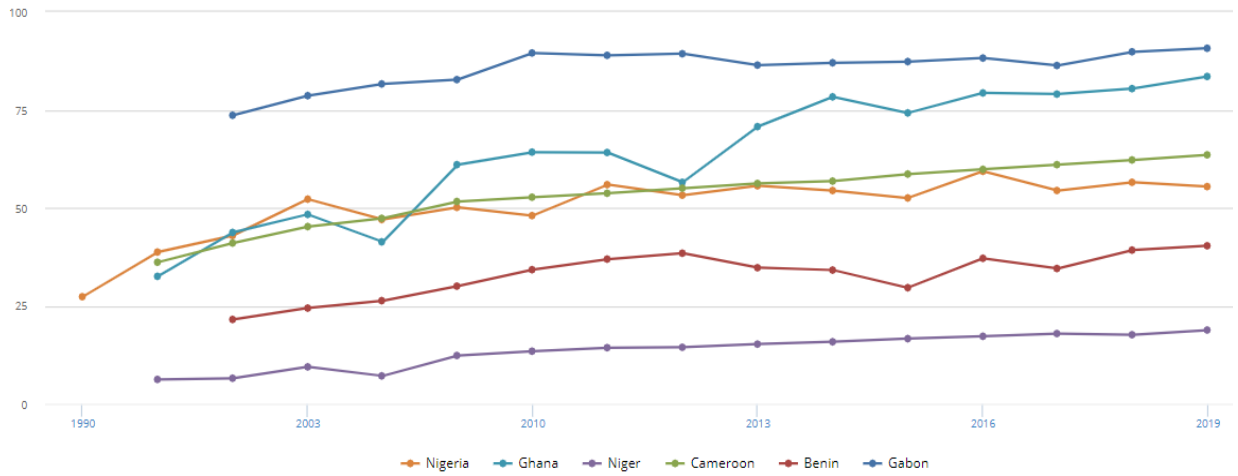
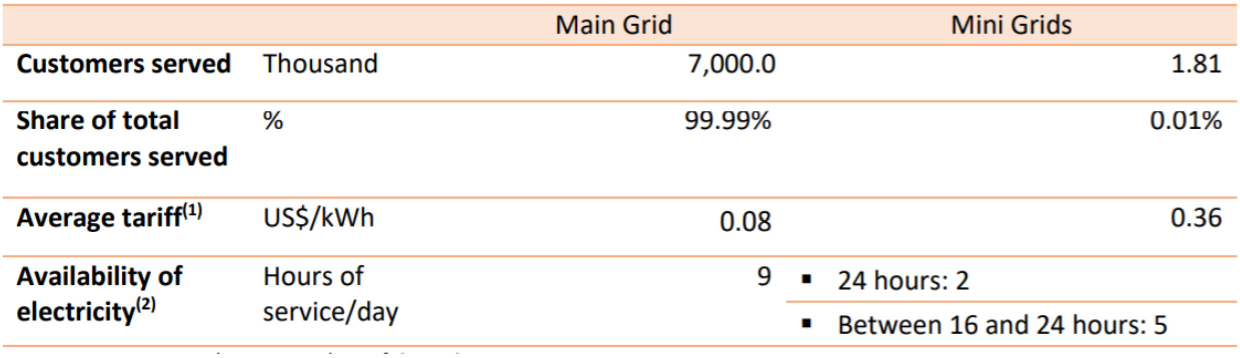


Figure 2.18: Access to Electricity (% of the population), 1990-2019 (*Source: World Bank, Electricity Access, http://data.worldbank.org/indicator, accessed 20 October 2021)*

The percentage of the population connected to mini-grids is very negligible when compared to the proportion connected to the main grid. Over ten years, the population connected to mini-grids increased to an estimated 9,000 in 2015 (ESMAP, 2017). In the Nigerian context, ESMAP further noted that mini-grids services are relatively higher in cost, but far more reliable than the main grid (Table 2.7, and Figure 2.19). Mini-grid customers pay on average twice the average tariff of the grid, which happens as a result of subsidies in the public power sector. However, mini-grids supply electricity for a time period about two to three times longer than the main grid.

Table 2.7: Mini-Grid and Main Grid Summary Statistics



		Main Grid	Mini Grids
Customers served	Thousand	7,000.0	1.81
Share of total customers served	%	99.99%	0.01%
Average tariff(1)	US$/kWh	0.08	0.36
Availability of electricity(2)	Hours of service/day	9	▪ 24 hours: 2 ▪ Between 16 and 24 hours: 5

Source: (ESMAP, 2017)

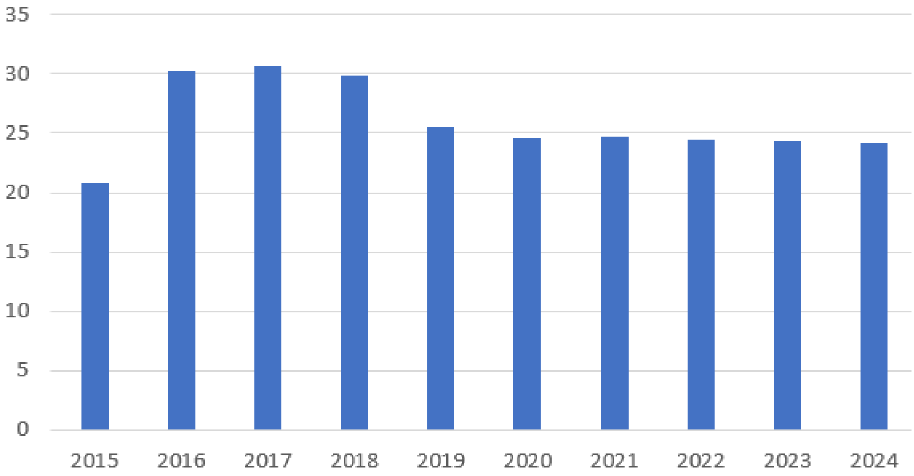


Figure 2.19: Household Electricity cost within Abuja Electricity Distribution Company (Source: (NERC, 2021)

2.7.4 Off-Grid Electrification

About 1.6 billion people live without electricity in some of the world's rural and remote areas (IEA, 2018). The socio-economic development of these remote villages lags behind their urban counterparts due to the unavailability of electricity. Extending the national grid over rugged terrain to rural areas, where the load is usually very low can be highly uneconomical and laborious, given the low level of activities in the areas. Off-Grid electrification, therefore, becomes a viable option for the electrification of these areas (ESMAP, 2007).

Off-grid electricity refers to all the means people have used and still using to generate electricity other than connecting to the national grid. In recent years, the use of domestic generator sets and renewable energy resources such as solar, hydro, wind power, among others, to generate electricity locally, has drawn much attention in the global energy sector. This way, isolated home electrification has been realized, and generating own electricity is increasingly becoming popular especially in commercial applications (Wiemann, Rolland, & Glania, 2011). Most rural areas that would have been otherwise difficult to get electrified, are now getting access to electricity as a result of the expansion of off-grid electrification technologies such as the concept of standalone renewable power systems. Sometimes they come with advanced energy storage methods and strategies for power control can be applied. It can be further facilitated for distribution and transmission, using a dedicated mini-grid or micro-grid that is isolated from the main electricity grid (Jayamaha, 2009).

A study in Nigeria identifies off-grid renewable electricity as a viable option for providing access to a steady and reliable electricity supply in the country, especially in the rural areas as well as an option for Nigeria to reduce the emission of greenhouse gases from the electricity sector. However, poor capital for investments in the off-grid renewable energy sector has hampered the development of off-grid renewable electricity projects (Ole, 2017).

Several types of energy technologies, including renewables, can be utilized in off-grid electricity systems (Figures 2.20 and 2.21) (Bhattacharyya & Palit, 2019; ESMAP, 2007; Koirala & Limbu, 2013; Wiemann et al., 2014)

- Small or micro-hydro: considered one of the cheapest technologies, but highly dependent on water resource availability with specific flow rate and volume conditions. Small hydro is a mature technology that has been installed all over the world for more than 3 decades.
- Solar photovoltaic (PV) is suitable for most locations around the world. It is considered easy to install, maintain, and scale up when compared to other options. The biggest challenge is the higher initial investment costs.

- Small wind power technology: this is another renewable energy-based option that is very site-specific. This is because wind conditions vary dramatically from place to place therefore, wind resources must be carefully studied before a system is installed.

