PAN AFRICAN UNIVERSITY

Institute of Water and Energy Sciences (Including Climate Change)

DESIGN AND OPTIMIZATION OF SOLAR PV/DIESEL GENERATOR HYBRID POWER SYSTEM FOR REMOTE TELECOMMUNICATION BASE TRANSCEIVER STATIONS IN NIGERIA

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DECLARATION

I, **Babalola Samuel Olatunde**, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signed: 24 - September - 2017

Babalola Samuel Olatunde **Date**

CERTIFICATION

This thesis has been submitted with my approval as the supervisor

Signed:  24 - September - 2017

Dr. M.G. Zebaze Kana **Date**

ABSTRACT

Due to the creeping growth of mobile telecommunication subscribers in cities and a compulsory demand for a telecommunication network in remote locations, Nigerian mobile network operators (MNOs) have begun to look for potential customers in previously unreached locations. Unfortunately, they are confronted with the prohibitive cost of powering remote off-grid macro base transceiver stations (BTS) with diesel generators and its associated environmental impacts. Nigeria is a country with huge potential for solar energy due to its closeness to the equator, but this resource has remained untapped for telecommunication sites despite its important benefits. Therefore, this study investigates the possibility of using a hybridized solar photovoltaic (PV)/diesel generator (DG) system (with battery) as a reliable, economical and environmentally suitable power source for off-grid micro BTS in the Nigerian rural areas.

In this thesis, HOMER (Hybrid Optimization Model for Electric Renewable) simulation tool was used to model an off-grid solar PV/DG/battery hybrid power system for a micro telecommunication site load. Five possible optimal system configurations (OSC) were presented from the simulation of the hybrid power system (HPS) amongst which hybridized solar PV/DG/battery was ranked as the most viable in meeting the objectives of this study.

The focal point of this thesis was to investigate the effect of varying climatic conditions (annual average solar radiations) on the OSC. To achieve this, six different annual average solar radiation values (4.33, 4.50, 4.76, 5.51, 5.81 and 5.97 $kWh/m^2/day$), which represent selected rural locations for the BTS across the geopolitical zones in Nigeria, are used as sensitivity variables with a hypothetic site which receives 5.68 $kWh/m^2/day$. Furthermore, three key aspects of the possible OSC for the regions were examined, namely; (i) energy output (renewable energy fraction), (ii) economic implication (net present cost), and (iii) environmental impact (carbon emissions). The results of this study showed the possibility of having at least 87% of Nigeria's remote BTS load demand from solar PV alone, which is a clean energy source. This helped to reduce the use of a diesel generator and consequently fuel consumption. It also provided important cost benefit to MNOs in terms of 47.3% drop in the net present cost when compared with the conventional diesel/battery system.

Although, the aim of this study is not to show the most viable location for the proposed hybrid power solution, however, the results obtained provides a valuable insight into the techno-economic implications of deploying solar PV/DG/battery HPS across the Nigerian remote off-grid sites.

Key words: micro base station, mobile network, optimal system, HOMER

RÉSUMÉ

En raison de la forte sollicitation des technologies de télécommunications mobiles dans les villes, et du besoin accru d'un réseau de télécommunication dans les endroits éloignés, les opérateurs de réseaux mobiles nigérians ont commencé à rechercher des clients potentiels dans des emplacements précédemment non atteints. Malheureusement, le coût prohibitif de l'alimentation des stations d'émetteur-récepteur de base hors-réseau (BTS) à distance avec des générateurs diesel et leurs impacts environnementaux associés rendent le système peu compétitif. Le Nigeria est un pays avec un énorme potentiel d'énergie solaire en raison de sa proximité avec l'équateur, mais cette ressource est restée inexploitée pour les sites de télécommunication malgré ses avantages importants. Par conséquent, cette étude explore la possibilité d'utiliser un système hybride photovoltaïque (PV)/générateur diesel (DG) (avec batterie) comme une source d'alimentation fiable, économique et respectueuse de l'environnement pour le micro-BTS hors réseau dans les zones rurales nigérianes.

Dans le présent travail, l'outil de simulation HOMER (Modèle d'optimisation hybride pour l'énergie électrique renouvelable) a été utilisé pour modéliser un système d'alimentation hybride photovoltaïque PV / DG / batterie hors réseau pour une charge de site de micro-télécommunication. Cinq configurations optimales possibles du système (OSC) ont été présentées à partir de la simulation du système d'alimentation hybride (HPS), parmi lesquels la PV hybride / DG / batterie a été classée comme la plus viable pour atteindre les objectifs de cette étude.

Le point focal de cette thèse était d'étudier l'effet de conditions climatiques variables (rayonnements solaires moyens annuels) sur la OSC. Pour ce faire, six valeurs annuelles moyennes différentes de rayonnement solaire (4,33, 4,50, 4,76, 5,51, 5,81 et 5,97 kWh / m2 / jour), qui représentent des zones rurales sélectionnées pour le BTS dans les zones géopolitiques au Nigéria, ont été utilisées comme variables de sensibilité Avec une valeur hypotétique de 5,68 kWh / m2 / jour. En outre, trois aspects clés de l'OSC possible pour les régions ont été examinés, à savoir: (I) production d'énergie (fraction d'énergie renouvelable), (ii) implication économique (coût actuel net), et (iii) impact environnemental (émissions de carbone). Les résultats ont montré la possibilité d'avoir au moins 87% de la demande de charge BTS éloignée du Nigéria de la PV solaire seule, qui est une source d'énergie propre. Cela a contribué à réduire l'utilisation d'un générateur diesel et par conséquent de la consommation de carburant. Il a également fourni des avantages importants aux MNO en termes de baisse de 47,3% du coût actuel net par rapport au système classique de diesel / batterie.

Bien que l'objectif de cette étude n'est pas de montrer l'emplacement le plus viable pour la solution d'énergie hybride proposée, les résultats obtenus fournissent un aperçu intéressant des implications techno-économiques du déploiement du PV solaire / DG / batterie HPS à travers la télécommande nigériane Sites hors réseau.

Mots-clés: micro station de base, réseau mobile, système optimal, HOMER

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LIST OF ABBREVIATIONS

ARPU: Average Revenue per User

BAT: Battery

BTS: Base Transceiver Station

CO_2: Carbon Dioxide

CRF: Capital Recovery Factor

DG: Diesel Generator

DOD: Depth of Discharge

EE: Excess Electricity

H: Hour

HESS: Hybrid Energy Storage System

HOMER: Hybrid Optimization Model for Electric Renewables

HPS: Hybrid Power System

KG: Kilogram

KWH: Kilowatt-hour

L: Liters

LPS: Loss of Power Supply

MNO: Mobile Network Operator

NASA: National Aeronautic and Space Administration

NE: North-East

NW: North-West

NPC: Net Present Cost

OPEX: Operational Expenditure

O&M: Operational and Maintenance

OSC: Optimal System Configuration

PV: Photovoltaic

REC: Rectifier

RF: Renewable Fraction

SFF: Sinking Fund Factor

SE: South-East

SS: South-South

SW: South-West

SOC: State Of Charge

SV: Salvage Value

TAC: Total Annualized Cost

$: US Dollar

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Chapter 1: INTRODUCTION

Outline

1.0 Introduction

This chapter presents an overview of the current situation of the Nigerian telecommunication sector. It focuses on the major inhibitor to the penetration of network coverage in rural areas and the importance of this study in addressing this issue. Finally, it provides the methodology employed in reaching the objectives of this study.

1.1 Background

The 2016 World Development Report identified access to telecommunication services in developing regions as a major contributor to job creation, increased labour productivity, development of businesses and entrepreneurship as well as other customer benefits [1]. This implies that individuals and organizations with access to mobile telecommunication services are at distinct economic and social advantages than the ones who lack it [2]. Particularly, the deployment of telecommunication infrastructures in rural areas has been recognized as a catalyst for improving their livelihoods and eradicating poverty [3].

However, whilst mobile telecommunication services continue to expand in most African cities, with important benefits such as 3G and 4G connectivity, mobile coverage does not exist in many rural areas [4]. Nigeria is identified as one of the countries which have a low penetration of mobile network coverage in remote areas [5] and this has led to a digital divide amongst the population. According to a Guardian news report released on the 28th June 2017 [6], Nigeria plans to add 40,000 telecommunication sites to strengthen its 4G services. The locations considered for this project are still the sub-urban and urban cities. Network deployment in rural areas has often been considered as uneconomical due to their low population density, the low average revenue per user (ARPU), uneasy geographic terrain and the prohibitive costs of powering macro site infrastructures in this locations [9,10,11]. The foremost of these is the cost of providing electricity [3].

A base transceiver station (BTS) is an essential part of a mobile telecommunication system which must be constantly powered for a link between mobile network operators (MNO) and end users [10]. They are also considered as the primary source of energy consumption in telecommunication systems. The cost of powering a BTS could make up a huge portion of MNO's income depending on the region and energy source [11]. This could be a defensible reason for MNOs to ignore rural areas.

Nevertheless, after a significant penetration in urban and suburban areas, mobile network operators have begun to experience a reduced growth in revenue due to market saturation [12]. At the same time, there is an intensified pressure on government bodies to include national coverage area in operation licenses given to MNOs [4]. For these reasons, MNOs must extend their coverage to previously unreached locations so as to increase their subscriber base and meet up with operational demands. This imposes an urgent need to solve the problem of electricity in a reliable and cost effective way.

1.1.1 Energy challenge in the Nigerian telecommunication sector

Poor power supply from the grid has been a major hindrance to telecommunication operations in developing countries [13]. In Nigeria, grid electricity has been characterized as unreliable in terms of inadequate power generation, weak and old transmission lines and highly inefficient distribution network system [14]. Overall access to the grid is about 55.2% and this is unevenly distributed across the country with urban areas having a larger share of 78% while the rural populace manages 22% [5].

According to Olatomiwa et al [15], from a total of 24,252 base transceiver stations in Nigeria, only about 11,692 have access to the national grid. Out of these, only 1,052 sites are able to get a daily electricity access of up to 18 hours while 1,169 have outage periods for up to 6 hours per day. The remaining fraction, which represents about 9,470 sites experiences up to 12 hours electricity outage per day [15]. Whilst cost consideration has limited the extension of the grid to remote areas, it has also been shown that even if this was possible, mobile operators in Nigeria would still require additional energy solutions to keep up with their services.

The problem of poor electricity supply from the grid and location of some BTS in regions without grid access has compelled most telecom operators in Nigeria to generate their own electricity using diesel generators as either the major or backup energy source. Figure 1.1 represents the distribution of cost for powering a typical on-grid BTS in Nigeria.

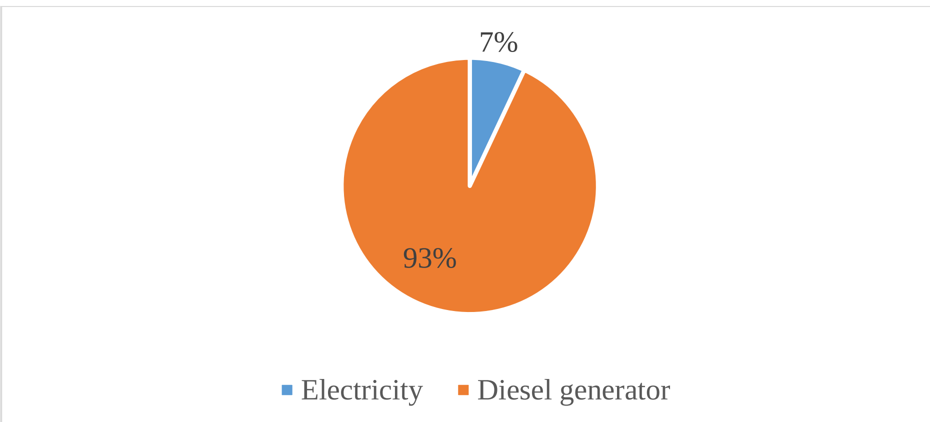

Figure 1.1: Power cost structure for on-grid BTS in Nigeria [5]

As at 2013, Nigeria had a total of 12,560 base stations in off-grid locations which are more than half of the total [5]. Collectively, these base stations consumed over 500 million liters of diesel [15]. In the *2010 IT News Africa* report [16], MTN Nigeria which is one of the country's foremost mobile telecommunication service providers spent at least $39.2 million in acquiring diesel generators for over 4,798 base stations and spent $1.63 million on oil and generator maintenance monthly. Usually, off-grid telecommunication sites have at least two diesel generator sets, one working continuously while the other alternates either weekly or at periods desired by the operators. These diesel generators are usually oversized to provide enough start-up power for the site load which usually has an air conditioner. Studies have shown that the size of a diesel generator directly relates to the amount of diesel fuel it will consume [5]. Therefore, for macro stations with large sized diesel generators, about half of mobile operator's income is spent on fuel [17]. This has discouraged the rate in which off-grid telecommunication base stations are deployed in the country. For most off-grid sites having diesel generator sets only, a reduction in the expenditure on fuel will certainly result in poor quality telecommunication services from mobile service providers.

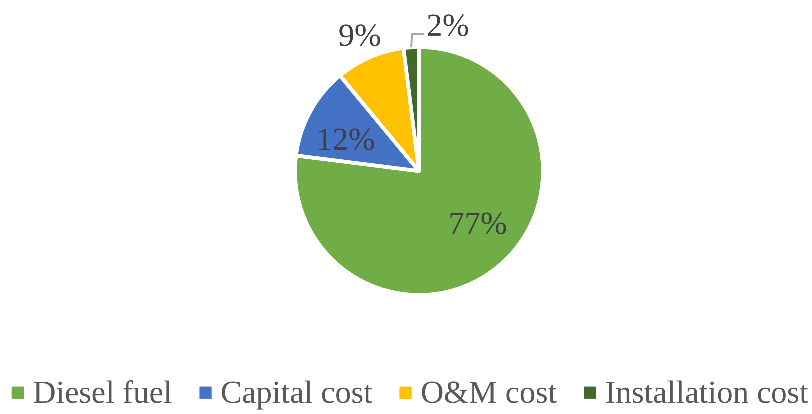

Figure 1.2: Net cost of operating a Diesel generator [18]

Despite that power generation from diesel generator provides a moderate initial investment (as shown in Figure 1.2), its application has significant disadvantages. Firstly, it creates a diesel dependent grid, which is a non-renewable and scarce energy resource. The energy generated is expensive due to the cost of getting the conventional fuel and the difficulty in transporting and storing it. Diesel-dependent telecommunication operators are also confronted with high operational expenditures (OPEX) which are a result of the fluctuating price of the fuel and lubrication of the generator parts. In addition, the emissions from diesel generators such as carbon dioxide, sulphur dioxide, and nitrogen oxide are constituents of global warming, environmental pollution which creates health issues [19]. The annual carbon emission from Nigeria's off-grid sites is estimated at about 1.3 million metric tons [20]. Furthermore, the efficiency of diesel generators is low. Practically, only about 30% of the fuel eventually gets converted into electrical energy, the remaining is lost as heat [21]. These impediments provide important reasons for telecommunication operators to reduce power demand at BTS as well as to consider cost effective and low-carbon solutions to power telecom infrastructures.

1.1.2 Potential for hybrid renewable solution in off-grid BTS in Nigeria

Recently, several attempts have been made in most countries to optimize energy cost at a base transceiver station by switching from indoor stations to outdoor units to eliminate the need for air conditioning system, installing energy efficient equipment and through the use of alternative energy solutions [3]. The use of renewable energy (RE) resources, in particular, have been proven as a viable approach to reducing the burden encountered with diesel fuel. This is because they offer clean, sustainable and reliable power at a low operating and maintenance cost. Amongst the renewable energy options, solar energy has been identified as the most viable solution for off-grid telecommunication power in Nigeria [16, 21]. This is because Nigeria lies along the equator and receives an abundant sunshine all through the year. Nigeria receives an average solar radiation of 5.25 kWh/m^2/day for about 6.25 hours. This ranges from 3.5 hours in coastal areas and 9 hours in the North. The average daily solar potential ranges from 3.5 kWh/m^2 in the coastal areas and up to 7 kW/m^2/day in the North [23]. Also, solar PV is the most available renewable energy technology in the Nigerian market which has common applications [5] and its price has reduced in the last years due to technology improvement and recent market saturation.

Although renewable energy (RE) resources offer cleaner and cost effective alternatives on the long run, they also have their shortcomings. They are location dependent resources which mean that their application depends on the amount of resources available in the area in consideration [15]. Furthermore, RE resources have higher initial cost and do not guarantee continuous electricity supply [21, 22]. Therefore, they also require an auxiliary energy source. This makes a hybrid power system (HPS) very essential.

Hybrid power systems like solar-diesel will offer important cost compensative advantage over diesel generator-only and drastically reduce the consumption of diesel fuels. The high initial capital cost of the renewable energy source is compensated by the low initial cost of the diesel generator and the high OPEX of a diesel generator will be compensated by low OPEX of the renewable energy source eventually [25]. Also, this hybrid power system can be made available anywhere in Nigeria.

Therefore, a solar photovoltaic (PV) energy system with diesel generator is considered to be an economically attractive and environmentally suitable alternative for MNOs compared to diesel only systems. On the long run, this hybrid power system will reduce the overall expenditure incurred in powering BTS. Furthermore, the addition of battery storage to the entire system will drastically reduce the consumption of the conventional fuel and boost the reliability of the energy system [15]. However, in order to significantly save on the cost of providing energy while ensuring that quality service is provided with the largest coverage possible, it is important that the components of the hybrid power system used in BTS locations be optimized effectively.

1.2 Problem Statement

The above overview provides a compelling evidence that lack of reliable and cost effective power supply are major impediments to mobile network penetration in Nigeria. However, as long as the extension of the grid to remote areas is termed uneconomical, it is very necessary to have a cheaper energy solution to power telecommunication infrastructures that would be deployed there so as to narrow the existing digital divide. Unfortunately, despite the highlighted issues surrounding the use of a diesel generator, it continues to dominate in all off-grid telecommunication stations in Nigeria, thereby, leaving alternative energy resources untapped for mobile telecommunication sites.

"Optimization" as used in the title is the process of evaluating the load and solar energy resource at a base station by using theoretically developed mathematical models in order to obtain cost effective and environmentally suitable power supply. Optimally sizing system components helps to guarantee the lowest investment with full participation of renewable energy technologies [26]. Optimal sizes of the components provide a vital information for financial commitment and eventually, it provides the most reliable design for an effective energy system which telecommunication base stations can depend on.

In order to evaluate the viability of the proposed hybrid power solution (Solar-diesel-battery) for off-grid telecommunication applications, this research will examine the following questions;

1. Can the adoption of solar energy resource provide adequate power to meet the demand of an off-grid micro BTS in Nigeria?
2. Which hybrid power system configuration provides the most economically viable solution, using net present cost (NPC in $) as the basis of comparison?
3. What size of the HPS components would guarantee that the load is met at the least possible NPC?
4. What is the effect of annual average solar radiation variation on the energy contribution, cost of the system (NPC in $) and pollution level (kg of carbon emissions)?

1.3 Significance of the study

It has been established that the amount spent on energy represents the most major expense incurred by the Nigerian mobile network operators. However, Nigeria's solar energy asset can be an important solution in reducing this cost if integrated to a diesel generator for a remote off-grid base station. Although, there are studies on the design of hybrid power systems for rural base transceiver stations in Nigeria, all of these have focused on macro BTS which may not be economical for areas which have less traffic as found in a typical remote region. Therefore, this study reported the design of a hybridized solar PV/diesel power solution for a deplorable micro BTS in remote regions. It is also an effort to show that solar PV/diesel/battery hybrid power system will be much more cost effective and constitute lesser environmental impact compared to the traditional diesel generators which are commonly found in off-grid BTS. Eventually, this study aims to encourage the adoption of hybrid solar energy power system for base stations in Nigeria.

1.4 Thesis objectives

General objective

1. To design a solar-diesel hybrid energy system with battery for remote base stations in Nigeria and optimally size its components for a configuration with low net present cost and reduced carbon emission while still ensuring that the system provides enough power.

The above objective can be further divided into the following specific research objectives:

i. Evaluate the peak load for a micro base transceiver station and the average annual solar radiation for six rural locations in Nigeria.
ii. Generate an optimized solar PV/diesel hybrid system design by using hybrid optimization model for electric renewables (HOMER) computer software tool.
iii. Show the financial and environmental benefits of using solar-diesel power system compared to other possible configurations across the six sites in Nigeria.

1.5 Scope of study

The areas under study include six rural locations which have been selected from the six geopolitical zones of Nigeria. They include; Umuoda (South-East), Ogbia (South-South), Wase (North central), Lisa (South-West), Chibok (North-East) and Bodinga (North-West). The annual average solar radiations for these sites are retrieved from HOMER based on their coordinates and are considered as sensitive parameters with that of a hypothetical site located at the central region of the country. The micro BTS load is developed based on a power model obtained from a literature source and is generalized for the locations studied. The investigation of the optimum hybrid power system for these areas is based on its net present cost (in $), fraction of renewable energy in the electrical energy output and carbon emissions (in kg). Finally, the optimal configuration is compared with the conventional diesel/battery system found in off-grid areas.

1.6 Thesis outline

This thesis is organized into 6 chapters. Following the introductory chapter, in chapter 2 we discuss the power technologies for telecommunication base transceiver stations. Chapter 3 provides the power consumption for the micro base transceiver station and solar resources for the locations considered in this study. The hybrid power system design and modeling are given in chapter 4 while the results of the thesis are presented and discussed in chapter 5. Finally, we conclude this work and provide some recommendations in chapter 6.