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Figure 2.20: An example of an off-grid solar home system (Source: Battacharyya & Palit, 2019)

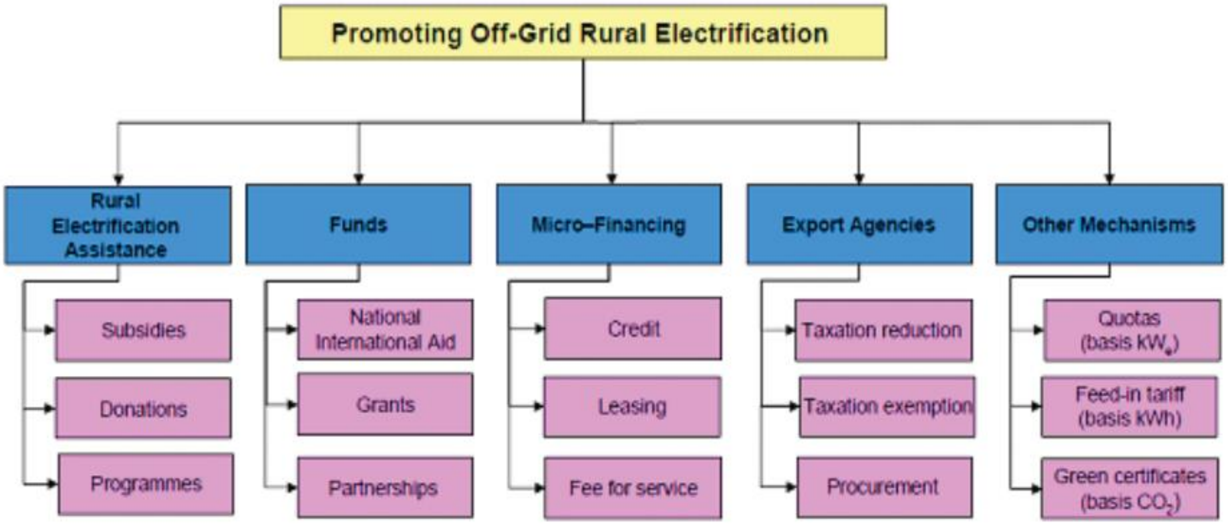


Figure 2.21: Instruments to support renewable energies and rural electrification (Source: Wiemann et al., 2014)

2.8 Energy Modelling Softwares

2.8.1 Overview of Hybrid Optimization Model for Electric Renewable (HOMER) SoftwareError! Bookmark not defined.

Hybrid Optimization of Multiple Energy Resources (HOMER) software has grown to become an international brand that is the global standard in decision making in the microgrid and distributed energy resource (DER) space. HOMER Energy LLC in 2009 commercialized HOMER, which was originally developed at National Renewable Energy Laboratory (NREL). HOMER Energy is primarily focused on the continued development, distribution, and support of HOMER software (HOMER Energy, n.d).

According to the HOMER Energy product description, the software works, whether for the design of hybrid microgrids or distributed generation systems. The software works as a guide for stakeholders to address such questions as (Energy Homer, 2020):

- What is the optimal mix of components for my microgrid?
- How will we find customers?
- How do we educate customers about our solutions?
- How do we quickly demonstrate the value of our solutions?

With solutions designed specifically to model renewable hybrid power systems either standalone or connected to the power grid — HOMER helps energy analysts make informed decisions based on: analysis, optimization and design, market access and promotion for your component, interface with your controller or web-based application, training and support

HOMER Pro can also be customized with up to nine individual modules to meet specific modeling needs, including Biomass, Hydro, Combined Heat and Power, Advanced Load, Advanced Grid, Hydrogen, Advanced Storage, Multi-Year and MATLAB Link (Homer Energy, 2020). This makes the use of the software quite vast. In application, Literature reveals that HOMER has been previously employed to investigate the prospects and cost-effectiveness of implementation of a hybrid standalone PV/wind system in Sokoto state in Northern Nigeria. The study applied daily electricity demand, yearly solar radiation and wind speed to determine the optimum sizing of the renewable energy (RE) system (Abubakar, 2017). An Economic analysis of hybrid energy systems for rural electrification using HOMER was carried out (Moses &

Shruthi, 2017), analysis results show that among three hybrid systems for supplying electrical requirements, the most economical is the PV - diesel -battery hybrid system.

2.8.2 RETScreen

RETScreen is software developed and maintained by the Government of Canada through the Natural Resources Canada's CANMET Energy Diversification Research Laboratory (CEDRL). It was developed to support awareness creation, innovation and unique renewable energy decision-support and capacity-building (Owolabi et al., 2019). RETScreen is a collective effort of over 307 networks of experts from the energy industry, government and academia. RETScreen collaborates with the National Aeronautics & Space Administration (NASA), the United Nations Environment Program (UNEP), the Renewable Energy and Energy Efficiency Partnership (REEEP), the Global Environment Facility (GEF), World Bank's Prototype Carbon Fund (PCF) (Natural Resources Canada, n.d). Several versions of the software are available for public use free with no cost, but users are required to make paid subscriptions to use the professional version of the software.

RETScreen has a broad range of applications in the energy field. Its major applications include feasibility analysis of clean energy projects, including energy-efficient technologies and renewable energy projects such as solar photovoltaic, wind energy and hydro projects (Lee, Lee, Baek, Kwon, & Lee, 2012). RETScreen enables energy feasibility assessment, performance evaluation of new and retrofit projects as well as for monitoring and evaluation of existing projects. It is very suitable for technical and economic assessments as well as environmental analysis, sensitivity and risk analyses. The RETScreen International photovoltaic project model is used worldwide to easily calculate the energy production, life-cycle costs, and greenhouse gas emissions reduction for three basic PV applications: on-grid; off-grid; and water pumping (Mirzahosseini & Taheri, 2012). RETScreen Expert worksheet RETScreen software is used to determine if a renewable energy project is financially viable. That is if it makes financial sense with an analysis capable of covering an entire project life cycle. The home interface of the software has three major analysis tools which include benchmark analysis, feasibility analysis, and Performance analysis. In this study, RETScreen Expert version 8 will be used to carry out the techno-economic analysis of an isolated mini-grid in Nigeria.

Figure 2.8.1: A chart of RETScreen workflow

2.9 Artificial Intelligence in HRES Modelling

In this section, we will present brief literature reviews on some of the related modelling techniques involving Artificial Intelligence (AI) for Hybrid Renewable Energy Systems.

2.9.1 Genetic Algorithm (GA)

Genetic Algorithm (GA) as used in Energy science was first introduced in biological sciences. John Holland first proposed it as a type of meta-heuristic search and optimization algorithm, inspired by Charles Darwin’s theory of natural selection and survival of the fittest. Similarly, the approach is applied in renewable energy optimization to select parameters from every level, to get the best parameter (Gunasekaran et al., n.d.).

To investigate the economic feasibility of a renewable energy system when ESSs are introduced in the electric grid with an expansion of a storage system as well as more renewable energy integration and less fuel consumption; Abbas et al., (2018) used the Artificial Neural Network to validate the forecast load model. The uncertainties associated with the renewable energy system were then handled by a chance-constrained model eventually solved by employing a genetic algorithm (GA) in MATLAB.

In similar research (Mahesh & Sandhu, 2020) the genetic algorithm (GA) was applied to optimize a solar photovoltaic(PV)-wind-battery hybrid system connected to the grid. Their objective was to minimize the cost of the hybrid system while maintaining its reliability. For the effective sizing of the hybrid system, they also considered along with the reliability constraint, some other parameters, such as the battery's state of charge (SOC), full utilization of complementary nature of PV and wind systems and fluctuations of power injected into the grid. Literature also exists on Genetic algorithm-based optimization on modeling and design of hybrid renewable energy systems (Ismail (M. S. Ismail) et al., 2014). An investigation of the ability of Genetic Algorithms to improve the accuracy of global solar irradiation prediction, where the Global Horizontal Index (GHI) is the primary output variable was carried out by (Gunasekaran et al., n.d.).

2.9.2 Particle Swarm Optimization (PSO)

Particle swarm Algorithm is one of the most important of these algorithms utilized in artificial intelligence, it is a modern approach based on stochastic optimization technique. It was first brought forward in 1995 by Kennedy and Eberhart and has been employed in solving global optimization problems, showing many successful applications in many scientific fields (Poli & Blackwell, 2007). Hence, its application in Energy systems optimization.

The Particle Swarm Optimization technique (PSO) was proposed and developed to minimize the cost of energy (Hazem et al., 2019). Swarm techniques have been shown to successfully solve optimization problems where the objective is to find one optimal solution, however, when there is a need to find multiple solutions, the technique may fail (Brits, 2002). In studying the optimization of Hybrid Wind/Tidal/PV/Battery Energy Systems, Hazem et al., (2019) employed the Particle Swarm Optimization. The (PSO) algorithm which was developed by the researchers exhibited several advantageous characteristics over more traditional techniques. It allows for the achievement of the optimal solution and the reduction of the overall cost with higher speed and accuracy (Hazem et al., 2019). MATLAB software was used to develop the PSO algorithm program.

A modified particle swarm optimization technique for the optimal design of a small renewable energy system supplying a specific load at Mansoura University was carried out (Mohamed et al., 2015). The technique was used to optimize the capacity sizes of different components of a hybrid PV/wind/battery power generation system for supplying energy to a center in the university. Literature also exists for enhanced particle swarm optimization algorithms for improving the renewable energy penetration and small-signal stability in power systems (Renuka et al., 2018). A study which implemented the PSO algorithm for maximization of renewable energy penetration to the test systems; secondly, the small-signal stability of the systems was improved with maximum renewable energy penetration in which the best locations for connecting the wind farm were identified by using the calculation of wind farm placement index and solar generation.

2.9.3 Artificial Neural Network (ANN)

Artificial Neural networks as a modeling approach have been shown to have more important and useful tools than the classical methods. It has marked a paradigm shift in computation and learning, by its way of presenting different modeling approaches to solving complicated problems (Kalogirou, 2000). Complicated practical problems in various areas, such as engineering, medicine, business, etc., have been solved using ANN. They have also been applied for optimization, modeling, prediction, forecasting, classification, identification, evaluation, and control of complex systems (Ata, 2015).

The application of ANN in hybrid renewable energy systems can be found in such kinds of literature as in (Kalogirou, 2000) where a review of ANN in Renewable Energy systems Applications for renewable and sustainable energy was done. ANN Technique in Renewable Energy Systems (Thiaw et al., 2014) was also carried out to show how a neural network technique could be employed to design a Maximum Power Point Tracker (MPPT) controller for photovoltaic generators, helping to achieve better efficiency, the possibility to assess the available and recoverable wind energy potential of a site, by finding an adequate distribution law of the wind speeds. Rahman et al., (2021) studied the prospective methodologies in Hybrid renewable energy Systems for energy prediction using artificial neural networks.

2.9.4 Artificial Neuro-Fuzzy Inference System (ANFIS)

To predict solar energy radiation in the tropical region, Lestari et al., (2019) used the adaptive neuro-fuzzy inference system. The aim was to develop a system of prediction of the solar irradiance in the tropical region for home energy needs, given that that the tropics get sunlight throughout the year. Input data such as maximum temperature, minimum temperature, precipitation, wind speed, and relative humidity were used while employing the using hybrid optimization method alongside the ANFIS. A similar study was also conducted (Kaur et al., 2021) on adaptive neuro-fuzzy inference system-based output power controllers in grid-connected photovoltaic systems. ANFIS was developed for the extraction of optimal power from a non-linear PV module. The designed ANFIS controller directly took irradiance and temperature as input parameters to give the crisp value of voltage, in which case, the maximum power can be delivered at all times. To bring out the optimal/maximum power for increasing the efficiency of solar photovoltaic (PV) under unstable weather conditions, Kamaraja & Priyadharshini, (2019) examined Adaptive Neuro-Fuzzy Inference System based PV Energy Generation. Several other pieces of literature exist on this topic, but the scope of the study limits further expansion.

2.9.5 Ant Colony Optimization

Ants are social insects such that when they come together, they form a colony; they exhibit a distributed system such that, despite the simplicity at the individual level, they present a highly structured social organization. This organization of colonies can accomplish complex tasks that far exceed individual capabilities (Dorigo & Stutzle, 2004). This characteristic of ants has led to the study of their nature, leading to the development of a simple stochastic model that adequately describes the dynamics of the ant colony.

Literature reveals that such studies as ant colony optimization-based energy management controllers for smart grid (Rahim et al., 2016) have been carried out in the energy field. A hybrid of ant colony optimization and artificial bee colony algorithm for probabilistic optimal placement and sizing of distributed energy resources (Dorigo & Stutzle, 2004) was also carried out to present optimal location and sizing of distributed energy resources (DERs) on distribution systems to minimize power losses, total electrical energy cost, total emissions produced by substation and resources, and improving the voltage stability. Furthermore, a study on the optimal sizing of hybrid energy systems using Ant Colony Optimization (Mittal et al., 2014) has also been conducted. consisting wind/solar/Battery has been analyzed for a particular load profile. This analysis was done to obtain optimal sizing of HES. Optimal sizing results were obtained while putting important factors into consideration, such as reliability, cost, and other unexpected uncertainties.

3.0 MATERIALS AND METHODS

This section discusses the methodology of this study, which considers the parameters, design, and technical specifications of the energy systems under study. We also discuss the data collection method and the type of data collected. Data collected on technical parameters include electricity demand/consumption, the power generation factor, PV module sizing, solar PV energy required inverter sizing, and battery sizing (Owolabi, Nsafon, et al., 2019) among others. The methodology is discussed in detail under the headings below.

3.1 Research Methods

This research involves an extensive literature review which was conducted using the desk review method. The keywords were inputted into online sources such as google scholar, ScienceDirect, and other renowned online journals. Over 250 related research publications, conference proceedings, reports, thesis, articles, and dissertations were found. They were sorted based on their relevance to the topic after their abstracts were read and findings reviewed. Eventually, the most relevant documents were selected and have been appropriately cited where necessary.

Secondly, we surveyed the mini-grid plant under study. Here we accessed all the technical and economic parameters from the operators. The mini-grid is designed to serve a cluster of households, hence, the loading data was also accessed from the survey. The data collected through the survey makes up all the primary data needed for the research. The remaining data used were secondary data accessed mainly from online data banks. The data were analyzed using two different software (RETScreen and HOMER), this was to enable the researchers to achieve the objectives stated in chapter 1.

3.2 Data Collection

As mentioned in the previous paragraph, the study involved the use of both primary and secondary data to enable the researchers to reach the objectives.

3.2.1 Primary Data

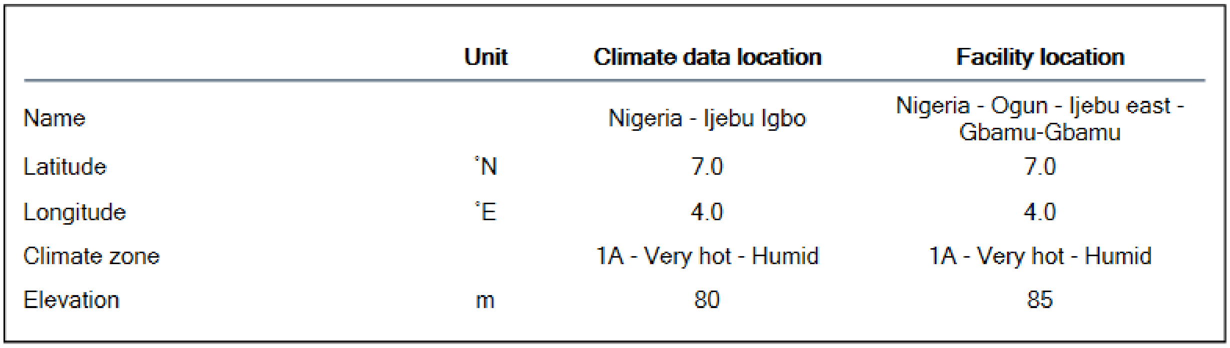
Primary data are data collected by the researcher first hand, directly from the affected source. In this research, a survey was conducted, which involved direct contact with the operators of a mini-grid system in Ogun state, Nigeria. All the data collected through this process is considered under the primary data category. The data that fall under this category include the technical parameters as well as the economic and energy load, collected directly from the operators of Gbamu-Gbamu mini-grid operators through interviews.

3.2.2 Secondary Data

The secondary data used for the study include the climatic data for the mini-grid location, which was made available from the National Aeronautics and Space Administration (NASA) as embedded in the program of both RETScreen and HOMER software. The number of households and commercial users, as well as their energy demand, was accessed from the mini-grid operators. The mini-grid uses a prepaid metering system. Hence, the bills were used to estimate the average household energy consumption. This information was collected and documented for the effective management of the plant.

3.2.3 Study Area

This study was conducted in the rural community of Gbamu-Gbamu in Ogun state, Nigeria where a solar PV of 85kWp was installed. Gbamu-Gbamu community is relatively large and comprises about 550 households and 5,000 inhabitants. It is located in Ijebu East Local Government Area and is a highly agrarian community producing, processing, and trading with a wide variety of crops (cocoa, palm produce, plantain, kola nut, etc) (Soremekun, 2020). Table 3.1 shows the details of the study area based on data from NASA.



	Unit	Climate data location	Facility location
Name		Nigeria - Ijebu Igbo	Nigeria - Ogun - Ijebu east - Gbamu-Gbamu
Latitude	°N	7.0	7.0
Longitude	°E	4.0	4.0
Climate zone		1A - Very hot - Humid	1A - Very hot - Humid
Elevation	m	80	85

Table 3.1: Summary of climatic data for plant location

The community is estimated to be 13 km away from the Expressway. Economic activities in the area that require electricity include agriculture, milling, hospitality, public, religion, and education. The alternative source of electricity for the community is private diesel and petrol-powered generators, which are expensive to run due to the high cost of petrol and diesel. They are also not environmentally friendly due to the high carbon emission. The hybrid mini-grid is designed to a capacity of 85 kWp of PV, 67 kVA of Diesel Generator, and 5.6 km of low voltage grid (covering 80% of the village). The mini-grid design is optimized to match the supply to the demand of the village.

3.3 Load Estimation for the Proposed Site

Load estimation refers to the energy demand of the end-users of the electricity generated by the power plant. To properly design a solar system requires the calculation of the total power and energy consumption of all loads to be supplied by the PV system (Chandel et al., 2014). They can be classified into domestic/household, commercial and industrial users. The sum is the total energy demand for the project which necessitates the power plant to provide at least enough energy for the intended consumers.