Chapter 2: POWER TECHNOLOGIES FOR BASE TRANSCEIVER STATIONS

Outline

2.0 Introduction

This section is dedicated to the various power technologies that are suitable for meeting the load demand of off-grid base transceiver stations. It provides information such as; the various factors that determine the load demand for a BTS, the main components that can be found in different types of BTS and the peculiar energy resources (including storage systems) that can be used in powering such stations in Nigeria. Lastly, it highlights previous research contributions made towards hybrid power technology for base stations and the important observations from them.

2.1 Power requirement for off-grid base transceiver stations

A BTS is an important telecommunication infrastructure used to facilitate wireless communication between subscriber devices (like mobile telephone, wireless Internet connection) and mobile network providers [19].

Typically, a BTS is made up of multiple transceivers (TRX) which control the transmission and reception of signals. The TRX in turn consists of a power amplifier (PA) which amplifies input signal, a radio frequency (RF) which is small-signal transceiver section, a base band (BB) for processing and coding, a DC-DC power supply, an air conditioning system (in some case) and a power supply input (AC or DC source) [19]. There are five different types of BTS based on the load components, power requirement and network coverage. These are: (i) macro station, (ii) remote radio head (RRH), (iii) micro station, (iv) pico station and (v) femto (or home) station [27].

The power requirement for a base transceiver station depends on a number of factors such as: (i) the position of the site (indoor or outdoor), (ii) its location (urban or rural), and (iii) the geographical region [28]. These variables make it practically impossible to generalize a load profile for all type of telecommunication stations. For example, an indoor base station usually requires air conditioning units in addition to other communication equipment existing at the station. This increases the load demand and size of the power system required compared to an outdoor base station. Also, rural and urban base stations differ in their subscriber base. In most cases, the traffic load in a rural BTS is much lower than in urban areas, therefore, a smaller station is preferred in these areas.

Lorincz *et al*. [29] classified the load components at a BTS into two, namely; radio frequency equipment, which is made up of the power amplifier and transceivers, and support system, which is comprised of the power converters, heating and/or air conditioning elements, analogue and digital signal processors, batteries and so on. Usually, the power amplifier and air conditioning equipment consume the largest share of energy provided to the station. Air conditioners are mostly required in macro stations. This adds to its overall power demand compared to the other BTS [27].

Based on a wider network coverage, macro stations are most preferred of all the forms of BTS and is mostly found in literature [25]. Remote radio heads are becoming more popular in modern base stations and offer advantages of no feeder losses through cables because the other equipment is hung close to the antenna interface, thus the equipment also becomes cooled by natural air. However, the disadvantage with this set up is the environmental reaction on the equipment causing corrosion. Likewise, micro, pico and femto stations, which are found in areas which have lower subscriber base do not require cooling therefore, their power requirement is lower than the other BTS.

The cost of powering a telecommunication station usually amount to a major share of mobile network operators' expenditure and this has been a burden [25]. Consequently, studies have highlighted certain energy efficiency principles to reduce costs of powering BTS, namely: (i) reduction of the energy consumption through sleep mode operation [30]; (ii) use of highly efficient technologies (like improved power amplifiers and highly efficient air conditioners) [31]; (iii) device-to-device (D2D) communications [32], and (iv) critical energy management [33]. A breakdown of the power consumption by components for the different BTS is shown in Figure 2.1.

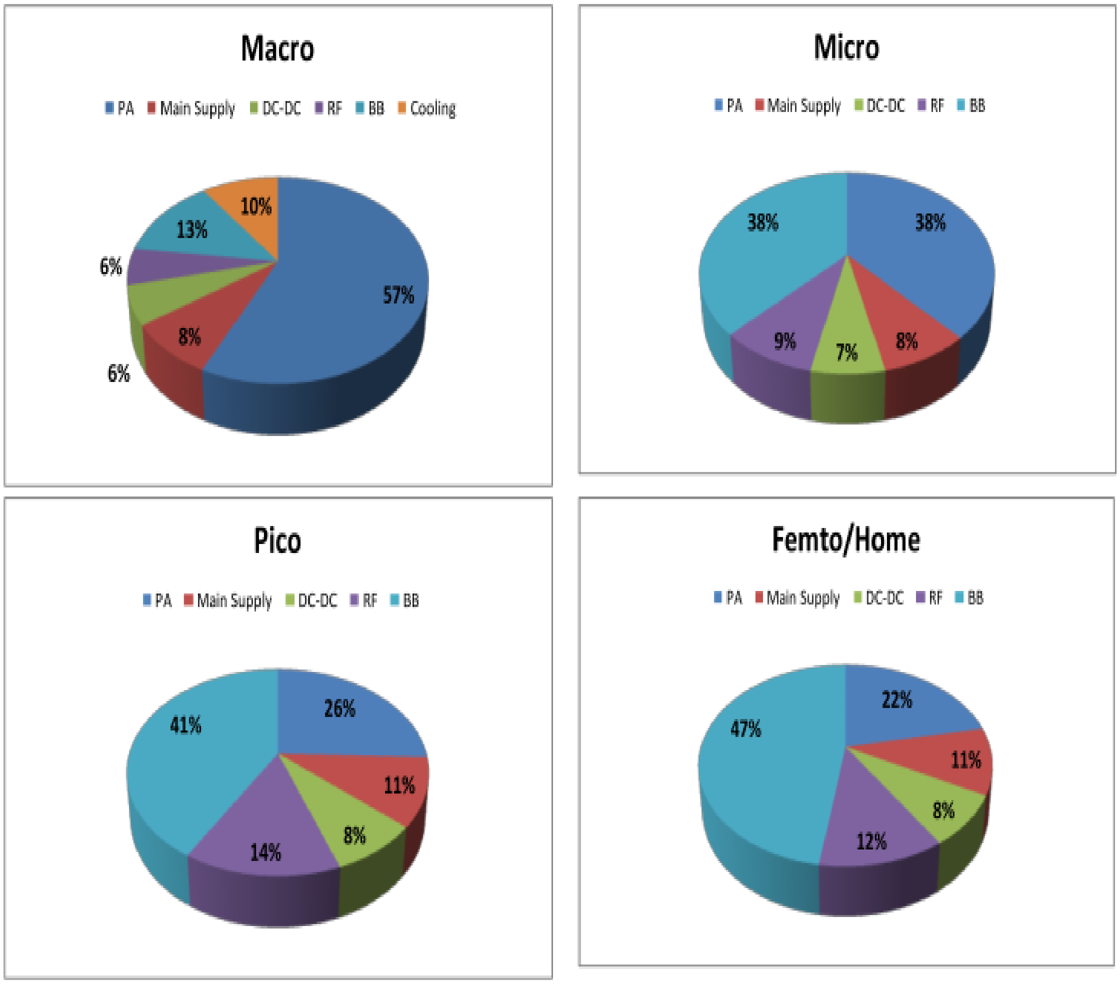

Figure 2.1: Power consumption breakdown for different BTS sites [27]

Macro BTS have a wider application compared with the other types of BTS. According to Aris and Shabani [25], there is approximately four million macro BTS worldwide and each consumes an average of 25 MWh. However, the deployment of micro BTS is very low [4]. Several kinds of literature have also tried to identify effective methods for obtaining the load demand for a BTS. An example of such work was carried out by Suarez *et al*. [34] which evaluated the energy efficiency and power consumption at component levels, access node levels, and network levels. Chapter three of this study provides the method used in estimating the power for the micro BTS.

2.2 Power solutions for off-grid base transceiver stations

An off-grid telecommunication base station is one which is not connected to the existing power grid. The major reason for this is usually because it is far from grid infrastructures and the cost implication of extending grid network to its location is high and unbearable [3]. Off-grid base transceiver stations are commonly found in remote areas [20].

Powering an off-grid telecommunication base station with a reliable and continuously available energy system is important in ensuring that mobile operators provide quality services to their subscribers without service outages. The power solutions for off-grid BTS discussed in this study include; diesel generator, renewable energy technologies with energy storage and hybrid power systems.

2.2.1 Diesel generators

Diesel generators are prominent technologies used in areas which have very limited grid access or experiences long electricity outages. They could be used either as back up or primary power supply source (standalone). The intrinsic advantage of diesel generators is that they can be started quickly and shutdown. This makes them a very dependable power source in meeting load requirements without delay.

The main functional units of a diesel generator are: (i) the synchronous generator, (ii) the diesel engine, (iii) the speed governor and (iv) the exciter which is coupled to an automatic voltage regulator (AVR). The mechanical power generated by the diesel engine is directly proportional to the rate of fuel consumption. Its speed is regulated by the speed governor which makes a decision by comparing the engine's working speed to its reference value. The exciter and AVR of the synchronous generator regulate the terminal voltage of the generator [35].

The size of a diesel generator depends on accurate estimations of the load it supports. This directly affects parameters such as; voltage, frequency and can cause distorted waveforms. If the diesel generator is under sized, it will trip off when the entire load is applied. To correct this, a generator with a larger capacity is thus required or a better alternator to improve the waveform [35]. Also, in common cases where the diesel generator is oversized, the performance of the generator set becomes affected as engine problem develops. Therefore, a diesel generator used in a telecommunication BTS site is normally sized based on the final load capacity it will power [25].

Usually, manufacturers of diesel generators recommend that the minimum permissible range of operation to be between 25% and 50% of its rated capacity [36]. Figure 2.2 shows that a considerable amount of fuel can be saved by allowing the diesel generator perform to its optimum capacity (high loads).

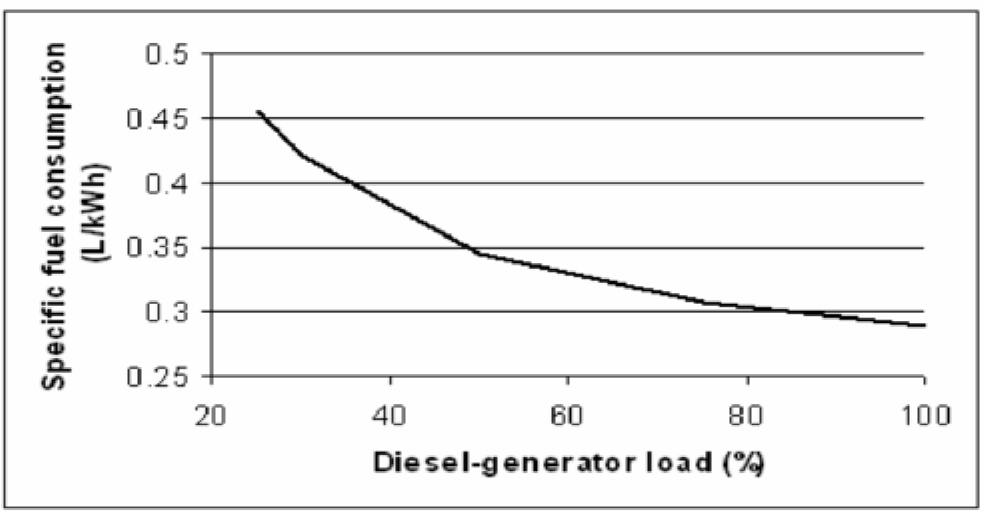

Figure 2.2: Diesel-generator fuel consumption characteristic [35]

Various researchers have pointed out the limitations of using diesel generators. NorthwesTel [37] in their publication reported the efficiencies of three remote telecommunication base site diesel generators installed in Northern Canada as only 19.4%, 20.6%and 19.8%. This means that while the generators consume much fuel, only a little amount become eventually converted into electrical energy whereas a larger portion is lost as heat. Neris [38] added that the mechanical performance of a diesel generator directly affects its rate of fuel consumption. Therefore, if a diesel generator is to supply high load demand, more fuel will be consumed which will increase the cost of fuel. The only way to reduce fuel consumption in such case is to allow the generator perform to its maximum capacity.

For a remotely located BTS, the cost of transporting diesel fuel via truck to this site usually increase the overall cost of fuel cost for the telecommunication station [1,8]. Also, in most countries, the availability and cost of diesel fuel are affected by importation costs and global fuel price variations. This occasionally leads to a complete shutdown of diesel powered BTS in the areas concerned.

Another limitation for the continuous use of diesel generators is that they have been associated with high level of air pollution. Consequently, an increase in off-grid base station powered by diesel fuel will automatically result in more emissions [8]. The *'Smart 2020: Enabling the low carbon economy in the information age report'* [40] showed that the global level of carbon emission will increase from 150 Mt in 2002 to 350 Mt in 2020 if compulsory actions are not taken to switch from conventional to green telecommunication networks. Likewise, the cost implication of running and maintaining a diesel powered telecommunication network site places a limitation on its continuous use [41]. This is due to the periodic break down that occurs with its use. Lastly, diesel generators are vulnerable to other challenges such as noise pollution, oil spillage, theft issues and a low life span. All of these makes it inevitable to have a clean and cost effective power option for BTS.

2.2.2 Alternative Energy Solutions

Alternative energy refers to energy sources other than fossil fuel. These energy sources are renewable in nature, that is, they cannot be used up and they do not use up the earth's natural resources, unlike fossil fuels. Examples are solar, wind, hydro and biomass. The use of alternative energy sources has become attractive in powering telecommunication base stations located in remote regions due to growing concerns about greenhouse and environmental issues, depletion of fuel reserve, increased cost of electricity and new regulation standards issued to telecommunication operators [42]. Goshwe *et al*. [22] highlighted that the choice of alternative power technology to be deployed in a telecommunication site depends on four important factors which are: (i) the resource available at the location, (ii) technology supply, (iii) it's commercial viability and (iv) acceptance in the market. The forms of alternative energy solutions for BTS are highlighted in the next paragraphs.

2.2.2.1 Solar energy

The energy from the sun (solar energy) is the most available alternative energy source and most suitable for distributed power generation, conveying power to where it is needed. This makes it a feasible solution for the telecommunication industry. Although it has certain challenges like the high initial capital cost of acquiring the system and the large space it occupies, solar energy offers an important advantage compared with other alternative energy solutions because it can be easily scaled to match any future rise in the energy demand due to its modular technology. Solar energy is particularly beneficial to Nigeria due to the country's position around the equator. It receives an average solar insolation of 5.25 kWh/m^2/day within an average of 3.5 hours in coastal areas to 9 hours of sunshine in the North. [5]. Therefore, solar technology is very applicable in Nigeria for telecommunication base stations.

2.2.2.2 Wind energy

The economic benefit of wind power technology can be realized in grid connected megawatt (MW) systems [5]. This is not the same for small scale energy generation which is characterized by high regular maintenance costs, low reliability due to unsteady wind speed thus creating investment risks. However, significant OPEX savings could be made by combining wind with solar technology or any other alternative energy source. Wind technology is not a generally feasible energy solution in Nigeria due to the uneven distribution of wind speed. Only a few areas in the northern part of Nigeria can be said to be suitable for wind applications because they receive wind speed of up to about 4 to 5.1 m/s [5]. Other areas, except offshores, receive much lower wind speed necessary for the rated power of a wind turbine which contributes to the poor market for wind technology in the country.

2.2.2.3 Fuel Cell

Fuel cell technology is among the important energy innovations which are recently attracting attentions due to the clean and widely available hydrogen fuel it uses. However, its drawback lies in its high initial capital cost, availability and supply of hydrogen fuel and the high cost replacing it which in cost case can be about 30% of the capital cost within 5 to 6 years [5]. Nevertheless, it could be a viable option for countries without reliable fuel supply chain.

2.2.2.4 Pico hydro

The potential for pico hydro based power for telecommunication stations is yet to be determined in Nigeria despite the current development of hydro technology in the country [5]. Hydro power is the most developed clean energy source in the country, but its major application has been for large scale (MW) grid connected purposes. The cost of constructing a pico-hydro power station in Nigeria is still unknown. In addition, pico hydro technology can only be utilized by telecommunication site close to a water body. These limitations make it currently unattractive in powering off-grid telecommunication stations for this study [5].

2.2.2.5 Biomass

Biomass is a widely available resource and its deployment as a green energy source has grown due to the innovative use of its various forms. Although it falls under the least choice of green technology for BTS as ranked by GSMA [5], it provides a good opportunity for small scale distributed energy generation. The limitations of using biomass technology lie in its operational complexity, sustainability, scalability and sometimes difficulty in integrating the energy generated to its point of need [22]. Nigeria is considered as a country with moderate potential for biomass as a source of electricity [5]. Traditional use of biomass resources like wood fuel for cooking dominates its applications in Nigeria.

2.2.3 Preferred choice of alternative power – Solar energy

Table 2.1 summarizes the discussed alternative energy solutions and the challenges impeding their application in off-grid TBS in Nigeria.

Table 2.1: Summary of alternative energy solutions for off-grid telecommunication sites in Nigeria [13]

	Availability	**Reliability**	**Market Acceptance**	**Supply chain**	**Policy Framework**
Solar	Very Good	Good	Good	Good	Yes
Wind	Poor	Poor	Poor	Good	Yes
Fuel Cell	Poor	Good	Poor	Poor	No
Pico hydro	Poor	Good	Very Poor	Very Poor	Yes
Biomass	Satisfactory	Good	Poor	Poor	Yes

Solar energy offers the most advantage of all the energy solutions because Nigeria has a huge solar potential and solar photovoltaic panels have recently been penetrating the country, thus the materials are readily available for use. According to [5], deploying solar energy technology in 10,890 TBS would save up to N 3.168 billion operation expenses and significantly reduce diesel consumption by about 76% from its current level. Also, a solar-diesel hybrid system is estimated to have a payback period of about 2.7 years with a capital investment of N 78.375 million per site where the generator runs for just 4 hours per day [5].

However, the use of renewable energy resources for powering telecommunication base stations has not started in Nigeria. Literature [5] identified two potential challenges limiting the adoption of alternative power for telecommunication sites. The first issue highlighted is that telecommunication industries have nonchalantly created a diesel economy as a result of their over dependence on diesel fuel. Therefore, it would be difficult for them to easily embrace green energy solutions and do away with the technology they have been used to. Also, theft issues have been a major problem associated with the domestic use of RE sources like solar PV in the country. Thus, more security measures would be needed at off-grid sites otherwise the OPEX will certainly increase. Another drawback with solar energy technology is the required space for its installation.

2.2.4 Solar photovoltaic (PV) power generation

A PV power system is a method by which electrical power can be generated through the conversion of solar radiation into direct current (DC) electricity using semiconductors [43]. Solar cells are the basic components and building blocks in the PV power system. They are commonly made of silicon material.

Basically, a solar cell is composed of two types of semiconductors, namely; (i) n-type semiconductor and (ii) p-type semiconductor. The n-type semiconductors are produced by doping intrinsic semiconductor crystals with pentavalent impurity atoms (dopants), such as phosphorus, to generate free negatively charged electrons. Similarly, p-type semiconductors are produced by doping trivalent impurity atoms, such as boron, to intrinsic semiconductor crystals to generate positively charged hole (due to electron vacancy). By bringing the n-type semiconductor in contact with the p-type semiconductor, the electrons (negatively charged ions) in the n-type semiconductor migrates to fill up the holes in the p-type region, while holes (positively charged ions) migrates towards the n-type region. Thus, at the junction between these two materials, a layer of static negative ions is formed close to the p-type semiconductor while a layer of static positive ions is formed close to the n-type semiconductor. After sufficient formation of the layer of positive and negative ions on each side, a barrier is created which inhibits more electrons and holes from diffusing further due to the repulsion of charges. This built-in layer created, called the p-n junction or the depletion region, acts as an internal electric field. This process is illustrated in figure 2.3.

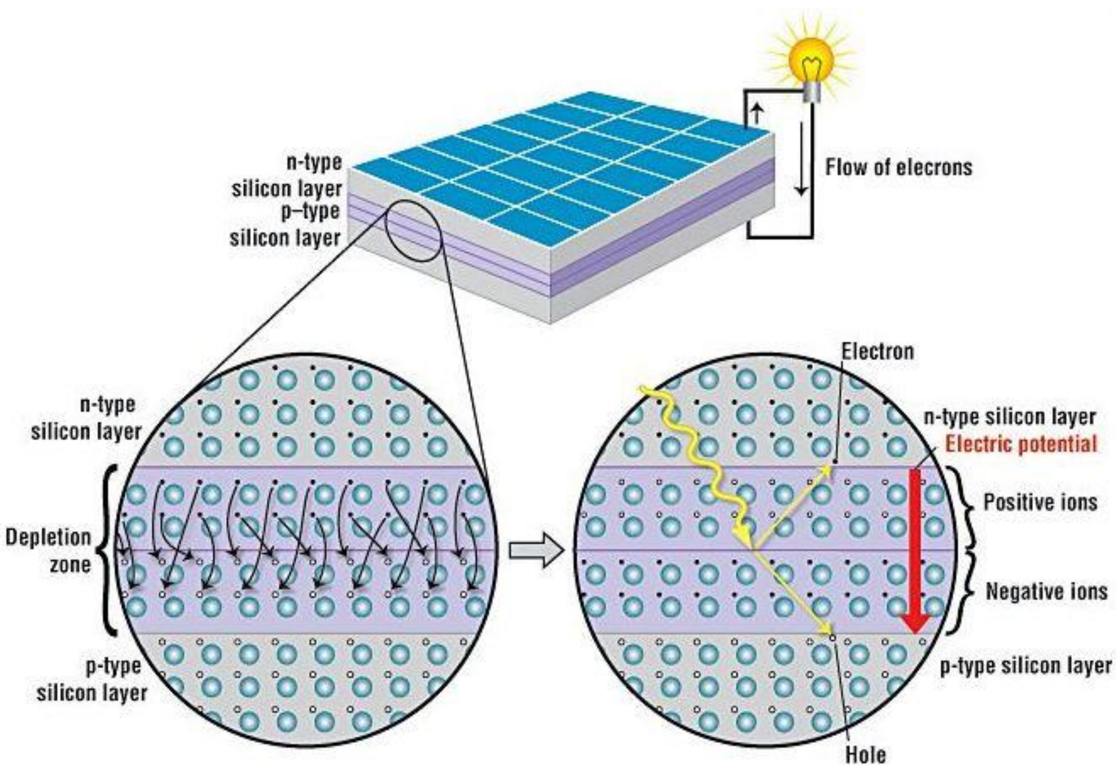

Figure 2.3: Electricity production in a solar cell [44]

When electromagnetic radiation from the sun hits the cells, a certain portion of it (called photon) is absorbed within the material to eject electrons thus creating holes in the process. Through the help of the existing electric field, the electrons will be driven towards the n-type layer while the holes migrate towards the p-type layer. By connecting a metallic wire between the n-type and p-type layers, the electrons will migrate from the n-type layer to the p-type layer through the wire by crossing depletion region. This is called the photoelectric effect and the influence of fields allow the flow of electrons in a direction to generate electricity.

2.2.4.1 Solar cell I-V characteristic curve

The electrical characteristics of a PV cell depend on the relationship between the current and voltage as indicated on a solar cell I-V curve as shown in figure2.4. This curve is based on existing conditions of irradiance and temperature. Essentially, the intensity of the solar radiation (called Insolation) that hits a solar cell influences the current produced while temperature rise reduces the voltage of a cell. Other parameters used in describing the performance of a solar cell are; power output, which is a product of current and voltage, efficiency and fill factor.

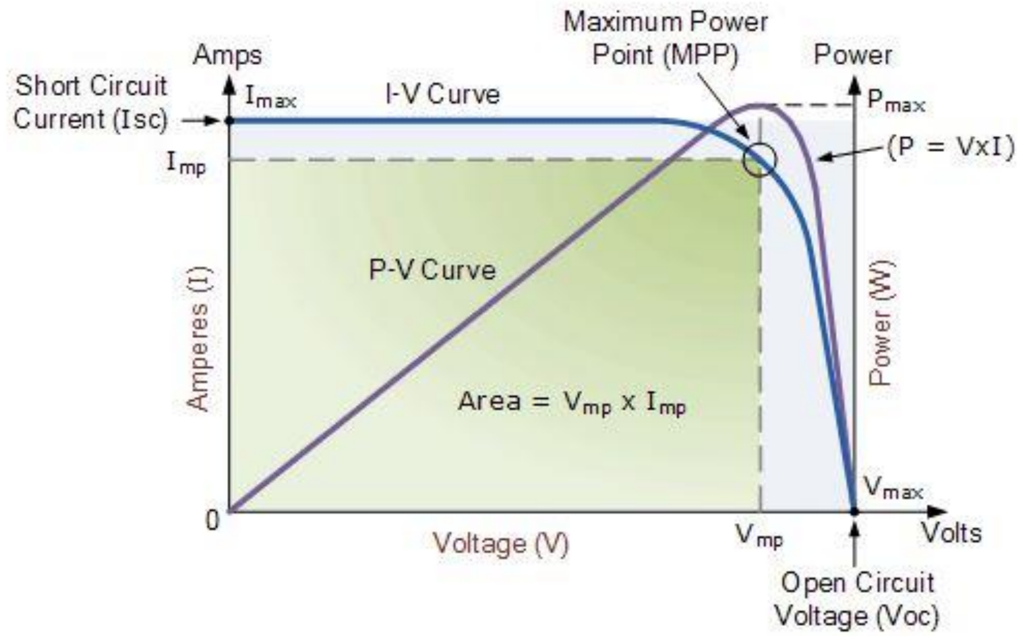

Figure 2.4: Solar cell I-V characteristic curve [45]

The I-V characteristics of a typical solar cell under normal condition are provided in figure 2.4. At open circuit (when a load is not connected), the current is at its minimum (zero) while the voltage across the cell is at its maximum, called the open circuit voltage V_{OC}. On the other extreme case, when the solar cell is short circuited, the voltage across the cell will be at its minimum (zero) while the current attains its maximum value, called the short circuit current, I_{SC}. The power produced by a solar cell is a product of the current and voltage generated. Normally at I_{SC} and V_{OC}, the power produced by the cell is zero. Therefore, the ideal operation of a solar cell is at an optimum point where the combination of the maximum current, I_{mp} and maximum voltage, V_{mp} generates the maximum power, P_{max} from the solar cell. This point is called the maximum power point (MPP). The efficiency of a solar cell is the ratio between its maximum power output to its solar irradiance at standard conditions (1,000 W/m^2). Fill factor represents the ratio between the cell's maximum power output to the power resulting from the multiplication of I_{SC} and V_{OC} [45].

Due to their low voltage and power, solar cells are usually connected together either in series or in parallel to give a specific voltage and power in a solar panel. By connecting solar cells in series, current increases, while those connected in parallel only increase in their overall voltage. A group of connected solar cells forms a module, while modules connected either in parallel or series arrangement form an array [46].

2.3 Energy storage systems

Energy storage systems (ESS) play a vital role for renewable energy sources in order to guarantee good power quality and bridge the gap between periods of low energy output from the intermittent source of power and high energy demand [11,16]. The power output from renewable energy systems like wind turbine depends on the speed of the wind available at a time so also does solar PV system's performance vary according to seasons, weather and climate [48]. Therefore, to make renewable energy resources a reliable primary source of energy, it is important to have a backup storage facility.

In telecommunication applications, energy storage has also been combined with conventional diesel systems to reduce fuel consumption and the period of operation of the diesel generator. Storage systems are also essential for storing surplus energy when energy supply surpasses demand and this is released when the demand outgrows the energy generated [49].

Energy storage systems have become very vital in remote BTS because the components rely on a continuous power supply in order to help mobile operators maintain a link with their subscribers. According to studies by European Telecommunications Standards Institute (ETSI) technical committee [42] and Yekini Suberu et al. [50], the common forms of energy storage technologies are batteries, supercapacitors, fuel cells, Pumped Hydro Storage (PHS), flywheels, Compressed Air Energy Storage (CAES), capacitors and super magnetic energy storage (SMES). Energy storage technologies can be distinguished according to energy capacity, time of service and transient response for their operation [36]. This is clearly shown in figure 2.5.

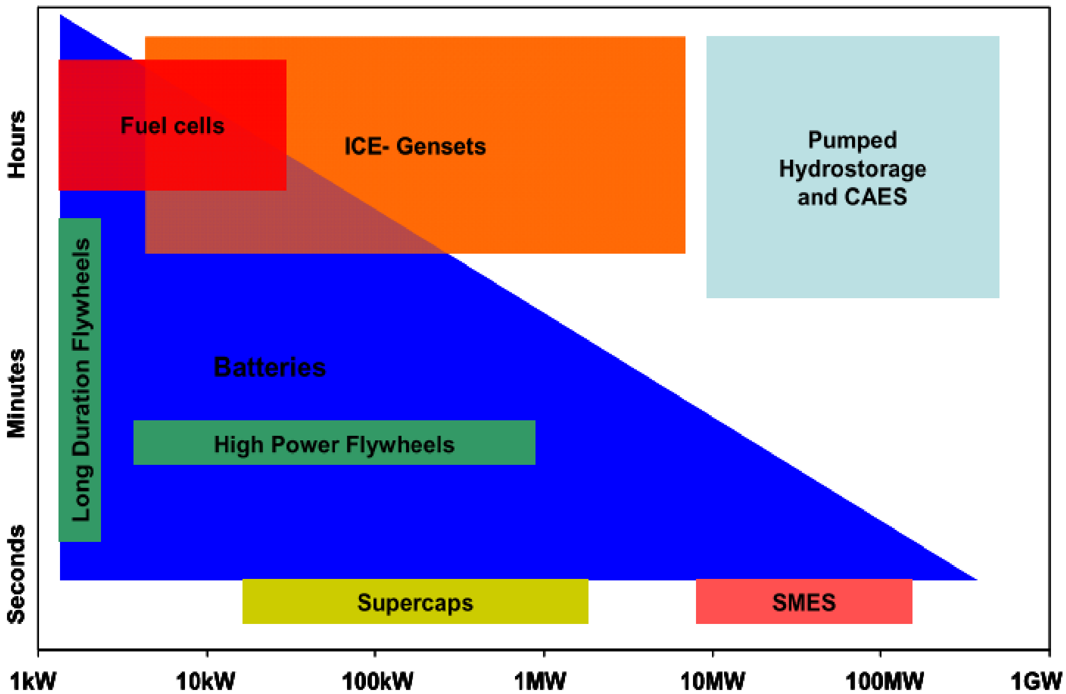

Figure 2.5: Classification of energy storage system according to energy output (Source ETSI) [42]

The application of storages has been studied by Bezmalinovi *et al.* [51] and Panahandeh *et al*. [52]. Feroldi and Zumoffen [53] focused on the application of fuel cells in renewable energy systems. The use of hybrid energy storage consisting battery and hydrogen was studied by Torreglosa *et al*. [54]. Yekini Suberu *et al*. [50] extensively examined the use of pumped hydro storage and all other forms of energy storages in their literature with emphases on the advantages and likely hindrances of using each storage technology.

Of all the storage systems, batteries have been given much consideration in powering off-grid telecommunication sites, especially in hybrid energy systems. This is because they can be tailored easily to meet any load demand at any location. Also, they are characterized by a high level of reliability and availability. In addition, batteries are the most economical storage solution. Therefore this paper focuses on battery storage technology and role in a hybrid solar-diesel system for off-grid telecommunication stations.

2.3.1 Batteries

Batteries belong to the classification of energy storage systems known as electrochemical storages [18,19]. There are two types; primary and secondary. Secondary chemical cells otherwise known as rechargeable batteries are storage devices that convert stored chemical energy into electrical energy (during discharge) and reverses electrical energy into chemical energy to regain its charged state [49]. The basic operation and components of a typical battery are described in figure 2.6.

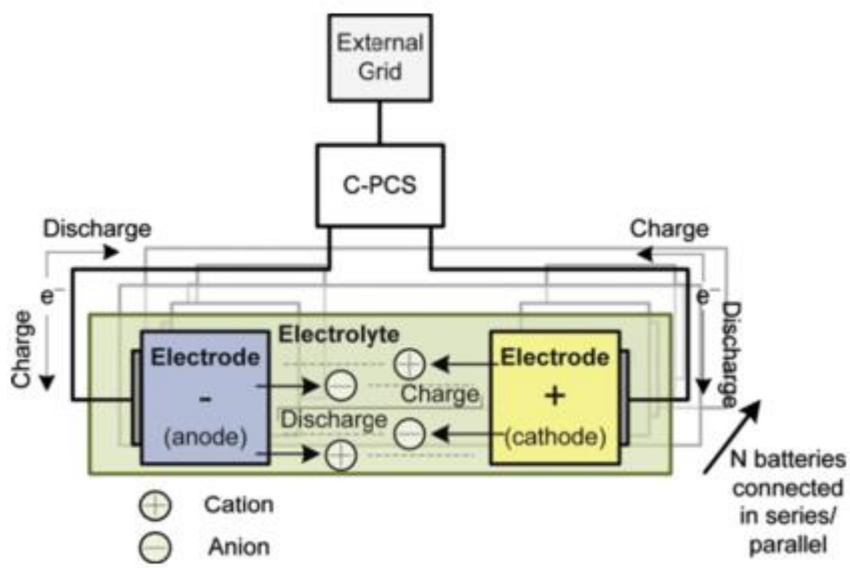

Figure 2.6: Components and operation principle of a typical battery storage system [55]

Batteries have a high energy efficiency and they deliver energy instantaneously. This makes them very reliable in storing energy. Their performance and life span strongly depend on their service operation and environmental conditions [42]. Aris and Shabani [25] gave two classifications for batteries in their literature, namely; low-temperature internal storage batteries and high-temperature external storage batteries. Low-temperature internal storage types of batteries are best suited for an environment with room temperature (i.e., 25^{o}C) therefore their performance is drastically affected when they are used in extremely high or cold environments. The common examples of this category are lead acid (PbO2), nickel cadmium (NiCd), Lithium ion (Li-ion) and Nickel metal hydride (NiMH) batteries. High-temperature external storage batteries are sodium sulphur (NaS), sodium nickel chloride (NaNiCl) and redox-flow batteries [50].

The lead-acid battery is far the oldest of the battery technologies. It is also the most matured and most affordable of the types of batteries [56]. This explains why it leads in most commercial applications. Lead acid-batteries are also highly reliable and efficient (70-90%) [57]. They have a lifespan of about 5 years or 250-1000 charge/discharge cycles which also depends on their depth of discharge (DOD) [50]. However, they have low energy density and low cyclic capability. Also, after some period of usage, the concentration of sulphuric electrolyte reduces and water is produced. This calls for periodic maintenance [50].

Ni-Cd batteries offer more advantage than lead-acid types because they have higher energy density, longer life cycle, and lower maintenance. However, they are more expensive and contain toxic heavy metals. Lithium batteries have wider applications for both low and high power devices as well as in portable electronics and telecommunication gadgets. Their key benefit is their higher energy density and efficiency. Other important benefits of lithium ion batteries are quick charge compared to their counterparts, low self-discharge and they can be produced in small sizes and weights while still delivering enough energy for load demand. However, they are expensive and their production costs depend on the lifetime required.

Despite the important role batteries play in mitigating the variability of renewable energy resources, some studies have been able to recognize some limitations with their use. For example, Panahandeh *et al.* [52] stated that batteries alone cannot be used for long-term storage because of their low energy density compared with other storage technologies. Hence, there is a need to have combinations of batteries and/or a hybrid storage system. The limitation of this is an increase in the cost of the energy storage systems. An example of hybrid energy storage system (HESS) comprised of battery and hydrogen was reported by Garcia et al. [54] with the use of supervisory control based on fuzzy logic. According to their work, wind turbine and solar PV operates to full power point and battery-hydrogen subsystem acts as the storage medium. The benefit of this was shown in the extended lifespan of the entire energy system, which is 25 years and cost reduction of up to 13% of other simpler energy systems [54]. However, having a hybrid storage system may not be an affordable solution because it will further increase the capital cost of powering a telecommunication station.

Generally, the energy density of batteries increases with temperature and decreases as their rate of discharge increases. Therefore, to increase their life cycle especially when combined with intermittent power sources like wind and/or solar for constant power, reference [42] stated that cyclic batteries should be adopted. Through this, the batteries are recharged by the sources delivering power to the load without interruption before the batteries are used to power the load at peak demands.

2.4 Hybrid power systems for off-grid base transceiver stations

The concept of hybrid power system implies combining two or more types of electricity generating sources such as renewable energy sources (e.g. solar photovoltaic panels, wind turbine, micro-hydro) and/or fuel generators. This helps to realize a reliable and environmentally suitable energy solution at a cheaper cost. The use of hybrid power systems are also appropriate ways of reducing dependence on expensive fossil fuels and are clean solutions for power generation [28, 29]. The reliability of this system is further enhanced by adding a storage system such as a battery as mentioned earlier. Hybrid power system uses an advanced system control logic (otherwise called dispatch strategy) to manage the energy sources (renewable or fuel generator) by triggering either of these to action when needed [13]. The common hybrid configurations applied in telecommunication industries are DG-battery, Solar PV-Battery, Solar PV-DG-Battery, Wind-DG-Battery, Solar PV-Wind-DG-Battery [60].

2.4.1 Diesel generator/battery hybrid system

This is the common source of power supply in traditional off-grid telecommunication sites. The addition of batteries to a diesel generator is used to reduce dependence on the costly diesel fuel and high OPEX that results from the continuous use of diesel generators. Figure 2.7 provides the system configuration for a DG/battery hybrid configuration.

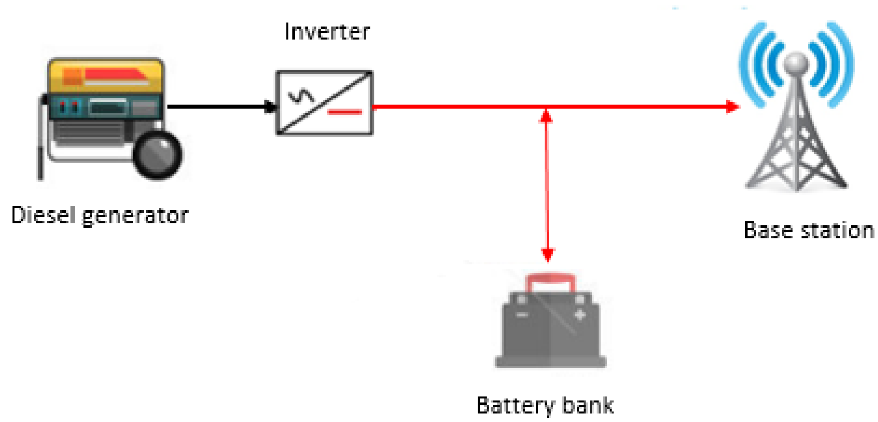

Figure 2.7: Configuration for DG/battery hybrid system for off-grid BTS

A study conducted for an off-grid telecommunication site in Iraq by Jasim and Abdul-Hussain [20] reported that the addition 32 batteries to a diesel generator of 5.5

kW capacity reduced the cost of energy (COE) for the entire system from a cost of energy (COE) of 1.D 874/kWh to I.D 798/kWh. Likewise, the total annual diesel fuel consumed reduced from 7,804 L to 5,902 L.

A similar study conducted by NorthwesTel [37] reported that a diesel-battery system would be more effective if incorporated in a cycle/charge scenario in which a diesel engine operates at its full power to supply a bank of batteries. When the batteries have been fully charged, the diesel engine is turned off and the battery supplies the DC power to the telecommunication equipment while a rectifier supplies AC to other auxiliary equipment like fans and lights [61]. Sugden and Drury [61] added that a cycle/charge scenario could save up to 50% of diesel fuel rather than continuously running a diesel generator.

2.4.2 Solar PV/ Diesel generator hybrid system

The arrangement of the components of a solar-diesel hybrid system is illustrated in figure 2.7. Due to the intermittency of solar energy, battery storage is added to increase its reliability. During peak sunshine periods, the energy produced by the solar panels is first stored in the batteries and extracted when solar radiation is low. The diesel generator is only used when the output from solar energy and battery are unable to provide the required load demand. The system configuration is shown in figure 2.8.

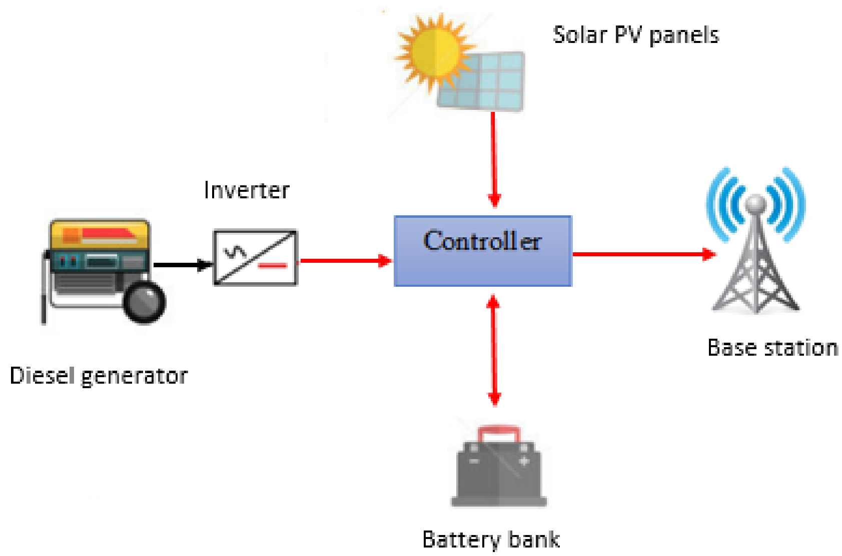

Figure 2.8: Configuration for solar PV/DG/battery hybrid system for off-grid BTS

The addition of solar PV to a conventional diesel generator system reduces the dependence on the fossil fuel and the operating time of the generator. Also, adding solar PV to the traditional diesel-battery system helps in reducing the battery size which also reduces OPEX in running the energy system. A solar-diesel hybrid system offers a cost compensative advantage over diesel system in that the high capital cost of solar PV is balanced by the low capital cost of the diesel generator while the high OPEX of the diesel generator is offset by low OPEX of solar PV [25]. This makes it a more viable energy solution for telecommunication stations in developing countries and it is the focus of this research work.

Also, a study carried out by reference [20] for a hybridized PV/Diesel system to power a remote site in Iraq focused on the economic and environmental impact of adding solar PV to the existing diesel generator-battery system at a base station. It was observed that the addition of 8 kW PV panel to 5.5 kW diesel generator on site reduced the cost of energy (COE) from I.D 874/kWh to I.D 795/kWh and the annual fuel consumption from 7,804 L to 1,050 L. In addition, the high capital cost of the solar panels was compensated for by the low capital cost of the diesel generator and the OPEX for the PV system was almost negligible compared with that of diesel generator.