3.3.1 Domestic/Households Load Estimation

The household load was estimated by observing the average electrical appliance usage by a typical (average) rural household in the region. Dominguez et al., (2018) estimated the average rural household energy consumption to be 1636 Wh/HH/day. This, however, is estimated to be lower in Gbamu-Gbamu. Given the 550 households in the community, 493 are connected to the mini-grid system amounts to about 88% of the total households. Table 3.2 illustrates the electrical appliances in an average rural household while Figure 3.1 shows the daily household load profile. The load profile informs the plant operators of the peak loading hours for efficient management of the mini-grid system. The chart shows that the households have their peak loading in the evening hours. Typical of a rural setting when everyone comes home to use electrical gadgets at night.

The Multi-Tier Framework identifies the listed appliances between tier 1 and tier 3 of energy access categorization. The majority of the rural dwellers use electricity mainly for lighting, radio, and charging mobile phones and for a limited time frame as well. With this, household consumption is estimated to be:

265 x 493 = 130,645 Watt (estimated household peak energy consumption per day = 130.64kw).

To validate the estimate, The power plant recorded a peak monthly consumption of electricity of 4591kWh by households. This amounts to 153kWh/d.

Table 3.2: Power estimate for an average rural household in Gbamu-Gbamu

S/N	APPLIANCE	POWER(W-h)	QTY	TOTAL POWER(W-h)
1	Light	20	4	80
2	Fan	50	1	50
3	Television	80	1	80
4	Radio	15	1	20
5	Miscellaneous	50	-	30
	Total			**265**

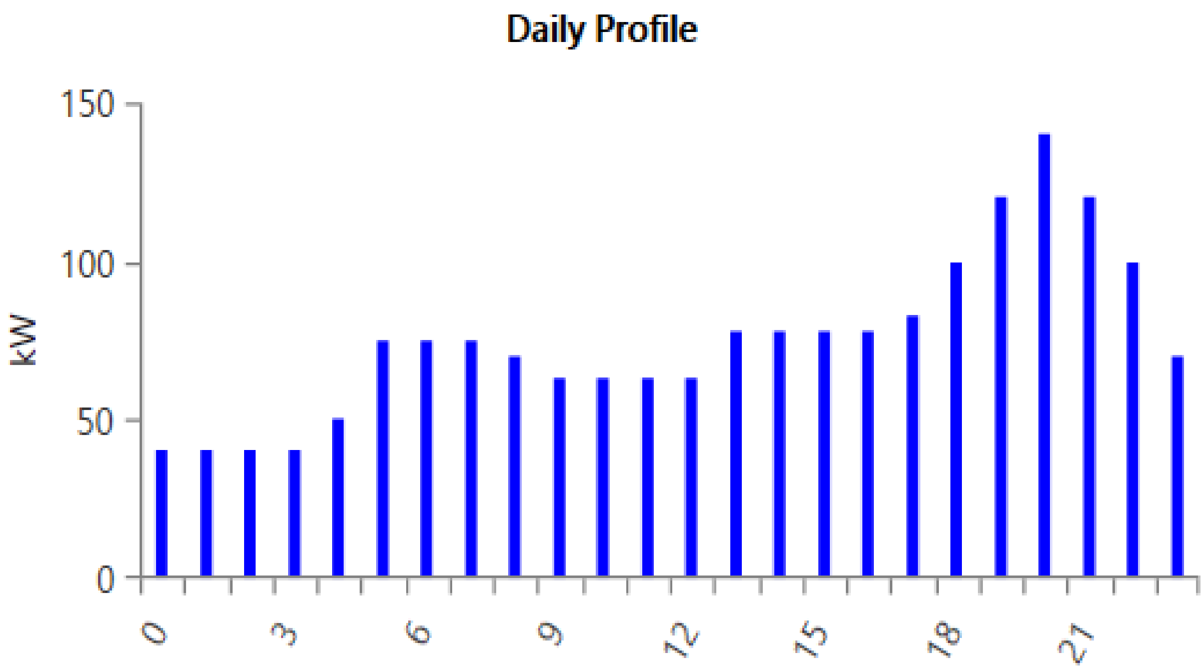


Figure 3.1. estimated daily household load profile in the study area.

3.3.2 Commercial Load Estimation

The rural setting under study exhibited a good level of commercial activities. Among the commercial customers were welders, a motel, restaurants, grocery shops, computer services, and others. Using the prepaid metering system, the cumulative energy consumed by the commercial customers numbering 147 in all was 3855kWh per month. This results in a monthly average of 128kWh/d. The plant also recorded a peak energy consumption of 338.2kWh/d. Figure 3.2 shows the estimated average daily load profile of the commercial customers of the mini-grid under study. The commercial customers exhibited a higher energy consumption during the day. This is typical, as their activities are mostly carried out during the day.

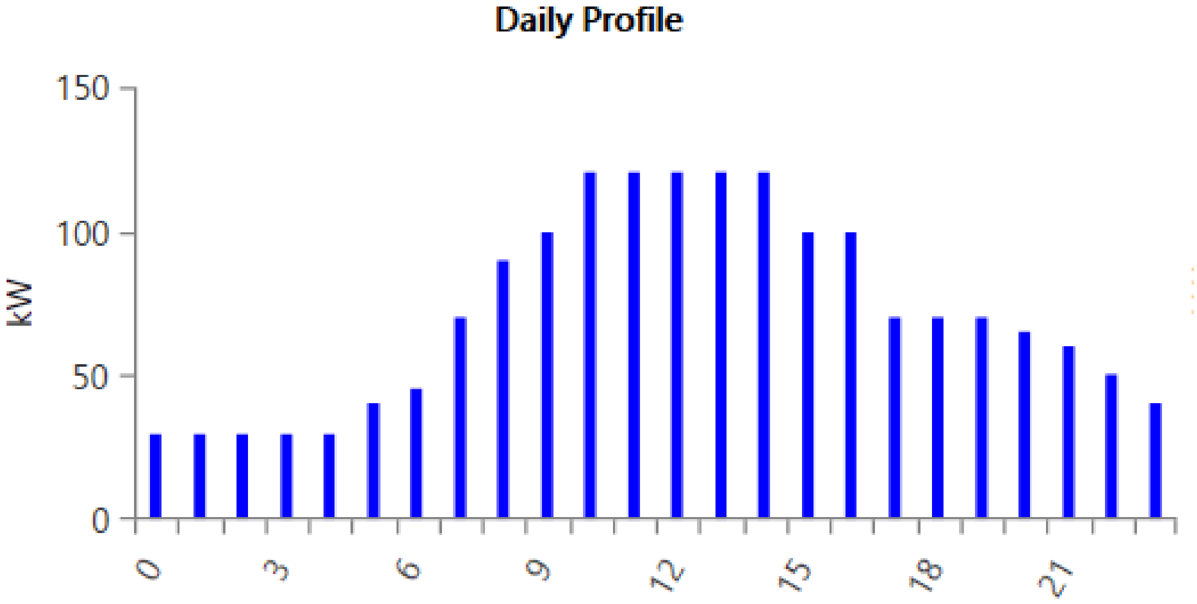


Figure 3.2: Estimated daily household load profile in the study area

3.3.3 Summary of Load Estimation Per Category

The load estimation for both household and commercial users has been summarized in Table 3.3.

Table 3.3: Load estimation

Item	***Household***	***Commercial***	***Total***
Number of users	493	147	640
Average daily electricity consumption	153kWh	128 kWh	281 kWh
Average Monthly electricity consumption	4591kWh	3855kWh	8446kWh

3.4 RETScreen and HOMER Pro Microgrid Analysis Tools

3.4.1 RETScreen Enviro-Economic analysis parameters

The RETScreen expert was mainly employed to access the environmental and economic analysis of the Power Plant, while HOMER was useful in determining the optimized size of the mini-grid system. Some economic parameters such as discount rate and inflation rate were collected from the relevant authorities such as the Central Bank of Nigeria and the National Bureau of Statistics, they were further cross-referenced with the data from the Financial Market Infrastructure Group (FMDQ) to ensure accuracy. The RETScreen software is also programmed with the carbon emission rate of all countries in the world, such that it can estimate the carbon emission avoided by adopting a clean energy system (Natural Resources Canada, n.d). The parameters used for the economic analysis are summarized in Table 3.4.

Table 3.4: Parameters for economic analysis

Financial Parameters	*Value*	*Source*
Inflation rate	11.8%	FMDQ
Project life	20 years	Plant Operators
Debt ratio	42%	Plant Operators
Debt interest rate	5%	Plant Operators
Discount rate	5%	Literature
Debt term	7	Plant Operators
Initial Cost	NGN 214,000,000 (@410/$)	Plant Operators
Electricity export rate	0.5$	Plant Operators
O&M	5,500,000 (@410/$)	Plant Operators
Electricity rate	NGN 170-200/kWh	Plant Operators

3.4.1 Solar Potential

The techno-economic analysis of the solar PV system was made possible using solar irradiance as the input variable to determine the electricity output of the power plant. There are different ways of getting data for this variable, following the fact that solar irradiance is subject to the specific plant location, (Pareek & Gidwani, 2019).

a. As ground data, whereby the data is collected using meteorological instruments on the site.
b. Through the RETscreen and HOMER software, access is granted to satellite meteorological data which is collected kept by NASA.