In another study done by Faruk *et al*. [59], the reliability and mean time between failure (MTBF) of a solar-diesel (with battery) system was compared with a conventional power system for a mobile cell site. The results of the study revealed that the hybrid system would satisfactorily provide power for about 23 years before it wears out. After 15 years of service, the reliability of the hybrid system was still as high as 80%. The authors further investigated the MTBF for a standalone solar power system and realized same reliability at 15 years of performance but a longer lifespan of up to 70 years. In contrast, the reliability of a diesel generator-only system reduces to 60% after just 5 years of operation and completely breaks down at 8 years.

A HOMER based study on the use solar-diesel for BTS in Nigeria was carried out by Anayochukwu and Nnene [13]. In their work, a control system for hybrid PV-diesel with battery storage was developed to coordinate the energy source that will power the load at a specific time. The result of this work showed that solar energy was able to provide up to 45% of the energy demanded by a BTS in the central region of the country.

Although these works are quite similar to this study, however, this study seeks to design a solar-diesel power solution for a smaller BTS station which can serve a rural population. Furthermore, it will compare the performance of solar power system under different climatic conditions and geographic locations.

2.4.3 Solar PV/Wind hybrid system

A hybrid system composed of solar PV and wind turbines makes up a completely clean energy source for BTS. Another benefit of such system is that the resources compensate each other to meet the load demand [62]. This is because both high wind speed and solar energy may not be available at a particular time. However, the initial cost of having this system might be too high for telecommunication operators to cope with. Also, having a completely renewable energy source may not guarantee a reliable energy solution because of the variability of solar and wind energy. Hence to over this, it is important to have a battery storage with the RE set up. An illustration of how this is incorporated is provided in figure 2.9.

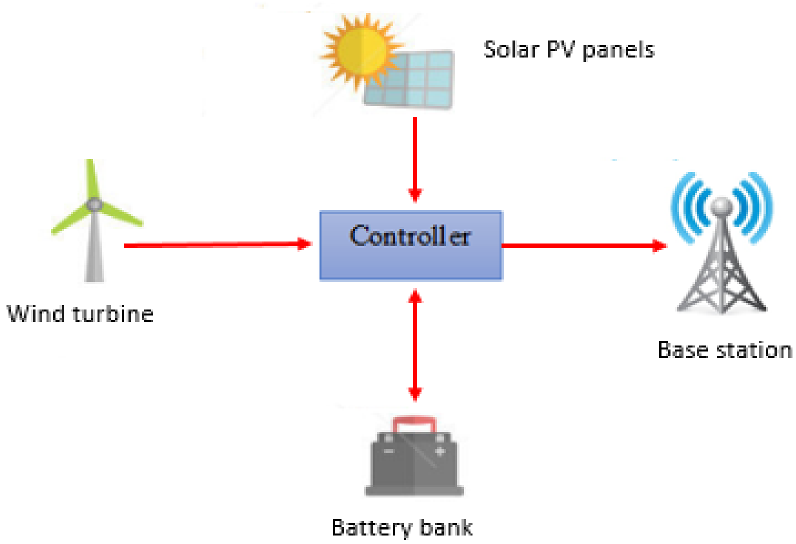

Figure 2.9: Configuration for hybrid Solar-Wind system in an off-grid BTS

Several authors have researched the application of hybrid solar PV-wind system for telecommunication base stations, and a few of them will be discussed. A research study was conducted by Belkhiri and Chaker [63] to show the performance of hybrid PV-wind in four remote zones considered for off-grid telecommunication stations in Algeria using HOMER simulation tool. The optimal results obtained from the simulation showed that more components of the hybrid system would be needed for a telecommunication site located in a coastal area which implies more capital cost whereas BTS located on high plateaus would be cheaper. The zones which gave the lowest capital cost are located very close to the Sahara, where the hour of sunshine is more and solar radiation is very high. For each case study, only a wind turbine is needed while solar PV and battery are optimized to provide a cost efficient energy system. Eventually, the results showed that solar energy has a greater influence on the viability of the project than wind.

Another study carried out by Notton *et al.*[64] estimated the optimal dimensions of a standalone PV/wind system that would adequately meet the energy demand for a remote customer. In this study, five sites located in Corsica Island were considered which were grouped as either windy or non-windy site. The results from the optimization showed that cost of energy depended on the quality of renewable energy available. For the windy sites, over 40% of the overall load is provided by the wind turbines, whereas non-windy regions require only 20% wind participation in its energy mix. However, since the solar radiation for the sites is the same, the COE of the system depends more on wind energy potential [64]. Nevertheless, due to the variability of wind speed, a reliable power may not be guaranteed by depending on it alone or oversizing wind turbines in the hybrid mix. Hence, the authors concluded that a hybrid solar-wind-battery would be an economical and a reliable solution for the sites.

Yang *et al.* [65] used hybrid solar wind system optimization sizing (HSWSO) model to optimize the capacity sizes of the components of a hybrid solar-wind-battery power system for a 1 kW communication station load based in China. The model is made up of three parts, which are; the model for each component of the hybrid system, a model of Loss of Power Supply Probability (LPSP) and model of the levelized cost of energy. The results obtained from the simulation showed that LPSP will reach zero only when the rated wind power is up to 10 kW and the number of PV modules is 270 (50 W capacity each) with one-day storage battery bank. Furthermore, the authors reported that with a three-day battery bank, LPSP will reach zero sooner with fewer PV modules and a wind turbine with smaller capacity [65]. This clearly showed that a hybrid solar PV-wind system would require more battery size to meet the demand of the site with less failure. In terms of cost, the configuration with fewer batteries seems to be an optimal solution because batteries are quite expensive and have a short lifespan. However, this system may not be 100% reliable when compared with a two-day storage battery bank. An alternative solution for the reduction of battery size is to increase the size of the solar PV as well as the capacity of the wind turbine. Regrettably, this does not make the system totally reliable. All of these shows that power reliability is a major drawback surrounding the use of a solar PV-wind-battery system and this issue cannot be addressed without increasing the initial capital cost of the system.

2.4.4 Solar PV/wind/ diesel generator hybrid system

The use of solar-wind-diesel hybrid system provides a much more reliable solution for sites located far from conventional power system compared to standalone solar-wind systems [66]. In this case, the primary source of electrical energy comes from solar and wind energy while the diesel generator is used to meet peak load demands as well as during periods of deficit energy from the renewable energy sources [1,28]. The advantage of this set up is that the diesel generator reduces the size of the solar-wind components while the solar-wind components help to reduce the cost of running diesel generators by reducing its operating period. A typical arrangement of the components in a solar-wind-diesel hybrid system is shown in Figure 2.10. In some applications, batteries are added to this system to further increase its reliability and reduce the dependence on diesel maximally.

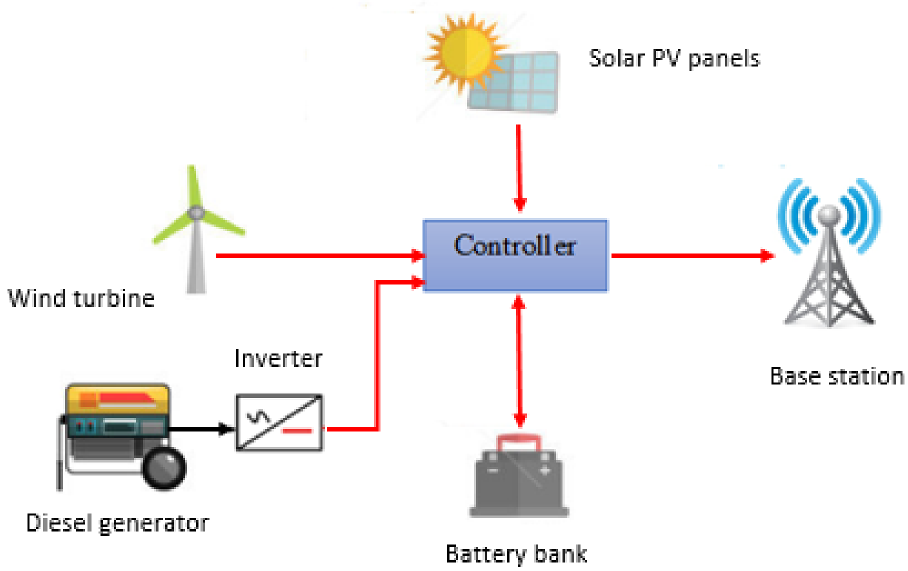

Figure 2.10: Configuration for solar-wind-diesel system for off-grid BTS

A deterministic approach (or direct algorithm) was used by Belfkira *et al.* [58] to optimally size a standalone wind/PV/diesel system for a remote area in Dakar, Senegal. The developed methodology was based on the use of long-term wind speed, solar radiation and ambient temperature obtained from the site. Hybrid wind/PV/diesel system including battery storage was compared with a case where batteries were absent. The result obtained from the study showed the influence of the site's energy potential (wind and solar radiation) and load profile on the optimum configuration of the hybrid system based on cost. Also, the addition of batteries to a standalone wind/PV/diesel hybrid system was reported to give a more techno-economic solution to meet a 15 kW energy demand which would reduce the operating hours of the diesel generator from 66,020 hours to 24,020 hours within a period of 20 years.

However, Olatomiwa *et al.* [67] used HOMER software tool to show that a PV/diesel/battery hybrid system is more feasible for remote telecommunication towers in Nigeria than a PV/wind/diesel/battery hybrid system in terms of cost comparison. Another similar study carried out by Salih et al. [68] on the optimal configuration of PV/wind/diesel/battery hybrid energy system for remote BTS in Sudan also using

HOMER software provided three different system configurations (PV/wind/diesel/battery, PV/diesel/battery and diesel/battery). Due to the low wind speed available at the location, the high cost of wind turbines, difficulty in installing wind turbines in remote roads as well as minimal technical expertise, PV/wind/diesel/battery configuration was ranked least amongst the options. PV/diesel/battery configuration was suggested as the optimum solution for the area in consideration based on 92% solar PV participation which reduced the diesel input to just 4%. Although diesel/battery system provided the least initial capital cost ($16,308), it had the highest NPC because of its high operating cost and least performance compared with other configurations.

Chapter 3: ESTIMATION OF POWER AND SOLAR ENERGY RESOURCES FOR THE BASE TRANSCEIVER STATION

Outline

3.0 Introduction

A pre-feasibility analysis regarding the rural micro site is presented in this chapter. This involves the estimation of the load demand and energy resources available at the proposed site location. The objective of this is to have a balance between the energy demand and supply which is important for obtaining an applicable system design and an optimal power configuration for the transceiver station. The pre-feasibility analysis is divided into the following steps; (i) estimation of the maximum power requirement for the site, (ii) evaluation of the solar resources for the proposed BTS locations, and (iii) brief description of the HPS components, the sizes considered and costs.

3.1 Estimation of the load profile for a micro BTS

In order to have a balance between power requirement and supply from the energy source, it is essential to estimate the load demand of the base station.

The load profile from a BTS can be measured remotely by using an ammeter connected to a GPRS modem which is able to collect data from the site and transfer to the network operation center (NOC). In most case this is usually unavailable, therefore load estimations are sometimes based on the power ratings of the site components provided by manufacturers or vendors and their period of operation. However, this is an unreliable method for estimating the load properties of a site because it does not take the energy losses for each component into consideration. Therefore, this will result in underestimation of the load demand and consequently, undersized system components.

Thus in this study, a state of the art (SOTA) approach for maximum power conditions has been adopted in obtaining the load demand for a micro BTS. This method was developed by Gunther *et al.* [27] and has also been used by Alsharif *et al.*[19] in developing a macro LTE site for Malaysia. The power model has been selected because it is able to quantify the energy saved on specific components in the BTS thus enhancing energy efficiency at the node and network level [27].

Based on literature [27], there are three important steps to obtaining a precise estimation of the maximum power demand of a BTS, these are listed below;

3.1.1 Defining a high-level block diagram consisting the main radio components in the BTS.

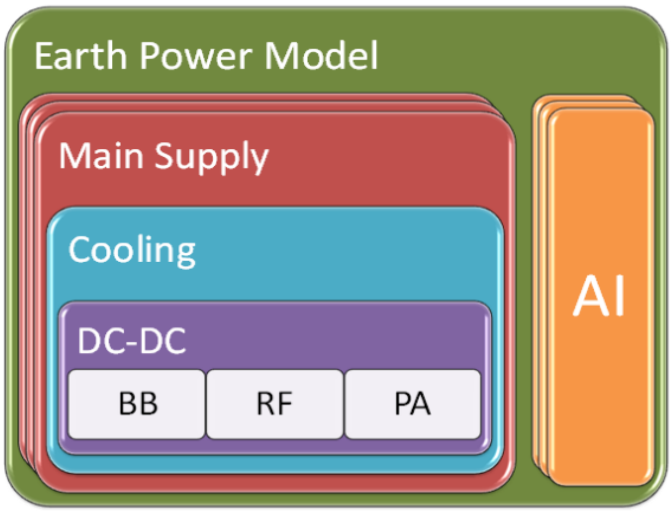

Figure 3.1: Simplified block diagram of a base transceiver station [27].

The block diagram shown in Figure 3.1 can be generalized for all forms of BTS. As mentioned earlier, BTSs have multiple transceivers with multiple antennas, depending on the customer demand and geography. With this illustration, it is easier to identify the components to be powered and the energy losses occurring in each one. This is particularly useful in developing the power model as described in the next subsection.

3.1.2 Estimation of the power consumption (in Watts) for the BTS components to obtain a maximum load.

The power model assumes that the power consumption for a BTS grows exponentially with the number of transceiver chains N_{TRX}.

Therefore the maximum output power per transmit antenna, P_{max} is provided in equation 3.1;

$$P_{max} = N_{TRX} \times P_{TRX} \text{ ....Equation 3.1}$$

Based on the block diagram provided in figure 3.1, the power for each TRX can be calculated as;

And $$P_{TRX} = \frac{\frac{P_{PA}}{\eta PA(1-\sigma_{feeder})} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{cool})(1-\sigma_{AC})} \text{ .... Equation 3.2}$$

where,

$\boldsymbol{P_{PA}, P_{RF}, P_{BB}}$ represents the power consumed by the power amplifier, radio frequency, and baseband respectively.

$\boldsymbol{\sigma_{DC}, \sigma_{cool}, \sigma_{AC}, \sigma_{feeder}}$ represents the loss factors from the DC-DC converter, active cooling, AC-DC supply and feeder losses respectively.

Also, the loss factor**,**

$$\boldsymbol{\sigma = 1 -} \eta \text{ ....Equation 3.3}$$

where **η** is the efficiency of the component

$$\eta = \frac{\boldsymbol{P_{out}}}{\boldsymbol{P_{in}}} \text{ ....Equation 3.4}$$

Note: For a micro BTS the following conditions hold [27];

- cooling is excluded as shown in figure 2.1, therefore $\boldsymbol{\sigma_{cool}}$ is zero(0)
- Feeder loss $\boldsymbol{\sigma_{feeder}}$ is negligible

Therefore with these conditions, equation 3.2 can be reduced to obtain equation 3.5;

$$P_{TRX} = \frac{\frac{P_{PA}}{\eta PA} + P_{RF} + P_{BB}}{(1-\sigma_{DC})(1-\sigma_{AC})} \text{ .... Equation 3.5}$$

Therefore equation 3.5 can be used to calculate the total power from the transceiver components at the micro BTS as shown in table 3.1.

Table 3.1: Total power for transceivers components, P_{TRX} [27].

Component	Quantity	Unit	Value
Power amplifier	Maximum rms power transmitted	dBm	38.0
	Maximum rms power transmitted	W	6.3
	Efficiency, η	%	22.8
	P_{PA}	**W**	**27.7**
Transceiver	Maximum power rms transmitted	dBm	-13.0
	TX P_{dc}	W	0.4
	RX P_{dc}	W	0.4
	P_{RF}	**W**	**1.0**
Baseband	Radio (inner rx/tx)	W	9.1
	LTE radio (outer rx/tx)	W	8.1
	Processors	W	10.0
	P_{BB}	**W**	**27.3**
	Total P_{TRX}	**W**	**72.3**
DC-DC converter	σ_{DC}	%	7.5
Cooling	σ_{cool}	%	0.0
AC supply	σ_{AC}	%	9.0
Sectors		#	1.0

Using equation 3.1, the maximum power estimation for a micro BTS can be obtained as shown in table 3.2.

Table 3.2: Maximum power for the micro BTS components [27]

Antennas		#	2.0
Carrier		#	1.0
Total power for the radio components (P_{max})	**Total P_{TRX} × Number of antenna chains for micro site (2)**	**W**	**144.6**

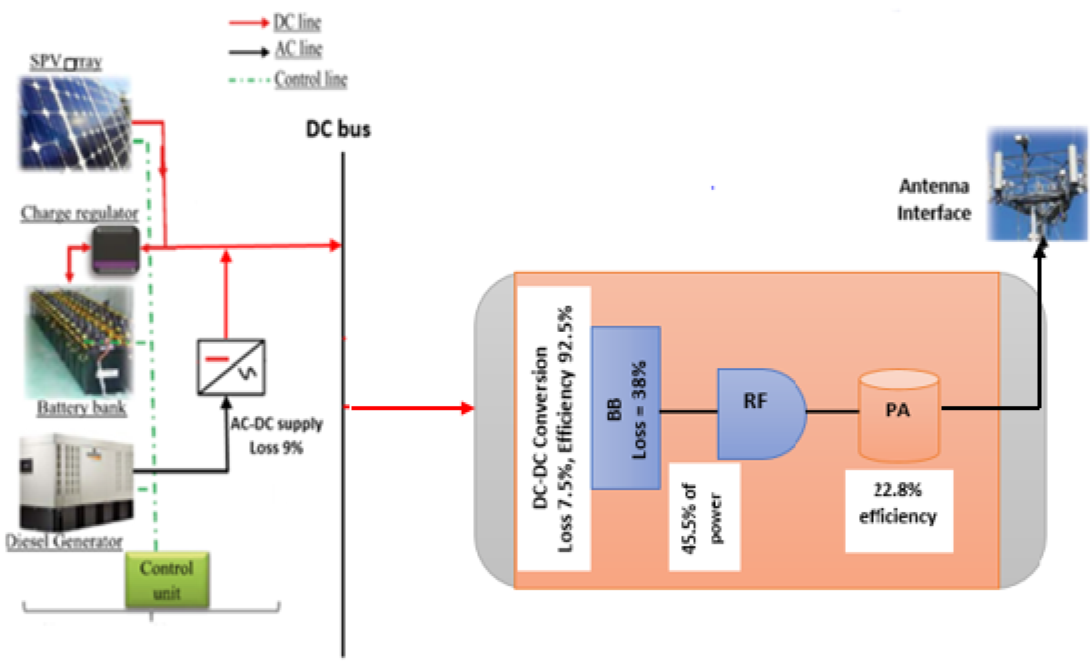

Figure 3.2: Layout of the hybrid power system with power distribution amongst micro BTS components

3.1.3 Evaluation of the power consumption for load variations

Power consumption by BTS equipment is majorly a function of the number of active subscribers. Therefore, it is expected that the load profile for a typical BTS will vary at different times of the day. Periods of high load consumption are generally referred to as high traffic periods and for most BTS this occurs at about 10 am till 6 pm. Low traffic periods kicks off between night and early hours of the day.

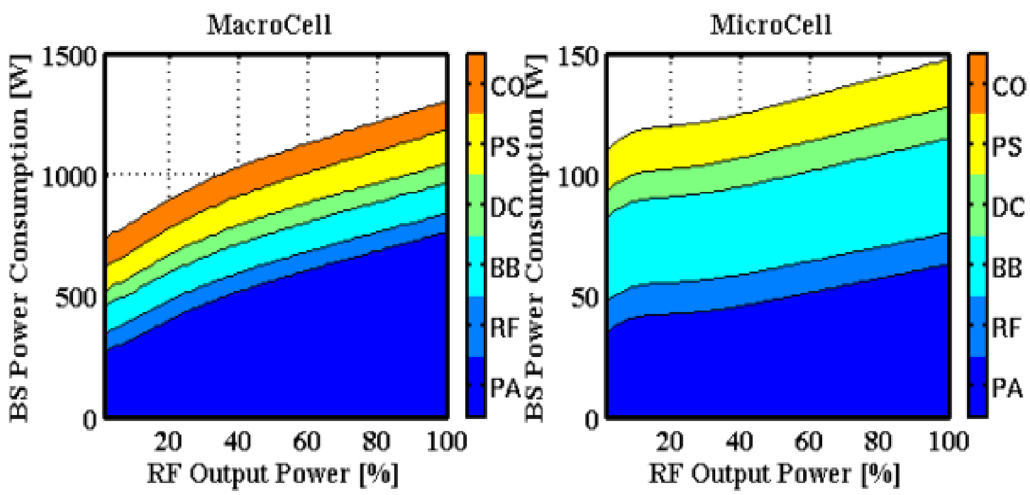

Figure 3.3: Variation of the power output for a macro and micro BTS [27]

During periods of low subscriber base, the power amplifier shuts down thus reducing the load demand. The reduction in load demand during low traffic varies amongst the types of BTS. For a macro BTS, power amplifier accounts for up to 38% of the overall consumption at full load and this can be reduced to about 30% of the overall load consumed during low power nodes [27]. This drastically reduces the load demand at such periods. However, for other types of BTS, the difference in power output is quite insignificant for all periods (as shown in Figure 3.3).