In this study, the NASA data was used directly from their database. Hence, there was no need to collect ground data for the analysis. The NASA database locates the closes climate data location to the selected site. In this case, the selected climatic data location was at Ijebu Igbo, a local council 26 kilometers away from the solar PV site in Gbamu-Gbamu, Ijebu east local council, both in Ogun state Nigeria. Results for daily average solar irradiance in the selected location are shown in chapter 4.

3.5 Hybrid Energy System

All input data for the hybrid system were collected directly from the existing mini-grid system as shown in the subsections.

3.5.1 Input Data for Solar System

The hybrid mini-grid system in Gbamu-Gbamu is designed to have a solar PV capacity of 85kWp. This means that it has a peak rating of 85kW/h. It is made with 250 Watt Monocrystalline solar panels manufactured by Jinko. The peak energy requirement of the plant is 338.12kWh/d

To arrive at 85kW (85,000 Watts), There are 340 panels in the solar array (340*250 = 85,000 Watt).

3.5.2 Input Data for the Battery System

The details of the input data for the battery system are summarized in Table 3.5.

Table 3.5 Input Data for the Battery System

Parameters	***Value***
The total battery Watt-hours used per day	392.5kWh
Battery loss	15% (estimate)
Depth of discharge for battery	40%
Nominal battery voltage	12V

$$\text{Battery capacity, therefore, } = \frac{\text{Total Watt used per day} * \text{days of autonomy}}{\text{battery efficiency} * \text{nominal voltage} * \text{rate of discharge}}$$

$$= \frac{392{,}000*1}{0.85*0.6*12} = 64{,}052.2 \text{ Ah}$$

3.5.3 Parameters of the Diesel Generator

The hybrid system includes a 60kW diesel Genset of 85kVA which consumes an average of 50 liters of diesel and runs for about 3-4 hours per day. The Generator was manufactured by Marapco. Its daily fuelling constitutes a great part of the operations and maintenance cost of the plant. The data gathered showed that the average cost of petrol is 315 Naira (0.77 USD) per liter (Table 3.6).

Daily fuel consumption is thus: 315*50 = 15,750 Naira (38.414 and 1152.4 USD daily and monthly respectively). These variables were pivotal in accessing the economic viability of the system and its environmental sustainability as well, given that diesel is a major emitter of CO_2.

Table 3.6: Input parameters of the Diesel Generator

Parameters	**Input values NGN**	**Current USD equivalent @410/$**
Capital investment	-N- 3,500,000 (estimate)	8,536.4
Fuelling price	-N- 315 per liter	0.77
Power rating	60kW	
Capacity	80kVA	
Daily fuel cost	-N- 15,750	
Monthly fuel cost	-N- 472,320	1152.4
Hours operated per day	4 hours (average)	
Operational time	15,000 hours	

3.5.4 Input Data for the Converter

The size of the inverter used in the PV power plant depends on the total peak watts requirement. The inverter must be large enough to handle the total peak watt requirement of the system at all times. Hence, it should be about 30% larger than the total loading of the system (Chandel et al., 2014). However, through investigation, the inverter at the plant was found to be an 80kW capacity. Following the position of Chandel et al., (2014), the peak energy rating of the plant was observed to be 85kW daily. Therefore, the inverter should be 1.3 times bigger, to give allowance for the error factor.

85 x 1.3 = 110.5kW

3.6 System Constraints

In estimating the optimal combination for the energy sources in the hybrid system, Olatomiwa et al., (2015) state that the constraints serve as pre-stated conditions which systems must meet, otherwise the HOMER software will neglect the non-satisfying systems. In the proposed existing mini-grid, we considered a range of 0 to 100% for the maximum renewable fraction, and the maximum unserved energy is assumed 0% following the position of (Olatomiwa et al., 2015), the values (0, 4, 6, and10%) are taken as the maximum annual capacity shortage.

3.7 Sensitivity Variables

Sensitivity analysis is a tool used for exploring the effect of the changes in the available resources and economic conditions. In this case, we consider all the related economic and technical conditions that might lead to changes in the performance or financial returns of the plant. It, therefore, shows the range of the variables for which it makes sense to include renewable energy in the system design (Olatomiwa et al., 2015). In this study, we consider the sensitivity of the Net Present Value (NPV) by varying the initial cost against the debt interest rate by ±25% for the first case and the initial cost against the electricity exported to the grid by the same ±25% for the second case.

4.0 RESULTS AND DISCUSSION

In this study, RETScreen Expert software was used to assess the economic and environmental viability of an existing 85kWp hybrid mini-grid PV/battery/diesel system in the Gbamu-Gbamu rural community of Ijebu East local government area of Ogun State, Nigeria. HOMER prove software was used to simulate the optimal sizing of the system. The climatic data of the location was calculated by the RETScreen software using the National Aeronautics and Space Administration (NASA) data. RETScreen used climatic data from the nearest climatic data location in Ijebu Igbo, which is just about 26km from the plant. Figure 4.1. shows the variation of the monthly average solar irradiance of the power plant location. The average monthly irradiance was recorded to be 4.78kW/h/m^2

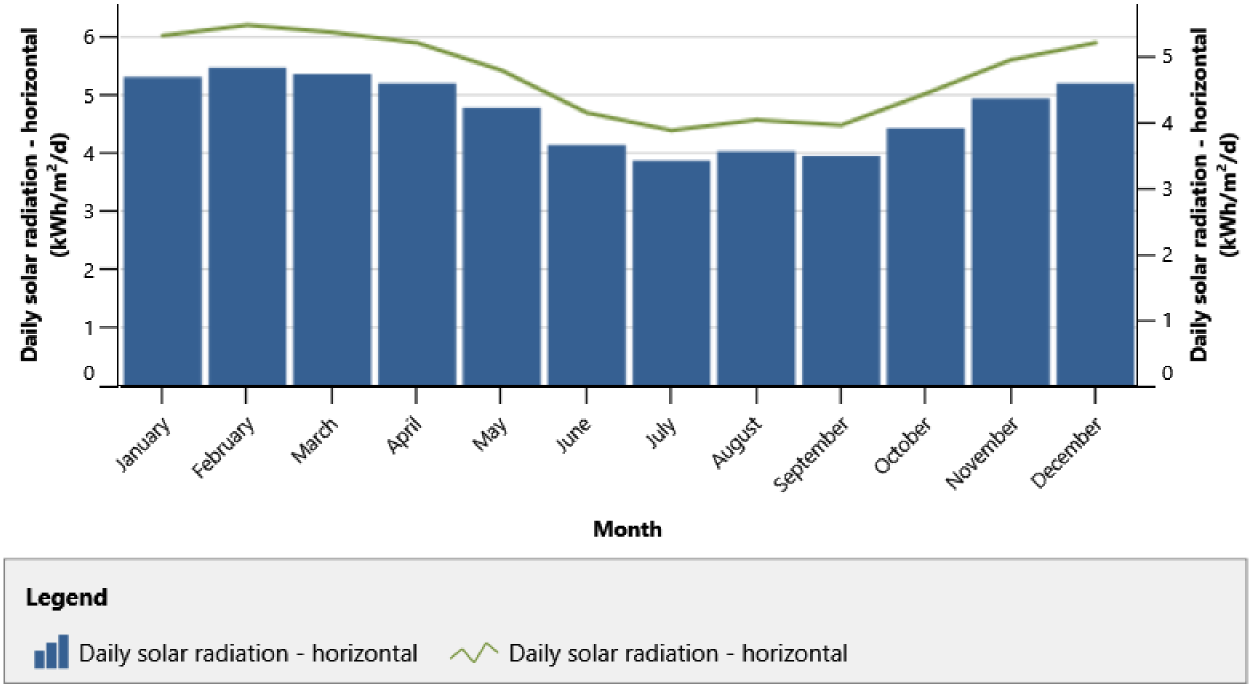


Figure 4.1: Average monthly solar irradiance

4.1 Technical feasibility

The technical feasibility and sustainability of the hybrid system consider the product specification upon which the efficiency and efficient utilization depend (Mehmood et al., 2014). The PV system used a fixed solar tracking mode for the location with the module tilted to an angle of 9 degrees to get the maximum annual average radiation. At this angle, the solar irradiance and the total electricity exported to the grid from the plant will be maximized