Different research works have tried to develop ways to estimate load variations at a BTS based on assumptions of energy level for each traffic periods. Olatomiwa *et al.* [3] categorized the load profile of an outdoor BTS into low hours (between 12 am to 6am), medium hours (between 7 am to 10 am) and busy hours (10 am to 6 pm). According to them, only 10 % of the full load is needed during low hours. This is because the system is ventilated by natural air. Between 7 am to 10 am about 30% of the full load is needed,

In another work done by Anayochukwu and Nnene [13], the load for a macro GSM base site in Nigeria was generalized for all hours of the day. Only the consumption by security lights was varied among the load components considered. Therefore the peak load only reduced between 7 am and 6 pm when natural light was available.

From figure 3.3, the power consumption for a micro base station at the low node is about 83% of its total. This means that there is a very little difference between its maximum load demand and its lowest demand. Therefore in this study, the load demand (145 W) for the micro BTS is considered to be constant for all the hours in the day and without a day-to-day variation. This gives the load profile in figure 3.4.

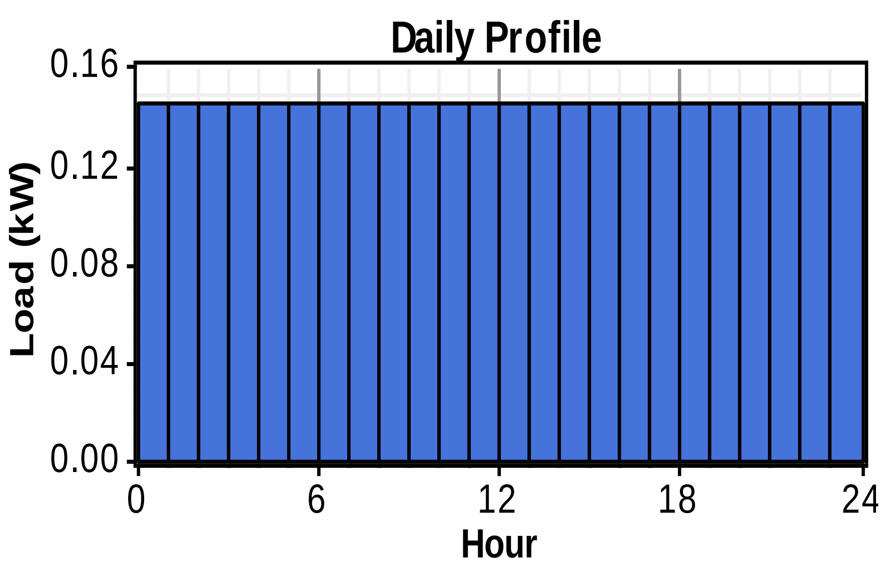

Figure 3.4: HOMER output for the load profile of the proposed micro BTS

3.2 Specification of components in the hybrid power system

Figure 3.2 provides a general description of the hybrid power system with the main components. For each component, different sizes have been selected for optimization. This helps to select a cost effective size for each component that meets the load demand. Also, the initial capital cost of a component includes the cost of purchasing the component and installing it. The main components of the hybrid energy power source are described in the following headings:

3.2.1 Solar Photovoltaic (PV)

As mentioned earlier, this is an electrical device composed mainly of semiconductors that convert light energy into direct current (DC) electricity by the photo electric effect [8]. It is used as the primary source of energy with the battery. The commercial types of solar panels are monocrystalline silicon, polycrystalline silicon types and thin films. Of these three, polycrystalline silicon panels are more economical and readily available in the Nigerian market, although, it is less efficient than a monocrystalline silicon. Table 3.3 provides the details about the PV module considered in this work and other important information about its installation. Usually, the cost of replacing a panel after its lifetime should lower than its initial cost considering the falling price panels per year, but considering the cost of decommissioning and installing a new system, a study [23] assumes that the replacement cost remains the same as the initial cost. Therefore, the capital cost taken for the panels is $ 4/W as obtained from literature [19]. No tracking method is used, in order to observe the performance of the system in the worst condition and to reduce maintenance cost. Also, since panels require a very little maintenance, therefore, the annual O&M for the PV is set at $10.

Table 3.3: Details of the solar PV module

Parameters	Unit	Value
Module sizes to be optimized	kW	1,1.5,2,2.5
Lifetime	years	25
Derating factor	%	80
System tracking	#	None
Azimuth	Degree	0
Ground reflectance	%	20
Initial Capital cost	$/W	4
Replacement cost	$/W	4
Annual O&M cost	$/year	10

3.2.2 Diesel Generator

This acts as the secondary energy source especially during peak demands and in situations where the primary energy source is unavailable and the batteries are completely drained. For optimum performance, it is highly recommended that a diesel generator should be operated between 70% and 89% of its rated power. The price set by the Nigerian National Petroleum Corporation (NNPC) for diesel as at when this work is done is N180 ($0.59/L) but considering the cost of acquiring the fuel and its transportation and storage at the remote site, the fuel cost is set at $1.1/L as estimated by Olatomiwa *et al.* [3]. Also, the price of fuel is usually unpredictable and varies according to the region. Therefore in this study, different fuel prices (0.8, 0.9, 1.0, 1.1, 1.2 $/L) have been considered in a sensitivity analysis. Various generator sizes have also been considered to obtain an optimal size. The capital cost of the diesel generator is assumed to be equal to the replacement cost at the end of its service year, and is set as $ 230/ kW. Further details of the diesel generator are provided in table 3.4.

Table 3.4: Details of the AC diesel generator

Parameters	Unit	Value
Sizes to be optimized	kW	0.5,1,1.5,2,2.5
Lifetime	hour	15,000
Minimum load ratio	%	30
Heat recovery ratio	%	0
Fuel price	$/L	1.1
Capital cost	$/kW	230
Replacement cost	$/kW	230
O&M cost	$/hour	0.5

3.2.3 Battery storage

This is otherwise called an 'energy bank'. It is used to store electric energy when the supply is more than the demand and releases its stored energy when demand outgrows supply. In most cases, the battery bank compensates for periods of no sunshine (usually at nights) or when the energy source is unable to meet up with the demand. A protective mechanism called 'charge controller' or 'battery regulator limit' is usually coupled with the battery bank to limit the rate at which electric current is added or withdrawn from the batteries [19]. Overcharging of the batteries is an unwanted condition because it poses risk to the batteries and reduces their lifespan. Charge controllers are also essential for ensuring that batteries discharge current according to the designed rate and to a permitted level. In this study, Trojan L16P battery has been considered because they require low maintenance. Also, the nominal voltage for a unit L16P is 6 Volts and this is arranged in a string of 4 batteries (making 24 Volts). This is because reference [4] has shown that the best range of voltage for BTS equipment is between 24V to - 48V. The capital cost (including installation) of a unit Trojan L16P battery, its replacement cost, and O&M were obtained from [19]. Further details for the battery can be found in Table 3.5.

Table 3.5: Details of the Trojan L16P battery

Parameter	Unit	Value
Strings to be optimized	# (4 per string)	1,2,3,4
Nominal voltage	Volts	6
Nominal current	Ampere-hour (Ah)	360
Nominal capacity	kWh	2.16
Lifetime throughput	kWh	1,075
Maximum charge rate	A/Ah	1
Maximum charge current	A	18
Round trip efficiency	%	85
Self-discharge current	%/hour	0.1
Minimum operation lifetime	Years	5
Capital cost	$ (per unit)	300
Replacement cost	$	300
O&M cost	$/year	10

3.2.4 Power converter

The proposed hybrid energy solution consists of both DC and AC power sources. However, the site equipment requires only DC voltage. Therefore, a power converter is required to maintain power flow from the energy source to the load [3]. The type of converter needed for this purpose is a rectifier. It converts AC voltage from the AC generator source into DC voltage which is needed to maintain a uniformity with other DC components like solar PV, batteries and also the BTS components for uninterrupted power (as shown in figure 3.2). The cost parameters for the converter were obtained from [14] and are provided in Table 3.6. Also, different sizes have been considered in the simulation to select an optimal size.

Table 3.6: Details for the rectifier

Parameter	Unit	Value
Sizes to be optimized	kW	0.5,1,1.5,2,2.5,3
Lifetime	Years	15
Efficiency	%	85
Capital cost	$	700
Replacement cost	$	600
O&M cost	$/year	10

3.2.5 Control system

This is the brain of the entire system. It controls, regulates and create a communication link between all components of the hybrid system. The common communication units used in a remote interface are wireless modems or network solutions. There are also other components such as alarm memory and data logger coupled with this system. All of these are managed by the sophisticated control system [19]. Further discussion on the control system and the algorithm can be found in chapter 4 of this study. However, the cost of the control system is not included in the analysis of this study.

3.3 Site resources.

To design an optimal power supply system for a BTS, it is also important to carry out a specific site study. Site study involves the estimation of the energy resources available at the location considered for the project. The energy resources available at a site is influenced by the climatic and geographic conditions of the area. In this study, the natural site resources were estimated so as to prioritize its use over the auxiliary energy resource (diesel fuel). The most important site resource for the micro BTS as mentioned in chapter 3 is solar energy. Information regarding the solar energy resource available at the locations considered is provided in the next subsections.

3.3.1 Source of solar energy resource

A power supply solution that uses one or more form of renewable energy source(s) requires meteorological data in order to accurately size and optimize its components. This data are usually based on historical information for the location considered; and in another case, experimental measurements or high accuracy estimations to predict the data [69].

Based on literature [69], there are two methods for estimating the meteorological data for a site; these are chronological approach and the stochastic approach. The chronological approach is a straightforward and common method of collecting data. It involves obtaining information from internet sources or producing data from calculations. The downside of this method is that it cannot be used to accurately predict a future data [69]. To overcome this limitation, some studies use the stochastic method [25]. The monthly solar radiation data for this study were obtained from the National Aeronautics and Space Administration (NASA) database for surface meteorological and solar energy over a 22 year period (July 1983 – June 2005) [70].

3.3.1.1 Solar Energy in Nigeria

Nigeria is described as a tropical country; which implies that it receives a considerable amount of solar radiation all year round [14]. This makes the utilization of solar PV technology very suitable for powering base transceiver stations. Figure 3.5 shows the variation of average monthly global radiation for a location with coordinates: Latitude 10^o N and Longitude 8^o E which is a central position in Nigeria [71] reflecting the true solar radiation pattern for Nigeria. This is used as the main case study in this work. The figure also shows the clearness index (the degree of cloudiness) which is responsible for the variation of the solar radiation in different months. The annual average solar radiation obtained from Figure 3.5 is 5.68 kWh/m^2/day.

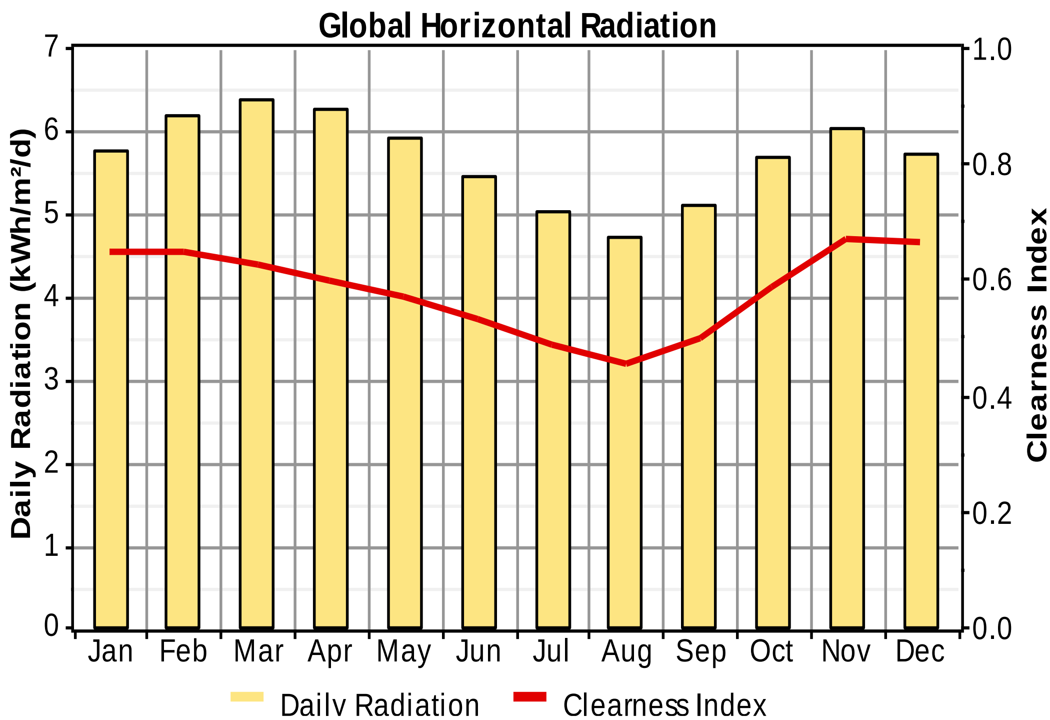

Figure 3.5: Monthly average global radiation and clearness index for the case study [70].

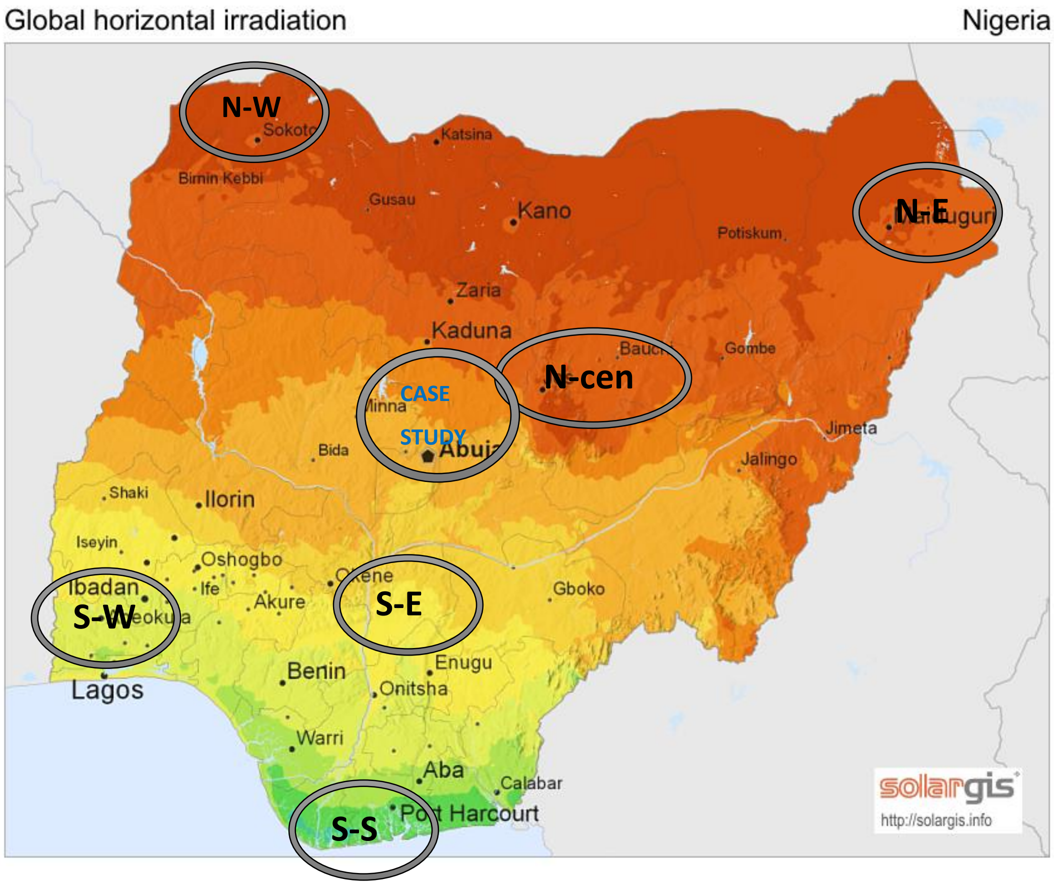

Figure 3.6: The Nigerian map showing the global horizontal radiation for the different BTS locations [72].

Figure 3.6 shows the solar radiation distribution in Nigeria with highlights on the regions considered in this study. It shows six hypothetic rural locations that have been selected from the six different geopolitical zones in Nigeria. Two rural communities each from the semi-arid North-West (N-W) and warm North-East (N-E) zones respectively, a community from the central part of the country, another in the South-West (S-W) zone, a community down South-East (S-E) and a community at the temperate South-South (S-S) zone. The case study is centrally positioned and indicted in blue.

Solar radiation varies across different parts of Nigeria. It is very high in the northern region and decreases down south. The purpose of selecting different sites for this work is to show the performance of the hybrid system under different climatic and geographic conditions. This will further demonstrate the possible energy contribution from the solar PV system in these locations. The details of the selected sites are provided in the next paragraphs.

1. South-East zone

   In the South-East zone, Umuoda has been selected. Umuoda is a village in Aboh Mbaise local government area in Imo state, Nigeria and has the coordinates; latitude 5^{o} 25' N and longitude 7^{o} 15' E. The average daily solar irradiation for the region is 4.5 kWh/m2/day.

2. South-South zone

   In the South-South zone, Ogbia town has been selected. Ogbia is a local government area in Bayelsa state, Nigeria and has the coordinates; latitude 10^{o} 51' N and longitude 12^{o} 50' E. The average daily solar irradiation for the region is 4.33 kWh/m2/day

3. South-West zone

   In the South-West zone, Lisa has been selected. Lisa is a small village located in Ifo local government area in Ogun state, Nigeria and has the coordinates; latitude 6^{o} 49' N and longitude 3^{o} 11' E. The average daily solar irradiation for the region is 4.76 kWh/m2/day.

4. North central zone

   In the North-central zone, Wase town has been selected. Wase is a local government area in Plateau state, Nigeria and has the coordinates; latitude 9^{o} 6' N and longitude 9^{o} 58' E. The average daily solar irradiation for the region is 5.51 kWh/m2/day.

5. North-East zone

In the North-East zone, Chibok town has been selected. Chibok is a local government area in Borno state, Nigeria. It has the coordinates; latitude 10^o 51 ' N and longitude 12^o 50 ' E. The average daily solar irradiation for the region is 5.81 kWh/m2/day.

6. North-West zone

In the North-West zone, Bodinga town has been selected. Bodinga is a local government area in Sokoto, Nigeria and stands at a location 12^o 53ˈ N Latitude and 5^o 10ˈ E Longitude. The average daily solar irradiation for the region is 5.97 kWh/m2/day.

Table 3.7: Long term monthly average daily global solar radiation for different zones in Nigeria [70].

Area	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Umuoda	5.03	5.05	4.99	4.65	4.39	3.92	3.63	4.07	4.24	4.32	4.75	4.99
Ogbia	4.76	4.77	4.79	4.55	4.29	3.94	3.42	3.68	4.02	4.29	4.74	4.76
Lisa	4.94	5.16	5.27	5.17	4.86	4.46	3.90	3.95	4.24	5.00	5.32	4.87
Wase	5.47	5.63	5.99	6.12	5.76	5.34	4.72	4.68	5.11	5.83	5.88	5.62
Chibok	5.50	5.98	6.42	6.43	6.31	5.85	5.07	5.07	5.42	6.06	6.02	5.62
Bodinga	4.59	6.04	6.11	6.52	6.45	6.26	5.72	5.50	6.11	6.04	5.85	5.45

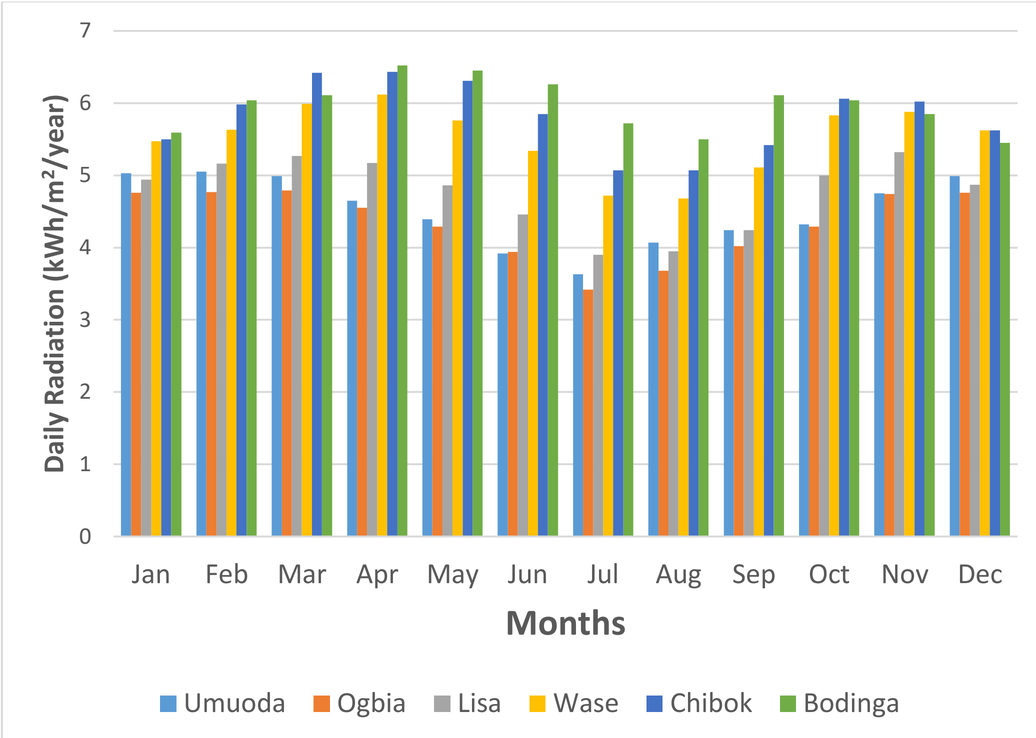

Figure 3.7: Comparison of the average daily monthly radiation for the selected zones in Nigeria

In general, figure 3.7 shows that the lowest solar radiation received in Nigeria occurs from June to August annually. This is due to an increased cloud cover during this period as shown in figure 3.6. The annual average solar radiation obtained from Figure 3.6 is 5.68 kWh/m^2/day and is considered as the solar resource for the case study in this present work. The six other annual average solar radiation values, representing the hypothetical rural locations are used to compare the performance of the system in different climatic and geographic conditions. A summary of the site information is provided as table 3.8.

Table 3.8: Summary of information for the selected BTS locations

Site location	Climatic condition	Latitude (^{o} N)	Longitude (^{o} E)	Annual average solar radiation ($kWh/m^2/day$)
Umuoda	Tropical savanna	5^o 25 '	7^o 15 '	4.50
Ogbia	Tropical monsoon	4^o 47 '	6^o 20 '	4.33
Lisa	Tropical savanna	6^o 49 '	3^o 11 '	4.76
Wase	Alpine(highland)	9^o 6 '	9^o 58 '	5.51
Chibok	Warm desert	10^o 51 '	12^o 50 '	5.81
Bodinga	Semi-arid	12^o 53 '	5^o 10 '	5.97

Chapter 4: HYBRID POWER SYSTEM DESIGN AND MODELING

Outline

4.0 Introduction

This chapter provides the procedure used in the optimal design of the hybrid power system considered in this study. The optimum design for the system is based on certain criteria which are specified by the designer. Based on this, mathematical models are developed to describe the performance of each component. These models are used in a software tool to simulate the behavior of a typical solar/DG HPS including its economic analysis. Also, in order to have an effective energy management, a control algorithm is described with dispatch strategies for the batteries and diesel generator.

4.1 Optimum sizing

A proper design of a solar PV-diesel hybrid energy system helps to increase the reliability of power delivered to the load without wasting energy and at the lowest possible cost. These objectives can be measured by criteria such as: (i) power reliability, (ii) economic criteria and (iii) environmental impact. These factors are discussed in this study. A detailed study of power and economic criteria can be found in reference [73]. Other factors such as technical and environmental analysis are discussed in the work of Theo *et al.* [74]. A recent study by Al-falahi et al. [75] included social criteria to these options.

4.1.1 Power reliability criteria

The reliability of a system is a measure of its electrical service integrity. Generally, a power system is considered to be reliable when it is able to avoid any possible power interruption. In the design of a solar-diesel hybrid energy system, it is important to carry out power reliability analysis due to the intermittency of solar radiation, which would highly influence the energy produced per load demand. There are several indicators used in examining the reliability of a hybrid system, some of these are; Loss of Power Supply Probability (LPSP), Loss of Load Probability (LLP), System Performance Level (SPL), Loss of Load Hours (LOLH), Loss of Load Risk (LOLR), Unmet Load (UL) and Level of Autonomy (LA) [74].

Loss of power supply probability method is the most popular in literature sources [76]. According to Yang *et al.* [77], LPSP is the probability that an insufficient power results when the hybrid power system (including storage) is unable to adequately meet the load demand.

Loss of load probability is the probability that the demand by a system will exceed the capacity of an energy system in a given period of time. This is often expressed as the estimated number of days over a long period. System performance level is expressed in terms of probability of the number of days in which the load requirement cannot be satisfied [78]. This is almost similar to LLP.

Loss of load hours is the number of hours in a year that the available generation was incapable of meeting the load demand. Loss of load risk is the probability of an energy system satisfying a daily load demand due to the unpredictability of renewable energy sources. The level of autonomy describes the ratio of the number of hours in which there was no loss of load to the total hours of operation. Unmet Load is the ratio of the unserved load to the total load available at a specific time [74].

4.1.2 Economic criteria

Economic evaluation is a condition used in optimally sizing a hybrid system. It is considered as the most important factor that determines the deployment of distributed energy systems. Economic analysis results in the configuration with the least capital investment, operational expenditure and cost of energy. This can be achieved by considering indicators such as the Net Present Cost (NPC), Levelized Cost of Energy (LCOE) and Life Cycle Cost (LCC) [74].

NPC is the sum of the discounted present values of a time series of cash flows, which includes the initial cost of the entire system components, the cost of replacing any of the components during the project lifetime, cost of maintenance and the salvage value [74]. In a solar-diesel-battery design, the life of the solar PV modules is considered as the overall project life time because it is the component with the longest lifespan [73].

LCOE is calculated as the ratio of the total annualized cost of an energy system to the annual electricity it produces. In other words, it refers to the cost required per kWh electricity generated. The electricity tariff levied on buyers of electricity is determined by LCOE. LCOE also considers the degradation of revenue realized from electricity sales as the project lifetime goes by. Optimum design considerations for a hybrid system is influenced by considering the configuration with the least NPC and LCOE. For example, LCOE was used to compare different renewable energy technologies in a study done by Jun *et al.* [79]. However, NPC and LCOE may not be sufficient for long-term decision perspectives. This is because they do not consider other costs such as the impact of the energy system on the environment.

Life cycle cost is an in depth evaluation of all cost of components as well as environment costs involved in an energy system over its entire lifetime. It incorporates plant installation, maintenance, and operation, replacement of equipment with pollution control, disposal of waste and other environmental impact control. Therefore, LCC is considered to be a better criteria for evaluating the economic feasibility of a design.

In some studies, LCC is combined with life cycle analysis (LCA) for a more detailed assessment and selection of a technology. One of such works was done by Petrillo *et al*. [80] which combined life cycle assessment and life cycle cost in deciding on a compressed air storage (CAES) system for an off-grid solar power plant which would be used to satisfy the energy demand of a radio base station for mobile telecommunication. In a similar study done by Ristimäki *et al*., [81] LCC and LCA were combined in the analysis of four different design options considered for a new residential energy system in Finland. The result of the analysis showed that the system with the highest capital investment paradoxically had the highest feasibility in a life cycle view point. In this study, NPC is used to rank the system configurations according to their viabilities. The configuration with the least NPC is considered as the most economically viable option.

4.1.3 Environmental impact

The important parameter used in evaluating the environmental impact of the power system is the kg of CO_2 released. This is because CO_2 makes up the largest percentage of the emissions from the combustion of fuel and is a chief cause of the greenhouse effect. It is considered that the kg of CO_2 produced in a year C_E represents the pollutant emitted for that year, therefore in this study, it has been set as an objective to be minimized [82].

4.2 Optimum design criteria

In order to realize the objectives of this study, three criteria are selected as objectives to be minimized, based on power reliability, economic advantage and environmental impact respectively. They are:

- Unmet load (must be zero)
- The total net present cost NPC ($)
- The carbon emissions, C_E (kg/year)

4.3 Methods for optimum sizing of hybrid power systems

Based on a study by Al-falahi *et al*. [75], the techniques for optimization can be categorized into three, namely; classical, modern and software tools. Classical techniques make use of numerical, analytical, iterative, probabilistic and geographic construction approach [83]. They use differential calculus in generating optimal solutions [84]. Modern techniques give a more accurate and convergent optimal solution [85]. This approach uses artificial and hybrid methods to determine the global optimum system [86]. The last optimization technique involves the use of computer software tools. Computer software tool has been adopted in this study because it is easier to use and gives an accurate optimization of a system based on predefined user constraints. Software tools will be discussed in the next paragraphs.

4.3.1 Optimization software tools

The use of optimization software tools has become common in evaluating the performance of hybrid energy systems. They provide a means of comparing the performance of the possible system configurations in terms of reliability and energy production costs. Also, optimization sizing tool helps to efficiently and economically utilize the renewable energy resource(s) in a hybrid system design by identifying the configuration which meets certain criteria. However, it is important to have a broad understanding of the available hybrid system models and software tools, their features, limitations, user requirement before selecting one.

Various optimization tools exist for designing hybrid energy systems. Sinha and Chandel [87] reviewed 19 software tools for hybrid renewable energy systems, namely; HOMER, Hybrid2, RETScreen, iHOGA, INSEL, TRNSYS, iGRHYSO, HYBRIDS, RAPISM, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, SOLSIM and HYBRID DESIGNER. Turcotte *et al*. [88], classified hybrid optimization software tools into four categories, namely; Pre-feasibility, sizing, simulation and open architecture research tools. Prefeasibility tools are used for pilot sizing and a detailed economic analysis of an energy system (a common example is RETScreen). Sizing tools are used for determining the optimal size of each component in the hybrid system and the direction of energy flow between them (a common example is HOMER). Simulation tools perform a similar function as sizing tools but in their case, the user has to provide the details of each component in order to have their optimum performance (an example is HYBRID 2). Of all these categories, open architecture optimization tools are more user dependent in that the user of the software is allowed to adjust the algorithm and the interactions of the hybrid components according to demand (an example of this category is TRNSYS).

Bernal-Agustín and Dufo-López [89] revised the simulation and optimization techniques and existing tools that can be used in the simulation and design of an off-grid hybrid system for electricity generation. Zhou *et al*. [73] gave a further description on the use of HOMER, HOGA, HYBRID 2 and HYBRIDS in the evaluation of the performance of a solar-wind energy hybrid system. Another work done by Erdinc and Uzunoglu [90] focused on the commercially available software tools which can be used in hybrid simulation.

In this study, the four most common software tools for hybrid optimization was discussed, namely; RETScreen, HOMER, HYBRID 2 and HOGA. The advantages and performance of these software tools are compared in order to select a desired choice for solar-diesel hybrid design.

4.3.1.1 RETScreen

RETScreen falls under the category of simulation tools used primarily for prefeasibility purposes. It was developed by the Ministry of Natural Resources, Canada for estimating the economic and environmental benefits of renewable energy technologies in different locations around the world [91]. RETScreen software was built on visual basic and C programming language and can work for both on-grid and off-grid applications. The software has a broad global climate database of more than 6000 ground stations, energy resource maps, hydrology data, renewable technology data details (like solar PV) as well as wind turbine curves. Data can be easily retrieved from the NASA climatic database. There are two separate versions of RETScreen tool, these are RETScreen Plus and RETScreen 4 tools. RETScreen Plus is an energy management software and a Microsoft Windows-based simulation tool. RETScreen 4 requires Microsoft excel for project analysis and can determine parameters such as technical and economic viabilities of renewable energy technologies. It can also work on energy efficiency and cogeneration projects.

In general, RETScreen provides the possibility of working on a number of worksheets which helps to carry out detailed cost analysis, energy modelling, emission analysis, sensitivity and risk analysis. In addition, the software covers energy production, life cycle cost as well as green gas emission reduction.

RETScreen has a number of limitations. To start with, it does not have an option for time series data import. Furthermore, there are only a few options to search, retrieve and visualize projects. Also, data sharing option is not available. Another limitation is that it does not consider temperature effects for PV performance analysis and more advance calculations cannot be done with the software [87].

4.3.1.2 HYBRID 2

HYBRID 2 is a system computer model developed by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts, USA in 1996 with the support of the National Renewable Energy Laboratory [92]. It is a succession of the HYBRID 1 which was originally developed in 1994. According to Sinha and Chandel [87], the recent HYBRID 2 1.3b version has been rid of issues like problems associated with curve fitting function on the insolation data graph and overflow error with low load simulation. The software was developed with the Microsoft Visual BASIC program and uses Microsoft Access Database.

HYBRID 2 uses a combined probabilistic/time series computer model to account for a time step variation in the performance of a hybrid energy system. It is useful for a detailed long-term performance evaluation, economic analysis and to predict the performance of different hybrid systems. The software allows time series simulation which vary from 10 minutes to 1 hour [92]. It employs a statistical approach to ensure that energy is conserved over the entire simulation process and in a consistent manner.

HYBRID 2 is made up of four parts namely, the Graphical User Interface (GUI), Simulation Module, Economics module and the Graphical Results Interface (GRI). GUI allows users to build projects easily and in an organized structure. Simulation and Economic modules helps users to run simulations and check possible input errors while GRI allows users to view detailed graphical results [92]. The drawbacks of this simulation tool are its limited access to parameters and lack of flexibility [87].

4.3.1.3 Hybrid Optimization by Generic Algorithms (HOGA)

This is a C++ program based simulation and optimization tool developed by Dufo-Lopéz and Bernal-Agustín for hybrid energy systems [93]. Optimization in HOGA is carried out by Genetic Algorithms (GA) and this occurs in two forms; primary and secondary GA. Primary Genetic Algorithm deals with the optimization of system components while secondary genetic algorithm optimizes the control strategy for the system.

HOGA optimizes hybrid system components by minimizing the total cost of the system which is presented in terms of the net present cost. This financial analysis is called mono-objective optimization function. The optimization tool can also incorporate other variables like carbon emissions or unmet load in a multi-objective case. Optimization results are therefore based on the minimization of costs, reduction in emissions or unmet load. Simulation in HOGA is in time steps of up to 1 minute and it uses very detailed models of the components to obtain a precise estimate of the system performance. HOGA can model systems with both DC and/or AC load consumption as well as Hydrogen and allows excess electricity or surplus hydrogen to be sold to the grid via a net metering design [93].

iHOGA (improved HOGA) is an upgrade of the old HOGA version. It has some added features such as new constraints, effects of degradation, sensitivity analysis, currency conversion, and database for components and so on. iHOGA can be used to simulate hybrid energy system comprising photovoltaic system, wind turbines, auxiliary generators (diesel and gasoline), converters, battery storage systems and battery charge controllers and components of hydrogen fuel(fuel cells, electrolyzers and hydrogen storage tank). The advanced optimization model it uses (generic algorithms) enable it to optimize systems in a low computational time. iHOGA exists in two versions namely; the free EDU version and the price tagged PRO+ edition.

Despite its remarkable performance, iHOGA has some notable disadvantages. All versions of HOGA require internet connection for their operation. The EDU version does not have important features like sensitivity analysis, probability analysis, net metering and permits an average load capacity of only 10 kWh per day [87].

4.3.1.4 HOMER (Hybrid Optimization Model for Electric Renewables)

HOMER is the most widely used, open access and user friendly software amongst the simulation tools. It was developed by the National Renewable Energy Laboratory (NREL), USA in 1993 and helps in the design of micro power hybrid systems, facilitating comparison between different types of power generation technologies across a broad range of applications [94].

HOMER software was developed with C ++ programing language and it uses windows operating platform. The software performs three important tasks: prefeasibility, optimization and sensitivity analysis on various possible configurations of the hybrid system. To do this, HOMER relies on input variables such as various technology options, cost of components, resource availability and manufacturer’s data. The software also provides its results in tables and graphs which makes it easier to compare the various configurations in terms of their technical and economic merits and can be exported [94].

HOMER is able to model a defined system configuration by executing an hourly time series simulation of its operation in a year. The simulation results from HOMER are based on constraints specified by the user and it examines whether these conditions have been fulfilled. The total net present cost of a configuration is used to represent its life cycle cost and the most feasible solution (optimal system configuration) from the simulation is that which has the lowest net present cost.

In sensitivity analysis, the software tries to reveal the future impacts of an input variable (or variables) on the outputs. Sensitivity input variables could be, fuel price, solar insolation, wind speed, price for the grid power and so on. All these are specified by the user when simulating the hybrid design and they allow the user to gain insight into uncertainties thus making better design decisions.

HOMER simulation tool would have been a perfect tool for all hybrid system designs, however just like the other tools, it has its limitations. The software was developed to allow a single objective function on which its results are based, this is the net present cost. It is therefore impossible to add another objective function such as the levelized cost of energy. Also, HOMER does not consider important design parameters such as the depth of discharge of batteries and the variations in bus voltage [87].

4.4 Choice of software

Following the analysis of each of the different optimization tools, a comparison was also made between them based on the features of each software as shown in table 4.1.

Table 4.1: Comparison between the selected optimization software tools

	Economical Analysis	Technical Analysis	PV	Wind	Bio energy	Hydro energy	Generator Set	Storage Device
RETScreen	YES	YES	YES	YES	NO	NO	NO	YES
HOMER	YES	YES	YES	YES	YES	YES	YES	YES
HYBRID 2	NO	YES	YES	YES	NO	NO	YES	YES
HOGA	YES	YES	YES	YES	NO	YES	YES	YES

A comparison between RETScreen and HOMER was done by reference [87]. The software tools show similarities in that they both accept global irradiation inputs and generate the diffuse irradiation internally. However, HOMER allows other functions such as the calculation of excess electricity produced, shortage capacity, effects of temperature on solar PV. It also gives a detailed graphical representation of options and more ways to input data, whereas, RETScreen does not. The only major benefit of RETScreen is that it provides a more detailed economic analysis of a project than HOMER. Also, HYBRID 2 has a very minimal application for economic analysis, hence cannot be used for this study.

According to Table 4.1, only HOMER and HOGA adequately satisfies the parameters necessary to optimally design and size a solar PV/diesel/battery hybrid system. However, HOMER is more user-friendly of the two and can be easily configured. Also, HOMER provides a better representation of results and has become the most popular computer tool for hybrid design because it is the most complete in terms of managed information. An architecture of HOMER is shown in Figure 4.1.

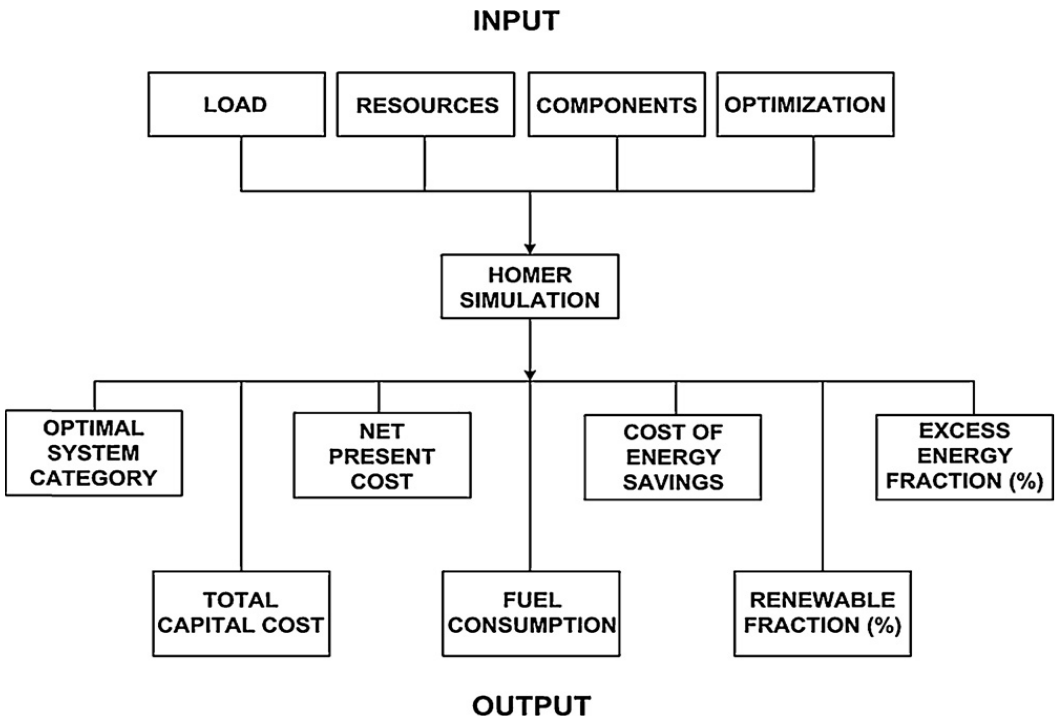

Figure 4.1: An architecture of HOMER software tool [90]

4.5 Design of solar PV-diesel design with HOMER software

The hybrid energy system considered for this study is comprised of electricity generation devices (solar PV and diesel generator), and usually would be composed of wiring and supporting structures as well as the balance of system (BOS) equipment which are the charge controller, batteries and converter. A layout obtained from HOMER software is provided in Figure 4.2. According to the HOMER layout, the current produced by the diesel generator is fed into the AC bus which is converted by a rectifier into DC and combined with other DC bus components (PV and battery bank) to feed the load demand. The energy consumption for the BTS under investigation is with a peak demand load of 145 W. The project lifetime is taken as 25 years, which represents the lifespan of the solar PV system. Also, the real interest rate is 9.6% based a five year average (2007-2011) obtained from reference [14]. HOMER makes a decision in each time step to meet the load demand at the lowest net present cost which is based on constraints such as the dispatch strategy, operational reserve and capacity shortage fraction.