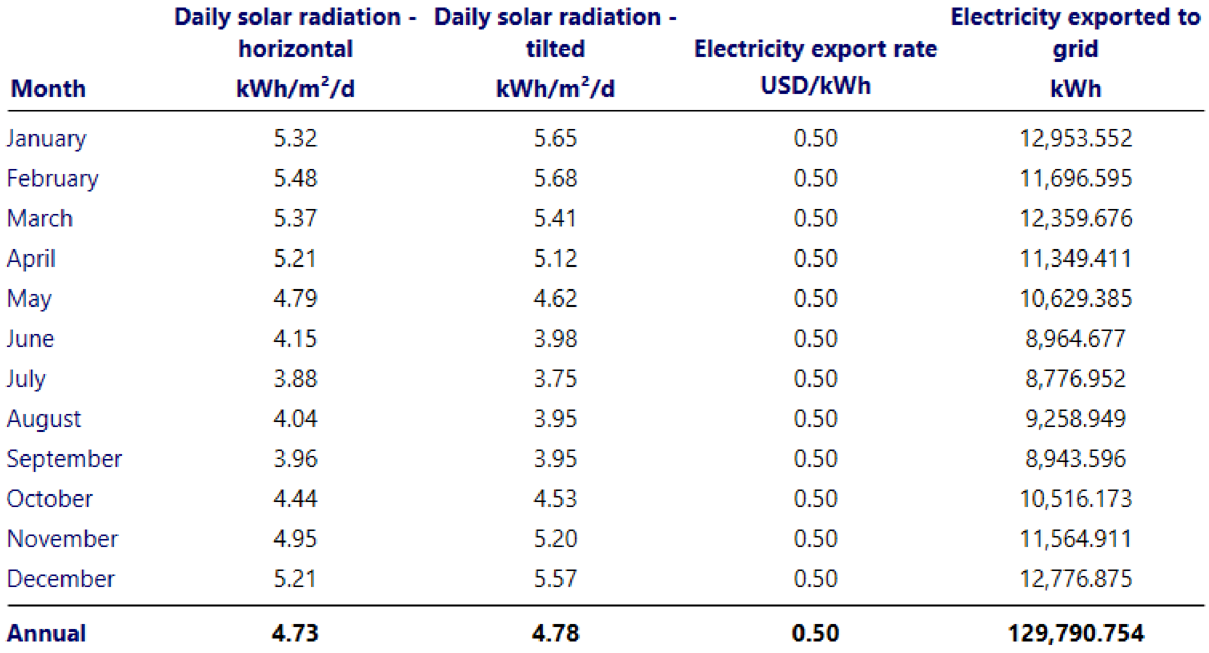
($4.78kWh/m^2$) when the module is sloped to an angle of 9 degrees as against $4.73kWh/m^2$ when it is set horizontally. The RETScreen Expert software calculated the parametric characteristics of the Jinko mono-si JKM-250m-60. The selected solar panel model covered an area of $557m^2$ and is made up of 340 units to make up the array. The parametric characteristics of the PV module are summarized in Table 4.1.

Table 4.1: Summary of PV parametric configuration

Property	***Value***
PV technology type	Jimko mono-Si
Power capacity	85kW
Manufacturer Model	JMK-250
Number of units	340
Efficiency	15.27
Nominal operating temperature	45
Temperature coefficient	0.5
Solar collector area	$557m^2$

The solar photovoltaic module’s energy produced is largely dependent on the solar irradiance of the PV location, the number of clear sunny days, and the number of sunny hours per day (Mehmood et al., 2014), which eventually affects the total annual electricity exported by the system. The total electricity exported will as well affect the revenue generated from the plant in a positive manner, whereby as export increases, revenue generated will increase and vice versa. The analysis from RETScreen also showed that the annual solar radiation from the module when set horizontally is $1.73mWh/m^2$ and when tilted, it would yield an annual $1.74mWh/m^2$. The RETScreen analysis showed that the highest amount (12,953.55kWh) of energy is exported in January, given the inherent high irradiance, while the lowest amount (8776.95kWh) of energy was exported in July (Table 4.2). The distribution follows what is obtainable in reality due to the weather condition in Nigeria where July marks the peak of the rainy season. The range of monthly energy export was given as 4176.6kWh.

Table 4.2: Irradiance and Electricity export summary



Month	Daily solar radiation - horizontal kWh/m^2/d	Daily solar radiation - tilted kWh/m^2/d	Electricity export rate USD/kWh	Electricity exported to grid kWh
January	5.32	5.65	0.50	12,953.552
February	5.48	5.68	0.50	11,696.595
March	5.37	5.41	0.50	12,359.676
April	5.21	5.12	0.50	11,349.411
May	4.79	4.62	0.50	10,629.385
June	4.15	3.98	0.50	8,964.677
July	3.88	3.75	0.50	8,776.952
August	4.04	3.95	0.50	9,258.949
September	3.96	3.95	0.50	8,943.596
October	4.44	4.53	0.50	10,516.173
November	4.95	5.20	0.50	11,564.911
December	5.21	5.57	0.50	12,776.875
Annual	**4.73**	**4.78**	**0.50**	**129,790.754**

According to a similar result gotten by validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using RETScreen Experts to assess its viability based on the technical viability of the solar system by Owolabi, Nsafon, et al., (2019), We can conclude that the system is technically feasible at the calculated capacity factor of 17.4%.

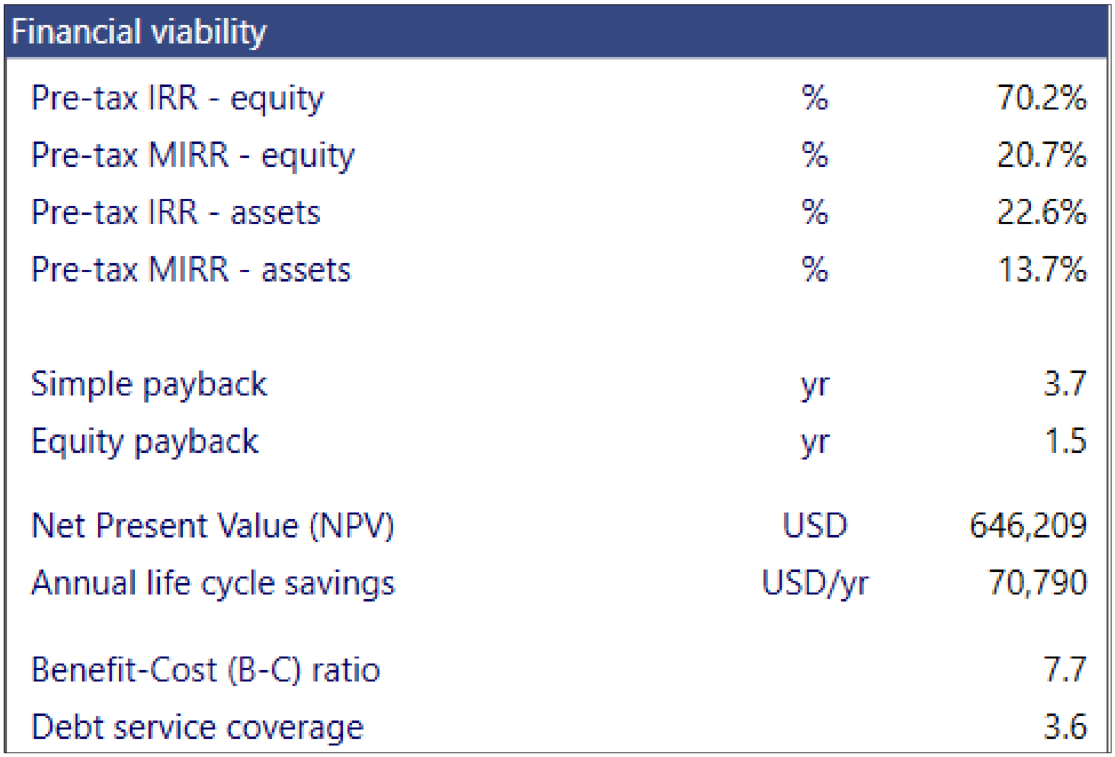
4.2 Economic Viability

Economic analysis is one of the most important aspects of developing a hybrid energy system as well as any other investment that expects returns. It is an important analysis because it is done to know the economic viability and sustainability (Owolabi, Nsafon, et al., 2019). As much as a project might be technically feasible, it must be economically viable before it can be embarked. In carrying out the financial analysis on the RETScreen software, the worksheet contains some financial parameters which must be provided and put into the system to get the desired results. These variables include; inflation rate, debt ratio, debt interest rate, discount rate, reinvestment rate, initial investment as well as operation and maintenance cost. These values and their sources have been previously discussed in section 3.5 and presented in Table 3.3.

We inputted values of the economic variables listed and the software generated results of the Internal Rate of Return (IRR), the Net Present Value (NPV), the annual life savings, alongside other decision-making financial parameters were calculated by the RETScreen software.

Mehmood et al., (2014) described the economic viability of a project as a measure of its NPV, IRR, and the payback period, which are the major determinants of the financial viability of a project. The outputs of the financial parameters have been summarized in Table 4.3.