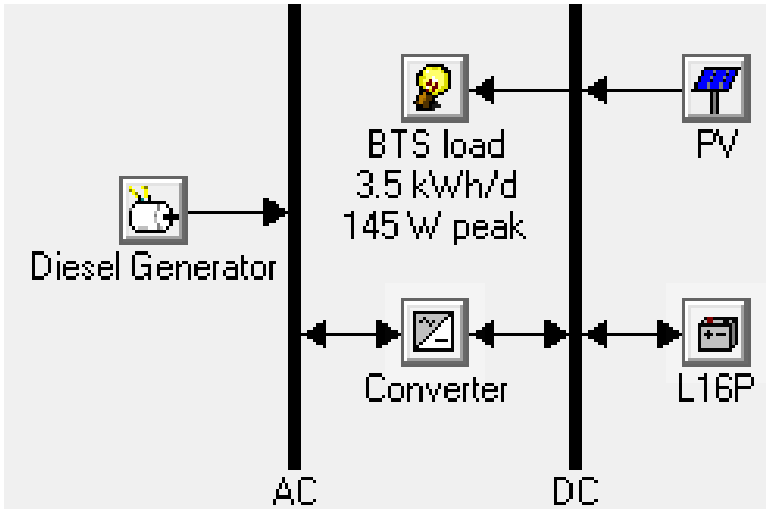

Figure 4.2: HOMER representation for the proposed solar PV-diesel hybrid power system

4.6 Operation and Control strategies

In a hybrid energy system, it is important to prioritize the order in which the different energy sources serve the load demand. This decision has to be specified by the system designer. Operation and control strategies helps to fully exploit the free available renewable energy resources, after which the stored energy (i.e., battery bank) is used and if there is a secondary energy storage (e.g., hydrogen) this also becomes converted to meet the required load at that instant [95]. The benefit of prioritizing energy supply sources is to ensure an effective management of energy flow for a continuous and stable power supply at the lowest cost.

Based on a literature discussed by Bajpai and Dash [96], the essential considerations for designing optimal operation and control strategies are; energy resources available, economic conditions (e.g., capital cost, O & M cost and the lifetime period) and storage conditions (e.g., days of autonomy, state of charge). Arul *et al.*[97] added that the complexity of the operation and control strategy would increase as the configuration of the power supply broadens. Another review done by Tan *et al.*[69], mentioned that the operation and control strategies applied in power supply systems are; component-level control strategies and system-level strategies Component-level control strategies are applied at the converter where the energy generators are interconnected to the system so that the converter provides the voltage and frequency in which the entire system depends on. In the case of system-level strategies, the decision is based on factors such as the load, estimated energy generated, economic dispatch and security constraints [69].

The control strategy described in this study is similar to that discussed by Anayochukwu and Nnene [13] which is also used by HOMER simulation tool. This control strategy is described in the next paragraph.

4.6.1 Control strategy for a solar PV-diesel-battery hybrid system

The control strategy proposed for this study was described by reference [13] and considers solar PV power output (P_{PV}) as the primary energy source for the BTS load, the battery bank capacity ($E_{ch-max,dsch-max}$) as energy supplements while the diesel generator power (P_{DG}) is used as a backup power supply. The algorithm for the control operation is described in Figure 4.3.

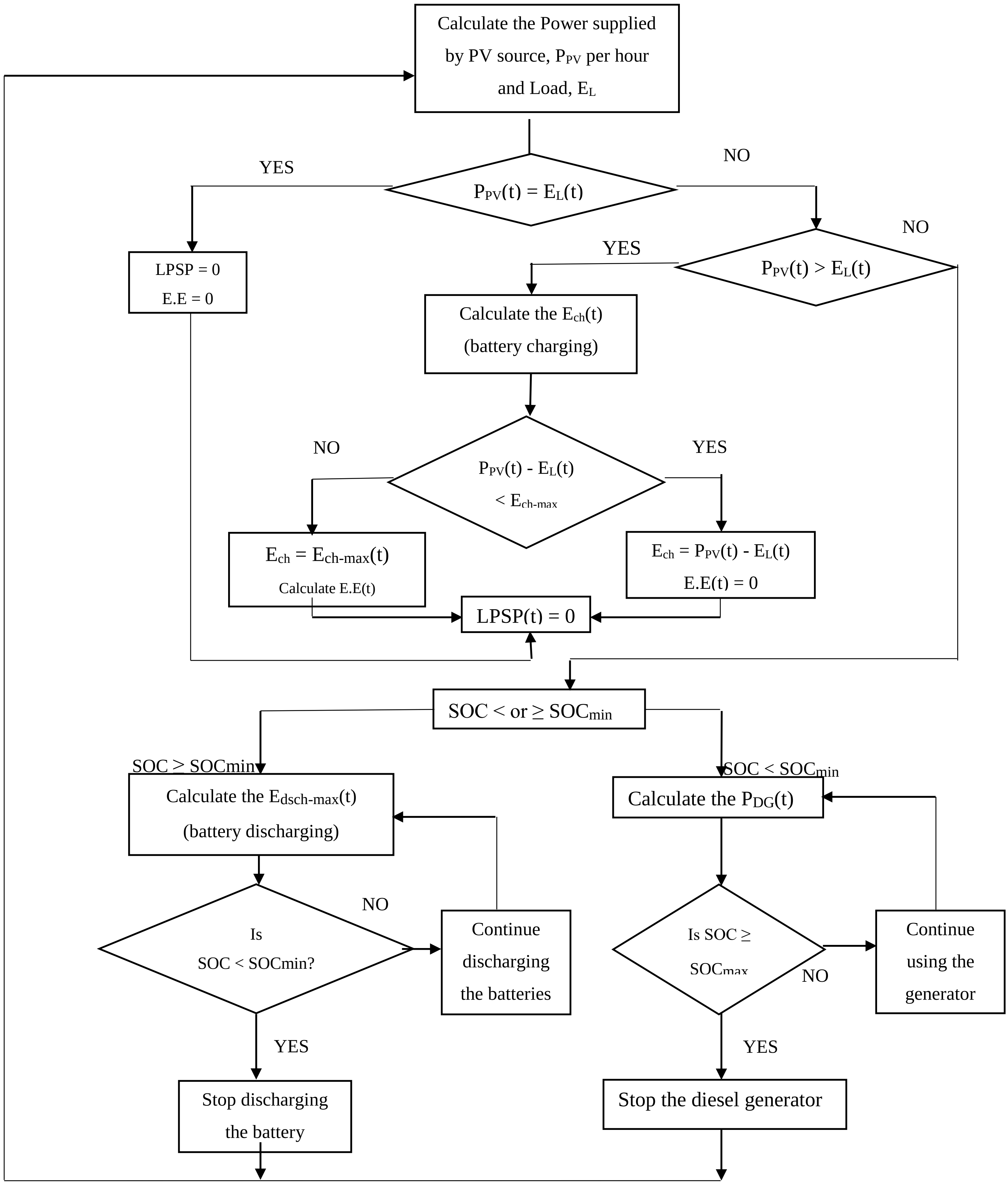

Figure 4.3: Algorithm for the control operation of the proposed solar-diesel hybrid system [11]

The energy required by the BTS (E_L) is expected to be provided the PV system. When the net difference between the energy output from the panels and the load demand is positive, the excess energy is used to charge the batteries to their rated maximum capacity. (E_{ch-max}). If the excess energy is less than the battery charging capacity, then there is no excess energy (E.E), but if the excess energy from the panels exceeds the $E_{ch-max,}$ the system calculates the excess energy. Overall, the loss of power supply (LPSP) is equal to zero because the load demand has been effectively met.

In another condition, if the net difference between the energy provided by the solar panels and load demand is negative (insufficiency), the system goes into a decision mode (SOC < or ≥ SOC_{min}). At this point, the system tries to determine the auxiliary component (battery or diesel generator) that will supply the required energy demand. Such decision is based on this conditions:

- Battery bank: The battery bank is the preferred auxiliary energy source if its current state of charge is above its minimum level (i.e., $SOC \geq SOC_{min}$).
- Diesel generator: If the energy from the panels is still insufficient for the load demand and the battery bank is at its minimum state of charge (i.e., $SOC < SOC_{min}$), the diesel generator is turned on to provide the deficit power and to charge the batteries.

The control simulation makes it possible to view the performance of the energy system and how the load is being supplied with power by each energy component in the hybrid system.

4.7 Dispatch strategies

Dispatch strategy is a set of rules that controls the operations of the diesel generator and the battery bank [3]. The dispatch strategies available in HOMER software tool are; load following strategy and cycle charge strategy.

4.7.1 Load following strategy

In a load following strategy, only the renewable energy sources charge the batteries whereas the generators do not [98]. The battery bank is charged by excess electricity so that the cost associated with battery charging is maintained as zero. Therefore, when the difference between the energy output of the renewable sources and the load demand at a certain time t (hours) is greater than zero, the battery bank is charged until it gets to its maximum state of charge (SOC_{max}). When the battery attains SOC_{max}, the continuous energy generated are termed excess load. Conversely, if the net difference between the energy from the renewable energy source and load is less than zero, the stored energy in the battery is discharged until the battery reaches a minimum state of charge (SOC_{min}). When the battery is unable to supply the load, the diesel generator is automatically turned on to directly serve the load. In a situation where both the battery bank capacity and the maximum output power from the diesel generator fails to meet the load demand, an unmet load exists.

4.7.2 Cycle charging strategy

In contrast to a load following strategy, the cycle charge considers the use of diesel generator to charge the battery [98]. As a result, in the cycle charge strategy, the diesel generator operates at its maximum capacity to produce excess electricity which can be stored in the battery bank. By doing this, it consumes more fuel which implies that the cost of charging the batteries is not zero as in the load following case. This present study employs cycle charge strategy because it allows the diesel generator to perform to its optimum capacity and the period of startups is reduced which prolongs the life of the generator. However, its drawbacks are that it wears the batteries out easily, produces electrical losses in the batteries as well as power converters. Cycle charge strategy is employed in the algorithm described in figure 4.3.

4.8 Mathematical models

Modeling enables proper designing, analysis and optimization of the mathematical representation of a system thus enabling easy observation of the changes in the system variables. In a hybrid energy system, the performance of the individual components affects the overall system design. Therefore, an overall economic design can only be obtained through the optimal modelling of the individual components of the system. The models for each component in the solar-diesel hybrid setup are discussed in the next heading.

4.8.1 Component models

4.8.1.1 Solar PV model

In HOMER software, the direct current produced by PV modules is directly proportional to the global solar radiation to which it is exposed but independent of its temperature and voltage [99]. Therefore, the output of the PV module can be calculated with the equation 4.1 as provided in [100];

$$P_{pv} = W_{pv} \times f_{pv} \times \frac{G_T}{G_S} \qquad \text{Equation 4.1}$$

where; W_{pv} is the peak power produced by the PV module (kW)

f_{pv} is the derating factor for the PV module (%)

G_T is the solar radiation received by module in the current hour (kW/m^2)

G_S is the incident solar radiation under standard test conditions (1 kW/m^2)

The derating factor (otherwise called performance ratio) is a scaling factor which accounts for effects of dusts on the panel, wire losses, elevated temperature or any other factor that will cause the output of the PV array to deviate from its expected value under standard conditions [19]. Therefore, it could be considered as the relationship between the expected yield and the actual. The details of the solar panel considered for this work is provided in table 3.3 (Chapter 3).

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4.8.1.2 Diesel generator model

Optimal sizing of a diesel generator is necessary because its power output directly relates to its fuel consumption. The fuel consumption F_G (L/hour) for a diesel generator is modelled in [100] as equation 4.2;

$F_G = F_i \, P_{G-rated} + F_S \, P_{G-out}$……………………………………….Equation 4.2

where,

F_i and F_S are the coefficients of fuel consumption specified as 0.05 L/hr/kW rated and 0.33 L/hr/W respectively in this study.

F_i represents the intercept coefficient (L/hr/kWh rated)

F_S represents the slope on the fuel curve (L/hr/kWh output).

$P_{G-rated}$ is the rated capacity of the diesel generator (kW)

P_{G-out} is the output power (kW)

The details about DG sizes and cost inputs are provided in the table 3.4 (Chapter 3).

4.8.1.3 Battery model

Storage devices play important role in the reliability of renewable energy sources. Thus, they are vital components of the hybrid energy system considered in the design of a reliable power solution for BTS. For this study, a Trojan battery storage has been considered. Further details about the sizes, characteristics and cost can be found in Table 3.5 (Chapter 3).

The essential characteristics of a battery that plays significant role in its design and application are: state of charge (%), battery storage capacity (Ah), battery voltage (V), days of autonomy (h), depth of discharge (%), efficiency (%) and battery lifetime (year) [19].

The depth of discharge of a battery (DOD) is the level (%) of stored energy that be extracted from it. It has a relationship with the minimum state of charge (SOC_{min}) of a battery which is the lower limit to which a battery can be drained. The relationship between DOD and SOC_{min} can be represented by equation 4.3;

$DOD = 1 - SOC_{min}$ ……………………………………..……..…Equation 4.3

The days of autonomy of a battery is the number of days in which a fully charged battery is able to adequately serve the load demand without contribution from an auxiliary energy source. HOMER calculates the days of autonomy for a battery storage with equation 4.4 as provided in [100]:

$$AD = \frac{N_{batt} \times V_{nom} \times C_{nom} \left(1 - \frac{SOC_{max}}{100}\right)(24h/day)}{E_{L-avg}\,(1{,}000\;Wh/kWh)}$$ ………..…Equation 4.4

where;

N_{batt} is the number of batteries in the battery bank

V_{nom} is the nominal voltage of a unit battery (V)

C_{nom} is the nominal battery capacity (Ah)

SOC_{max} is the maximum state of charge of the battery (%)

E_{L-avg} is the average daily load (kWh)

Battery lifetime Y_{batt} is an essential feature which directly affects its replacement costs. There are two independent factors that limits the life of a battery bank, these are; the battery float life and the lifetime throughput. The relationship between these variables is represented by the equation 4.5 as obtained from [100];

$$Y_{batt} = \min\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{ann-throughput}}, R_{batt-f}\right) \quad \text{.........................Equation 4.5}$$

where;

$Q_{lifetime}$ is the lifetime throughput of a single battery (kWh)

$Q_{Ann-throughput}$ is the annual battery throughput (kWh/year)

R_{batt-f} is the battery float life (year)

4.8.1.4 Converter model

The proposed schematic illustration for the hybrid set-up (as shown in figure) considers only a rectifier. This is because all the components being powered (including the battery storage) require only DC voltage. Thus, the rectifier is used to convert AC voltage produced by the diesel generator into DC voltage at constant voltage. Details regarding the specifications and cost of the converter are provided in Table 3.6. A simple model for the converter can be represented as equation 4.6.

$$E_{rec-out} = E_{rec-in} \times \eta_{rec} \quad \text{..Equation 4.6}$$

where,

$E_{rec-out}$ is the energy output from the rectifier (kWh)

E_{rec-in} is the energy input to the rectifier (kWh)

η_{rec} is the efficiency of the rectifier (%)

4.8.2 Economic models

Economic optimization provides a means to identify the most economically attractive solution amongst the various combinations of the components. The important economic parameters to be considered in the design of a solar PV-diesel hybrid energy system consists of: capital investment for purchasing the components, the operation and maintenance cost, replacement cost, energy costs (fuel cost and other associated cost) and other costs.

4.8.2.1 Net present cost (NPC)

In HOMER software, the total net present cost represents the life cycle cost of the system and is the criteria for selecting the optimal design configuration. NPC of a system is the present value of all the costs it incurs over its lifetime minus the present value of the revenue it earns over its lifetime. In this study, the costs include parameters such as the capital costs, replacement cost, O&M costs and fuel costs, while revenue include the salvage value of the system. HOMER calculates NPC as equation 4.7;

$$C_{NPC} = \frac{C_{TAC}}{CRF} \quad \text{…Equation 4.7}$$

where,

C_{TAC} is the total annualized cost (defined as the sum of the annualized costs of each component)

CRF is the capital recovery factor and is given by equation 4.8;

$$CRF = \frac{i(1+i)^N}{(1+i)^N-1} \quad \text{…Equation 4.8}$$

where,

N is the project lifetime (years)

i is the annual real interest (%)

In HOMER, all prices is assumed to escalate at the same rate. Hence, annual real interest rate is used rather than a nominal interest rate. By doing this, inflation can be factored out of the analysis. The project lifetime is taken as the expected life time for the solar PV system which is 25 years. Also, the real interest rate is considered to be 9.6% based a five year average (2007-2011) obtained from reference [14].

The salvage value SV of the component is the residual value of the power system at the end of the project lifetime. HOMER assumes a linear depreciation of the components, therefore, the salvage value is directly proportional to the remaining lifetime of the components and inversely to the lifetime of the components as shown in equation 4.9.

$$SV\ (\$) = C_{rep}\frac{N_{rem}}{N_{comp}} \qquad \text{Equation 4.9}$$

$$N_{rem} = N_{comp} - (N_{project} - N_{rep}) \qquad \text{Equation 4.10}$$

where, N_{comp} is the actual lifetime of the component (years)

N_{rem} is the remaining lifetime of the component (years)

N_{rep} is the replacement cost duration (years)

4.8.2.2 Annual cost

The annualized cost of each component is composed of the annualized capital cost C_{acap} and the annualized operating cost C_{aop} (which consists of the annualized replacement cost C_{arep}, O&M cost, and fuel cost) [62].

4.8.2.2.1 Annualized capital cost

The annualized capital cost for each of the component in the hybrid system can be obtained from [62] as equation 4.11.

$$C_{acap} = C_{cap} \,.\, CRF \qquad \text{Equation 4.11}$$

$$C_{acap} = C_{cap} \cdot \frac{i(1+i)^N}{(1+i)^N - 1} \qquad \text{Equation 4.12}$$

where,

C_{cap} is the initial capital cost of each component ($)

4.8.2.2.2 Annualized replacement cost

The annualized value of all replacement costs that occurs over the entire lifetime of the project is referred to as the annualized replacement cost and can be calculated from [62] as;

$$C_{arep} = C_{rep} \,.\, SFF\left(i, N_{comp}\right) \qquad \text{Equation 4.13}$$

$$SFF\left(i, N_{comp}\right) = \frac{i}{(1+i)^{N_{comp}} - 1} \qquad \text{Equation 4.14}$$

$$C_{arep} = C_{rep} \,.\, \frac{i}{(1+i)^{N_{comp}} - 1} \qquad \text{Equation 4.15}$$

where,

C_{rep} is the replacement cost of the component ($)

SFF is the sinking fund factor, a ratio that gives the future value of a series of equal cash flows

N_{comp} is the lifetime of the component (in years)

4.8.2.2.3 Annualized operational expenditure

In this study, the operational expenditure (OPEX) $C_{opex,t}$ entails costs such as the operation and maintenance costs $C_{opex,t}$and fuel cost $C_{opex,t}$ and can be calculated as equation 4.16,

$$C_{opex,t} = C_{O\&M,t} + C_{f,t} \quad \text{Equation 4.16}$$

Therefore annualized operational expenditure can be determined by equation 4.17;

$$C_{aopex} = \sum_{t=1}^{365} C_{opex,t} \quad \text{Equation 4.17}$$

where,

$C_{O\&M,t}$ is the operation and maintenance cost in the year t ($)

$C_{f,t}$ is the fuel cost for the year t ($)

4.8.2.2.4 Annualized operating cost

The annual operating cost, $C_{aop,t}$ is defined as the annual value of all costs and revenues with the exception of the initial capital cost. The revenue in this study is the salvage value of the component. The annual operating cost of each component can be calculated as equation 4.18,

$$C_{aop} = C_{arep,n} + C_{aopex,n} - SV_n \text{..Equation 4.18}$$

Therefore total annualized cost can be determined by equation 4.19;

$$C_{TAC} = \sum_{n=1}^{4} C_{acap,n} + \sum_{n=1}^{4} C_{arep,n} + \sum_{n=1}^{4} C_{arep,n} - \sum_{n=1}^{4} SV_n \text{ ... ... Equation 4.19}$$

where,

n represents the individual components in the solar PV/DG hybrid power system. There are four major components in the HPS, namely; solar PV, DG, battery and rectifier.

4.8.3 Renewable Fraction (RF)

The renewable fraction is the amount (in percentage) of the system's total annual electrical output originating from renewable energy source(s). In this study, RF can be calculated by equation 4.20.

$$RF\ (\%) = \frac{E_{pv}}{E_{total}} \times 100 \text{...Equation 4.20}$$

where,

E_{pv} is the energy produced by the solar PV system

E_{total} is the total energy produced by the hybrid system

4.9 Design constraints

Constraints are conditions that systems must meet to be feasible. HOMER allows users to specify some constraints under which the simulation would be performed. Lambert *et al.* [100] and Dalton *et al.* [101] highlighted the important constraints necessary for HOMER simulation as operating reserve and capacity shortage.

4.9.1 Operating reserve

The operating reserve is the additional reserve capacity a system requires to account for a sudden rise in electrical load or drop in the renewable power output [100]. Usually, HOMER tries to ensure that the operating capacity is always sufficient to supply the primary load as well as the operating reserve. An hourly load reserve of 10% was defined in this study.

4.9.2 Capacity shortage fraction (CSF)

This is the fraction resulting from the addition of the total load and the operating reserve that the system fails to supply power (otherwise called, allowable blackout) [101]. CSF for this study is set at 0 %.

Chapter 5: RESULTS AND DISCUSSIONS

Outline

5.0 Introduction

This chapter presents the results from HOMER simulation for the design of solar PV-diesel-hybrid power system for rural micro BTS in Nigeria. Six average daily solar radiation values; 4.33, 4.50, 4.76, 5.51, 5.81 and 5.97 kWh/m^2/day, are used to simulate the application of solar energy across the six geopolitical zones in Nigeria (as explained in Chapter 3). The case study has an average annual solar radiation of 5.68 kWh/m^2/day. The maximum power consumption for the micro BTS is 145 W (details can be found in Tables 3.1 – 3.2) and this is generalized for all the locations. Five optimal configurations was presented by HOMER simulation which were ranked according to their net present cost (NPC in $) and carbon emission benefits. The simulation results are explicitly discussed under three major factors, namely; (i) energy output, (ii) economic implication (NPC in $), and (iii) environmental impact (kg of CO_2 emitted). Furthermore, statistical analysis of the results are based on the case study at average annual solar radiation of 5.68 kWh/m^2/day and can be extended to other locations giving slight variation in values per annual average solar radiation.