Table 4.3: Financial viability from RETScreen



Financial viability

Pre-tax IRR - equity	%	70.2%
Pre-tax MIRR - equity	%	20.7%
Pre-tax IRR - assets	%	22.6%
Pre-tax MIRR - assets	%	13.7%
Simple payback	yr	3.7
Equity payback	yr	1.5
Net Present Value (NPV)	USD	646,209
Annual life cycle savings	USD/yr	70,790
Benefit-Cost (B-C) ratio		7.7
Debt service coverage		3.6

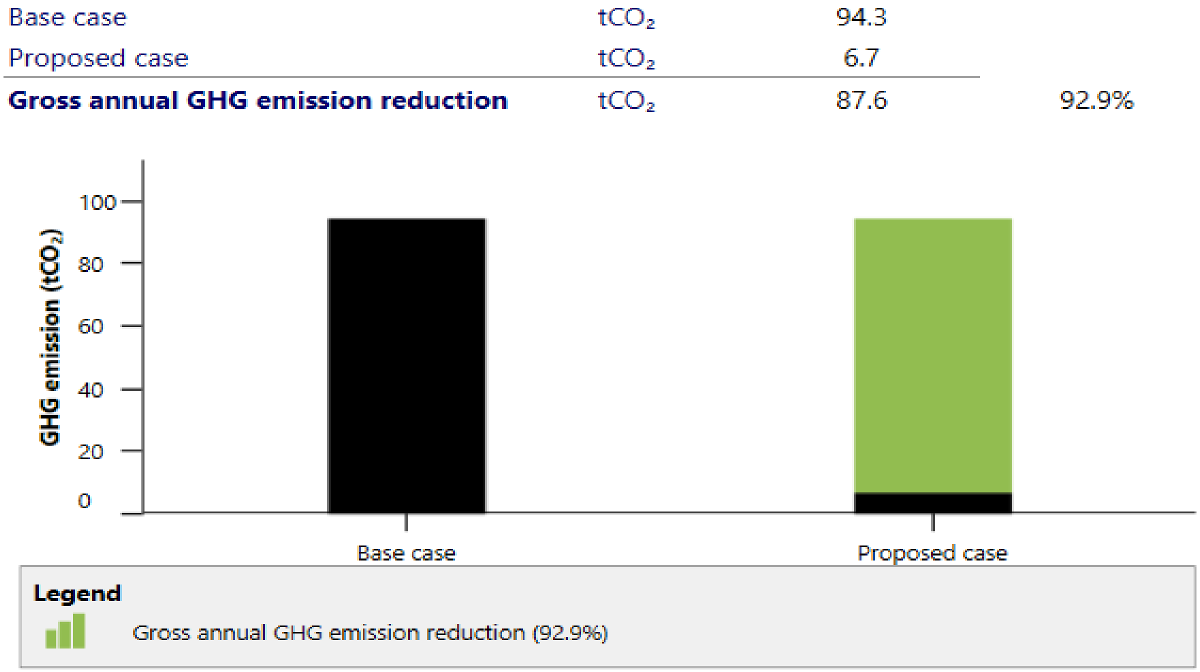
The net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. This parameter is positive from our results, which means that the project is financially viable. This is in line with the results from similar research (Owolabi, Nsafon, et al., 2019) done in Nigeria. We can conclude that the project is both financially and economically feasible (Chandel et al., 2014; Mehmood et al., 2014; Rehman et al., 2017). The IRR which is a measure of a project’s profitability has a positive value that is higher than the expected rate of return (see figure 4.3) it can be said also that the project is economically acceptable.

A simple payback period is an economic tool of analysis that refers to the length of time that it will take to recoup the initial investment of a project. In this case, the simple payback period is 4 years. This means that the investment will return all cost of investment by the fourth year if we do not take the discount rate and inflation rate into account. Similarly, the model calculates the equity payback. This represents the duration that it takes for the owner of a facility to recoup their initial investment out of the cash flows generated from the project. The equity payback considers project cash flows from its inception as well as the leverage of the project, This makes the equity payback a better time indicator of the project merits than the simple payback. In this model, the equity payback as seen in figure 4.3 is 2 years. This makes real economic sense, as the project shows a good sign of economic sustainability and viability.

4.3 Emission reduction assessment

The emission analysis worksheet is used to calculate the greenhouse gas (GHG) emission reduction resulting from carrying out the solar PV installation (Owolabi, Nsafon, et al., 2019). In some cases where the emission reduction attracts revenue, the system calculates the revenue that may occur from the sales of the GHG reduction emission. Considering the calculated transmission and distribution losses of 7% and a GHG emission factor of 0.4325847tCO2/MWh, there will be an 87.556tCO_2 reduction in emission from the production of 203mWh annual energy from the mini-grid system.

4.3.1 Business as usual vs Proposed case



Base case	tCO_2	94.3	
Proposed case	tCO_2	6.7	
Gross annual GHG emission reduction	tCO_2	87.6	92.9%

Figure 4.2: CO2 emission in base case vs proposed case

In this study, one of our objectives is to assess the environmental sustainability of the existing mini-grid system. Figure 4.2 above shows how environmentally sustainable the project is as compared to the base case which is referred to as the business as usual scenario. The proposed case reduces the GHG emission by 92.9%. This means that if the 203mWh annual energy produced from this hybrid energy system would have generated a total of 87.556tCO_2 from other sources of energy. Achieving the sustainable development agenda of the United Nations by 2030 requires a serious commitment, not only to tackling poverty, hunger and inequality, but achieving inclusive growth and sustainably managing and sustainably utilizing the Earth's natural resources. Table 4.4 shows the extent to which this energy system will save the environment by what it has averted. That is the opportunity cost of the mini-grid system.

Table 4.4. Summary of the equivalences of 87.6 tCO_2

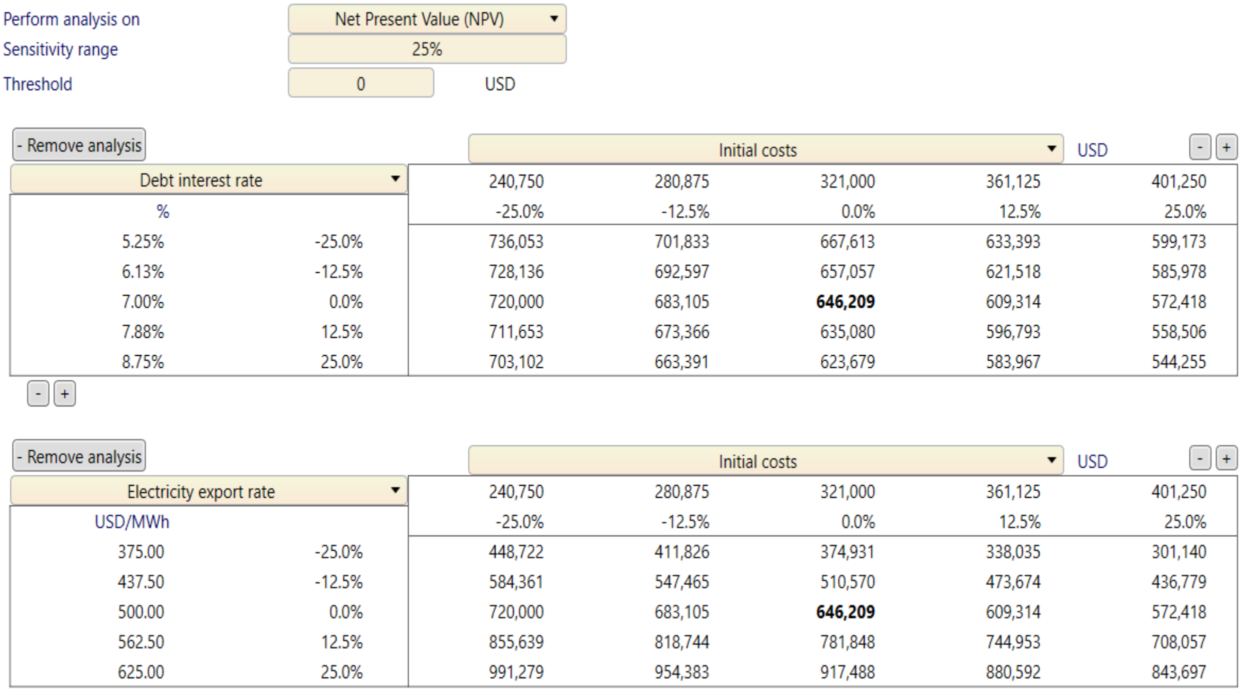
Environmental parameter	Equivalence
Cars and light trucks not used	16
Liters of gasoline not consumed	37,620
Barrels of crude oil not consumed	204
People reducing energy use by 20%	87.6
Acres of forest absorbing carbon	19.9
Hectares of forest absorbing carbon	8.1
Tones of waste recycled	30.2

Following the values in table 4.2 which shows what the project is achieving, this project will help in achieving the set goals SGD goals if further adopted and implemented across the country.

4.4 Sensitivity and Risk assessment

Saltelli & Annoni, 92010) describe sensitivity analysis as the process of Identifying factors or groups of factors mostly responsible for the uncertainty in the prediction of a variable. The sensitivity analysis in the RETscreen software worksheet defines how the level of uncertainty can be reduced by considering two inputted parameters against the calculated financial variables (Owolabi, Nsafon, et al., 2019).

In case 1, the value of the initial cost is 321,000, the sensitivity of the NPV shows that with ±25%, the value of the initial cost increases to 401,250 and reduces 240,750 respectively. Similarly, the actual debt interest rate initially used for the computation is 7.0% but with a ±25% it will be 8.75% and 5.25% respectively. By recalculating the NPV for the combination of initial cost and debt interest rate holding all other parameters constant, we see that a 25% increase in initial cost and a 25% decrease in debt interest rate will result in an NPV of +599,173, on the same note, a 25% decrease in initial cost and a 25% increase in interest rate will result in an NPV value of +703,102. In this case, all the NPV values are positive which means that the project remains feasible, despite the changes in the variables. However, in extreme cases, the NPV may be more sensitive to initial cost than the debt interest rate, given the results discussed. No negative NPV was recorded in the sensitivity matrix as seen in Figure 4.3. The situation is similar to scenario 2. Figure 4.3 does not show any negative NPV, despite the ±25% changes in electricity export and initial cost. This further extends the claim that the project is highly economically viable.



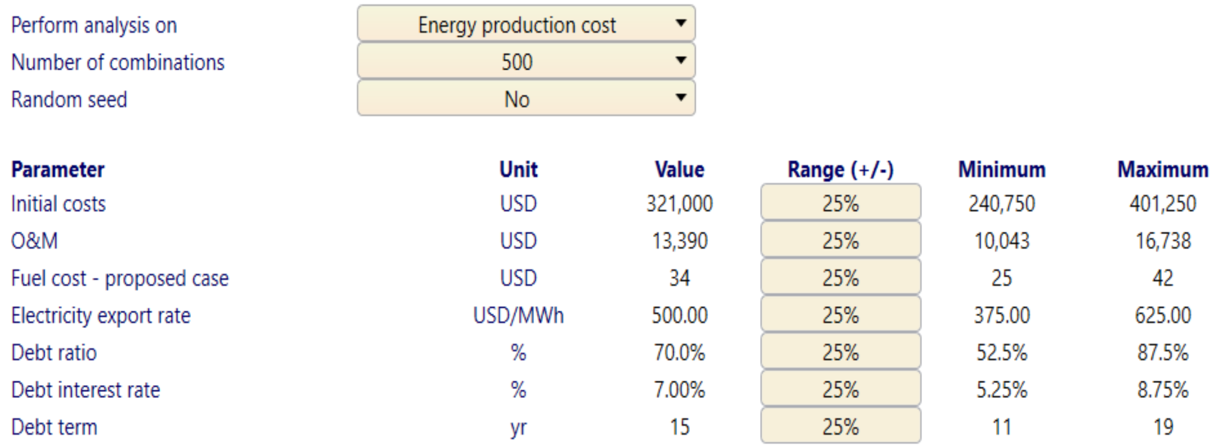
Perform analysis on	Net Present Value (NPV)	
Sensitivity range	25%	
Threshold	0	USD

Debt interest rate		Initial costs				USD
		240,750	280,875	321,000	361,125	401,250
%		-25.0%	-12.5%	0.0%	12.5%	25.0%
5.25%	-25.0%	736,053	701,833	667,613	633,393	599,173
6.13%	-12.5%	728,136	692,597	657,057	621,518	585,978
7.00%	0.0%	720,000	683,105	**646,209**	609,314	572,418
7.88%	12.5%	711,653	673,366	635,080	596,793	558,506
8.75%	25.0%	703,102	663,391	623,679	583,967	544,255

Electricity export rate		Initial costs				USD
		240,750	280,875	321,000	361,125	401,250
USD/MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
375.00	-25.0%	448,722	411,826	374,931	338,035	301,140
437.50	-12.5%	584,361	547,465	510,570	473,674	436,779
500.00	0.0%	720,000	683,105	**646,209**	609,314	572,418
562.50	12.5%	855,639	818,744	781,848	744,953	708,057
625.00	25.0%	991,279	954,383	917,488	880,592	843,697

Figure 4.3: Sensitivity summary

The risk analysis is similar to sensitivity analysis, however, a little different following the fact that all the parameters are allowed to vary with each other during the analysis within a specific range. The energy production cost is selected as the financial indicator and the range considered is±25% for all the parameters. Figures 4.4 and 4.5 show the impact graph and the distribution graph of the risk analysis. From the impact graph, the variation in the energy production cost is a result of the changes in various parameters included in the analysis. The initial cost and operations and maintenance cost exhibited the highest impact on the production cost, followed by the debt interest rate and they move in the same direction. A debt ratio and debt term both showed a negative relationship with production cost. This means that as the debt ratio and debt term increase, the production cost will reduce. Figure 4.4 showed how the parameters will affect the energy production cost when varied by +25% increase and decrease.



Perform analysis on: Energy production cost
Number of combinations: 500
Random seed: No

Parameter	Unit	Value	Range (+/-)	Minimum	Maximum
Initial costs	USD	321,000	25%	240,750	401,250
O&M	USD	13,390	25%	10,043	16,738
Fuel cost - proposed case	USD	34	25%	25	42
Electricity export rate	USD/MWh	500.00	25%	375.00	625.00
Debt ratio	%	70.0%	25%	52.5%	87.5%
Debt interest rate	%	7.00%	25%	5.25%	8.75%
Debt term	yr	15	25%	11	19

Figure 4.4: Risk impact summary

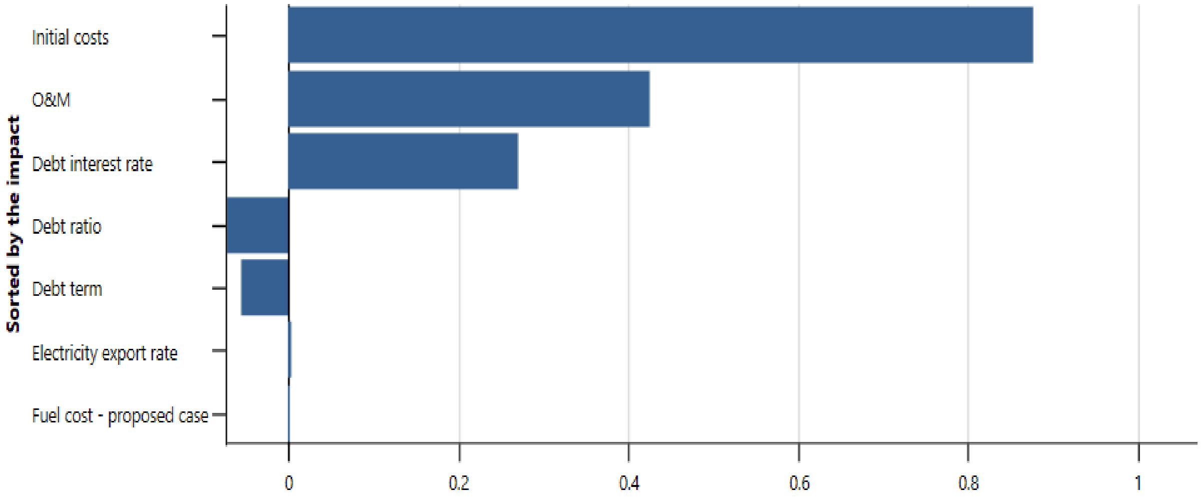


Figure 4.5: Risk distribution chart

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study was conducted to ascertain the technical and economic feasibility as well as environmental sustainability of an existing mini-grid in Nigeria. An extensive literature review was conducted where several aspects of PV technology were reviewed, as well as the regulatory framework of the energy sector in Nigeria. A survey was carried out to obtain all the relevant data from the power plant operators, which were then inputted into RETScreen expert. The software modeled and gave results. It was discovered that the power plant is both technically feasible and economically viable. The results were in line with some existing literature on the subject, both within (Olatomiwa et al., 2015; Owolabi, Nsafon, et al., 2019) and outside (Chandel et al., 2014; Mittal et al., 2014; Pareek & Gidwani, 2019) Nigeria. The results also showed a massive cut in GHG emissions.

5.2 Recommendations

Following the results of the study, we recommend the following

i. There should be an inclusion of more renewable energy sources in the national grid through the national energy policy as this will help to cut down on GHG emissions.

ii. The research showed high energy export to the grid. This means that there is high solar potential in Nigeria. The adoption of solar PVs should be encouraged to increase energy access in Nigeria.

iii. There should be incentive to the private investors in mini-grid in the form of grants and tax holidays since they will be helping to solve a global problem by providing electricity which in turn increases economic activities in rural areas.

iv. Public-Private-Partnerships would serve to a great extent in increasing investments in mini-grids. This will shake some loads off the government as public funds can be utilized in other sectors.

v. The public should be sensitized on the need to move away from conventional energy sources and the adoption of cleaner energies. This will encourage a shift in their resistance to the adoption of cleaner energy arising from socio-cultural barriers.

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