5.1 Simulation results

HOMER simulates the operation of the proposed hybrid system by making energy balance calculations for every time step in each year. In each time step, the energy demand is compared with the supply from the HPS. This process is repeated for every possible system configuration. After this, it determines the most feasible configuration based on the pre-defined constraints and evaluates the costs of running the system over its lifetime.

The results obtained from HOMER are provided in tables 5.1 – 5.5. Table 5.1 shows the ranking of the feasible system configurations. Table 5.2 provides a techno-economic summary for the optimal configuration, while tables 5.3 – 5.5 provides a classification of the simulation results based on renewable energy output, economic implication, and environmental impact respectively.

5.1.1 Optimization criteria

Earlier in this study, it was mentioned that a hybrid power system may be considered as the optimal solution for a BTS if it constitutes the least financial demand (NPC) and the least environmental impact (CO_2 emission), while still providing adequate power for the site load. These variables are considered as the objective functions to be minimized in this study (as stated in Chapter 4). Table 5.1 provides the rankings of the optimal system types obtained from HOMER simulation based on lifecycle cost which has been represented as NPC.

Table 5.1: Optimal hybrid power solutions and their ranks

Configuration	**Rank**	**PV (kW)**	**DG (kW)**	**Battery (Units)**	**Rectifier (kW)**	**Initial capital ($)**
PV/DG/Batter/Rectifier	1	1	0.5	4	0.5	5,665
PV/Battery	2	1.5	-	8	-	8,400
DG/Battery/Rectifier	3	-	0.5	4	0.5	1,665
DG/ Rectifier	4	-	0.5	-	0.5	465
PV/DG/ Rectifier	5	1.0	0.5	-	0.5	4,465

The rankings of the possible configurations shown in table 5.1 also reflect the advantages of each system based on minimal environmental impact and system reliability. Further details on these for each BTS location can be found in tables 5.3 – 5.5. It can be observed that the required component sizes for each configuration vary which consequently affects the capital investment. Nevertheless, initial capital cost alone is not a sufficient information to be considered in the selection of an optimal power technology for BTS. This is because a hybridized solar PV/DG/battery system which satisfies the objectives of this study more than the other possible configurations is the second most expensive configuration. Investing in traditional DG/battery system seems fairly logical because it has a very moderate initial capital cost ($ 1,665), however, this configuration is ranked as the third of the possible five configurations, showing that it cannot be considered as a long term economic solution for the BTS. It is also interesting to see that solar PV/battery system which constitutes the highest initial investment is ranked as the second most viable solution. This is because a very minimal operating cost will be incurred over the project's lifetime which will compensate for its high initial capital cost.

Based on the rankings in table 5.1, solar PV/DG/battery is taken as the optimum system configuration that satisfies the objectives this study. Also, table 5.1 shows that 1 kW PV module and 500 W DG with 4 units of 6 V (360 Ah) battery and 500 W rectifier makes up the most economical component sizes. An overview of the techno-economic details for the optimum hybrid configuration at different annual average solar radiation is presented in Table 5.2.

Table 1.2: Summary of the optimal techno-economic results for solar-diesel hybrid system

Technical factors					**Economic factors**			**DG factors**	
Annual average radiations (kWh/m^2)	PV (kW)	DG (kW)	Battery (units)	Rectifier (kW)	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Diesel fuel (liters)	DG (hours)
4.33	1	0.5	4	0.5	5,665	423	9,630	73	495
4.50	1	0.5	4	0.5	5,665	384	9,258	60	392
4.76	1	0.5	4	0.5	5,665	337	8,821	42	280
5.51	1	0.5	4	0.5	5,665	287	8,349	24	164
5.81	1	0.5	4	0.5	5,665	273	8,222	20	133
5.97	1	0.5	4	0.5	5,665	267	8,165	17	121

Table 5.2 shows that the optimal configuration for the micro BTS is the same for all the annual average solar radiation considered in this study. This implies that the size of the components at each proposed location remains the same as well as the initial capital ($ 5,665). However, the energy contribution from solar PV and DG differs in each location (details are provided in table 5.3). In general, table 5.2 shows that an increase in the annual average solar radiation reduces the operation period of the DG and the consumption of diesel fuel. This is because the energy contribution from solar PV increases with radiation rate which reduces the energy contribution from DG. Therefore, the operating cost associated with the use of DG reduces. Eventually, the benefit of this is revealed in the reduction in NPC per increase in average solar radiation rate.

5.2 Analysis of results

The analysis of results is classified into three subsections, namely; (i) energy output analysis, (ii) economic analysis, and (iii) environmental impact analysis. The results for each classification are provided as tables 5.3, 5.4 and 5.5 respectively. In each table, the proposed hybrid configuration is compared with the existing condition in most rural off-grid BTS in Nigeria. Statistical analysis is carried out under each category for the annual average solar radiation of 5.68 kWh/m^2/day taken to be the case study. Thus this study assumes that a slight variation in result will be obtained if other annual average solar radiation

5.2.1 Energy output analysis

The service integrity (or reliability) of a power system is the first consideration that qualifies it to be deplorable for a base transceiver station. This is because BTS equipment must be constantly powered for effective connection between the network providers and the end users. Renewable energy power systems have been identified with a lower maintenance requirement compared to DG [25]. Therefore, in this study, the proposed hybrid power system is expected to have a very high penetration of solar PV power in its electrical energy output which will be sufficient in increasing the renewable energy contribution and consequently reducing energy contribution from the diesel generator. As a result, the operation hours of the DG and the consumption of the conventional fuel can be significantly decreased. Thus, renewable energy fraction is considered to be an important criterion in the energy output analysis discussed in this study.

Table 5.3: Classification of results according to the renewable energy fraction in the energy mix

BTS sites		**Hybrid configuration**				
Area	Average annual radiations (kWh/m^2/day)	PV/DG/Bat/Rec	PV/Bat	DG/Bat/Rec	DG/Rec	PV/DG/Rec
Ogbia	4.33	0.87	1	0	0	0.48
Umuoda	4.50	0.90	1	0	0	0.49
Lisa	4.76	0.93	1	0	0	0.51
Wase	5.51	0.96	1	0	0	0.55
Chibok	5.81	0.97	1	0	0	0.56
Bodinga	5.97	0.98	1	0	0	0.57

Note: *Values in blue colour represents the proposed hybrid configuration while the ones in red colour represents the current case (conventional power source for off-grid) in Nigeria*

Table 5.3 shows the fraction of renewable energy (RF) in the electric energy output for the different annual average solar radiation values. As earlier defined, RF is the fraction of energy produced by the solar PV system in the overall electrical energy from the hybrid power system. It increases as the average solar radiation values increases. According to table 5.3, it is possible to have at least 87% of the micro BTS's needed energy from solar PV even in an area like Ogbia which has a very low annual average solar radiation. The penetration of renewable energy increases up North. For the same BTS situated in the Northern areas, like Bodinga and Chibok, RF can rise to as high as 98%. Having high values of RF as shown in table 5.3 further supports the need to fully adopt renewable solar energy resource in powering a micro BTS in Nigeria which is an important contribution made by this study. Contrary to this, Anayochukwu and Onyeka [102] reported the RF for a macro BTS in Nigeria to be just 14%, while a larger portion of the energy contribution (86%) comes from DG. The annual energy contributions from each power system are provided in figure 5.1.

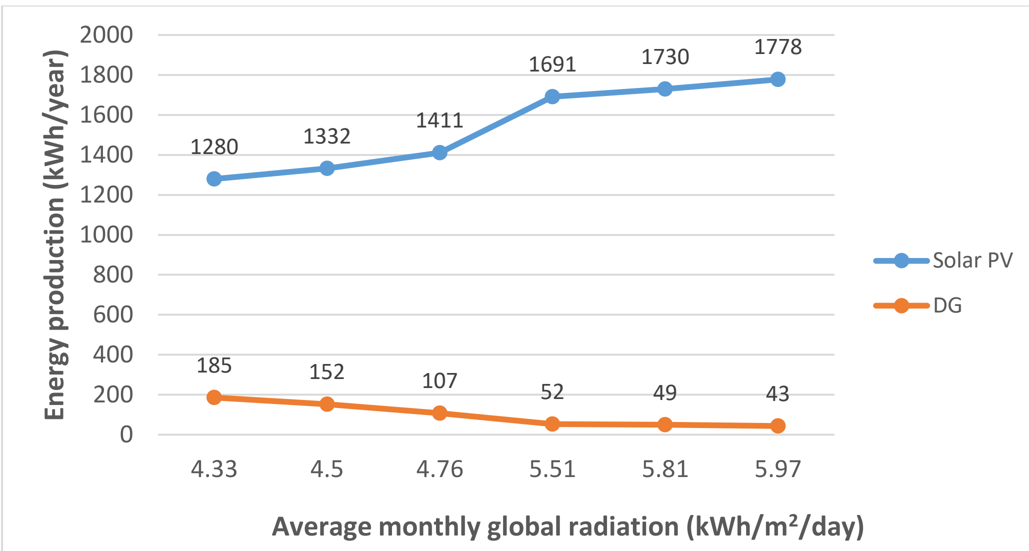

Figure 5.1: Annual energy contribution from solar PV and DG for different annual average solar radiations

Figure 5.1 illustrates the annual energy contribution from solar PV and DG for the different average solar radiations. The annual contribution from solar energy increases from 1280 kWh/year to 1778 kWh/year while energy from DG reduces from 185 kWh to 43 kWh. This clearly shows that an increase in annual average solar radiation favours higher energy contribution from solar PV and consequently reduces the energy consumption from DG. This is a much-desired result because the increased penetration of solar energy reduces the use of DG which is the traditional power source in off-grid BTS. Alsharif *et al.* [19] reported a similar observation in their study for Malaysia.

However, for these sites, the maximum energy contribution from DG is between June and September. This is due to the increased cloud cover between these months for a typical Nigerian climate, which reduces the solar insolation received (as shown in figure 5.2). Thus, areas up north, with much higher solar irradiance can power the micro BTS with only solar energy for almost the entire months of the year, while DG is used between June and September.

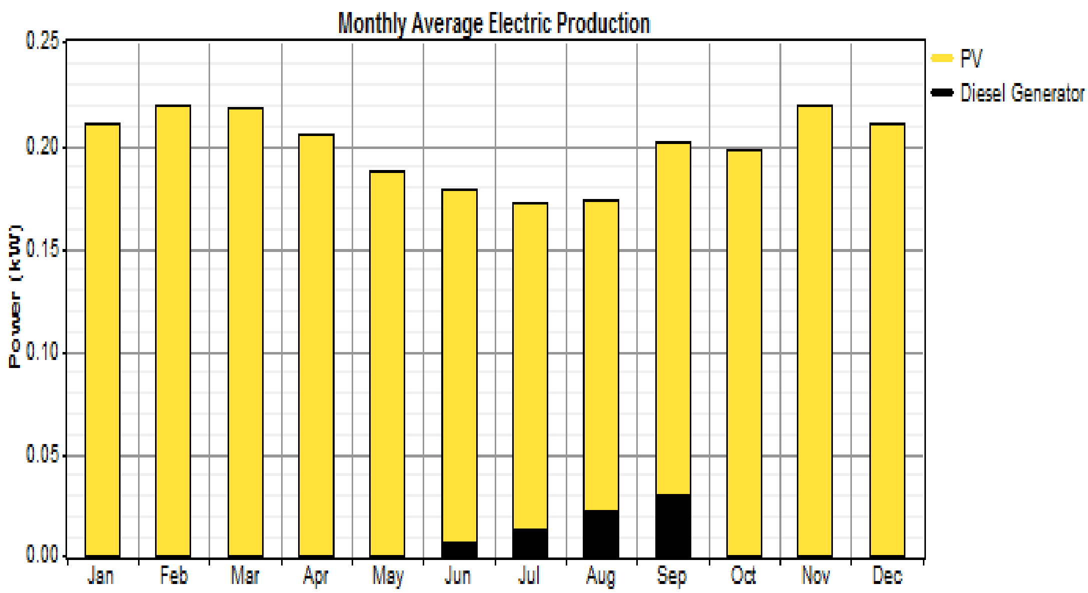

Figure 5.2: Electrical energy output from solar PV/DG for the case study (5.68 kWh/m^2/day)

A detailed statistical analysis of the energy output is based on an average daily solar radiation of 5.68 kWh/m^2 which is considered as the case study. All statistical analysis is based on the mathematical models provided in chapter four and can be extended to each of the locations to give a slight difference in values per annual average solar radiation used in characterizing these locations.

The load demand for the micro BTS is estimated to be 145 W (table 3.1), which gives an annual energy consumption of 1270 kWh/year (145 W × 24 h × 365 days/year). The annual energy contribution from the solar PV system in the overall energy output is 1,691 kWh. This is computed based on equation 4.1 as 1,691 kWh/year (1 kW PV capacity × 5.68 peak sunshine hours × 0.8 PV derating factor × 365 days/year). No tracking system was used in the simulation of the solar PV to determine its worst performance. DG supplies the remaining portion of the energy (3% of overall output) in the mix which is 52 kWh/year with just 10 start-ups per year.

Therefore, the total annual energy output from the hybrid system is 1,743 kWh (1,691 kWh from solar PV and 52 kWh from DG), while the energy demand by the micro BTS is 1,270 kWh/year. The difference between the energy output and energy demand amounts to an excess electricity of 343 kWh/year plus 122 kWh/year battery losses and 7 kWh/year rectifier losses.

A battery string contains six batteries of 4 V each. The annual energy-in is 825 kWh/year, while the energy-out is 702 kWh/year using a round trip efficiency of 85%. Therefore, the battery bank autonomy is calculated as 41.7 hours using equation 4.3 - 4.4 (4 batteries × 6 V nominal voltage × 360 Ah nominal capacity × 0.7 × 24hours/day) divided by (daily average for the micro BTS 3,480Wh). Also, the energy-out for the inverter is calculated as 41 kWh/year based on equation 3.4 with energy-in 48 kWh/year and 85% efficiency.

5.2.2 Economic analysis

The economic implication of the optimal hybridized system is the second optimal criteria used in assessing the proposed hybrid power system for this study. The economic analysis for the various average daily solar radiations is further divided into 3 categories, namely; (i) initial capital cost, (ii) annual operating cost, and (iii) NPC. However, the detailed statistical analysis is based on a cash flow summary obtained at an average solar radiation of 5.68 kWh/m^2/day (shown in figure 5.3) which is considered as the case study in this work.

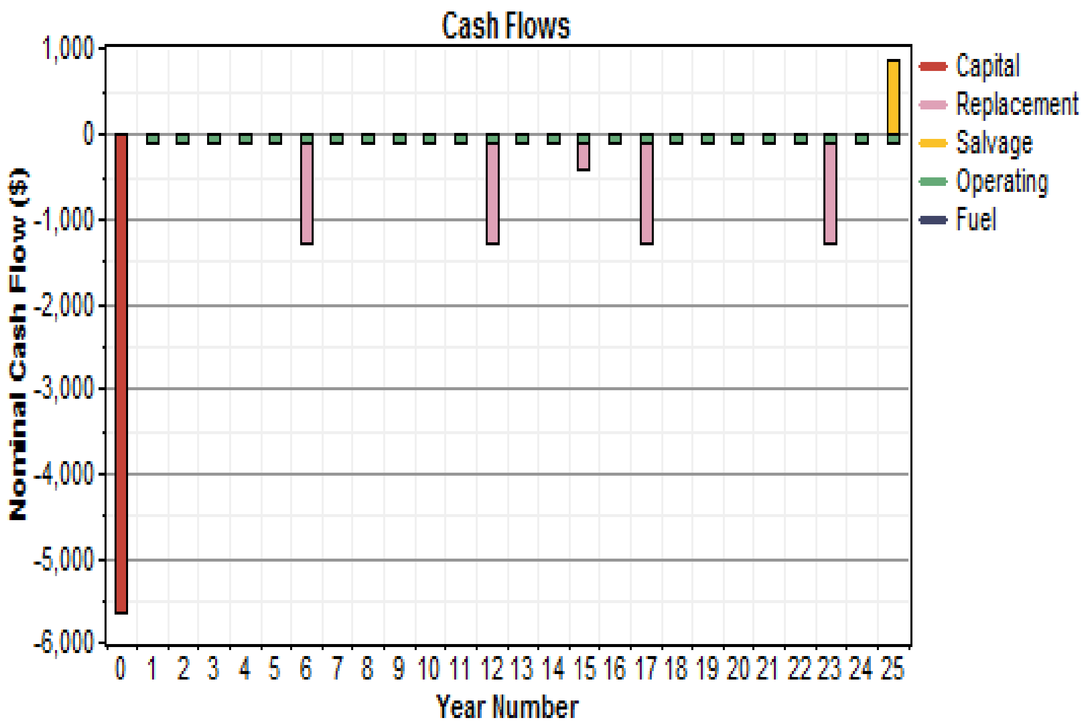

Figure 5.3: Cost flow summary for solar PV/DG hybrid power system for 5.68 kWh/m2/day

5.2.2.1 Initial capital cost

This represents the amount (in $) paid to acquire the energy components and install on site. This varies directly with the size of the energy system as earlier shown in table 5.1. Also, according to figure 5.6, the initial capital cost for the optimum configuration is set at $ 5,665 irrespective of the average solar radiation values. The reason for this is because HOMER simulation gave the same optimal design for the six daily solar radiation values that were studied. The percentage share of each component in the initial capital cost is provided in figure 5.5 based on the cost for each component shown in figure 5.4. Solar PV amasses 71% ($ 4,000/$ 5,665) of the total initial investment. The next most major share goes to the energy storage medium 21% ($ 1,200/$ 5,665), while rectifier and diesel generator may be considered as the least financial burden because they account for just 6% ($ 350/$ 5665) and 2% ($ 115/$ 5,665) of the initial capital cost respectively.

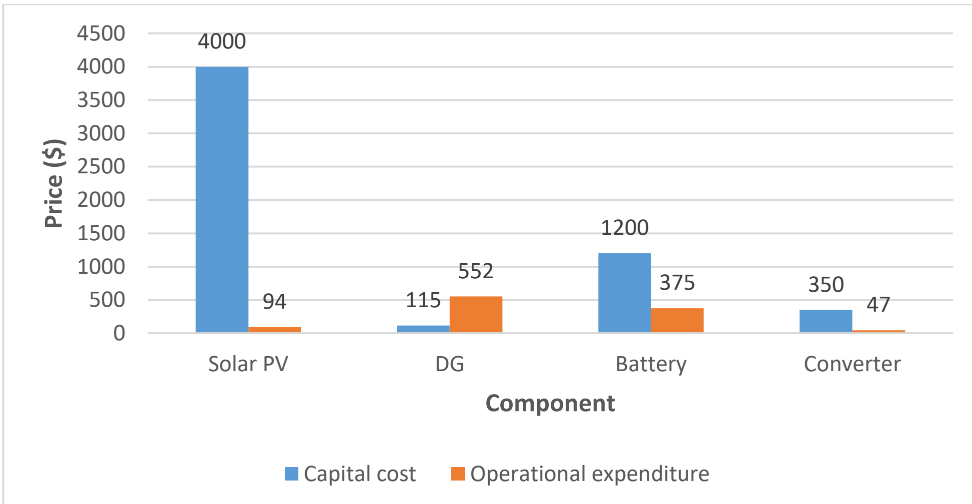

Figure 5.4: Comparison between the capital and operating costs for the optimal hybrid components

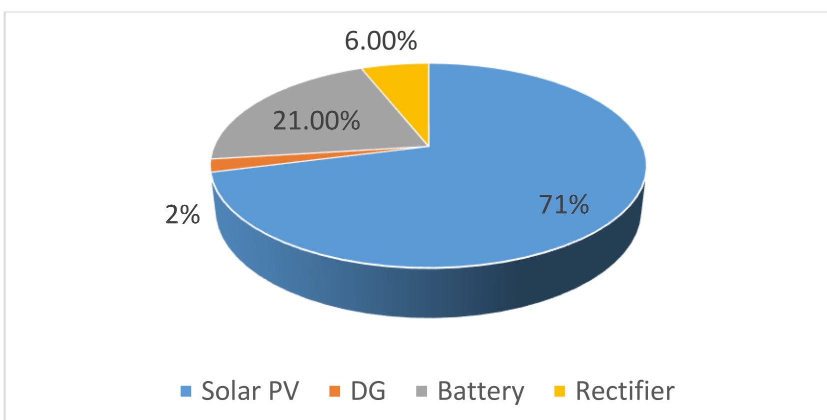

Figure 5.5: Share of capital cost between components in the solar-diesel hybrid system for 5.68 kWh/m2/day

5.2.2.2 Annual operating cost

This is comprised of all cost values except the initial capital cost. Therefore, it is the addition of the annual OPEX, annual replacement cost and the salvage value.

OPEX consists of the O&M and fuel costs incurred in running the energy system. For the case study, the total OPEX is calculated based on equation as $ 1,067 ($ 852 O&M + $ 215). The annualized value of OPEX is $ 114 ($1067 divided by a capital recovery factor of 0.107). The distribution of OPEX amongst the hybrid system components is shown in figure 5.6. Also, the figure shows that the major part of the operational expenditure is used in running the DG. This is because DG alone requires additional fuel cost which influences the OPEX of the entire energy system. This implies that more OPEX will be incurred when DG energy contribution increases.

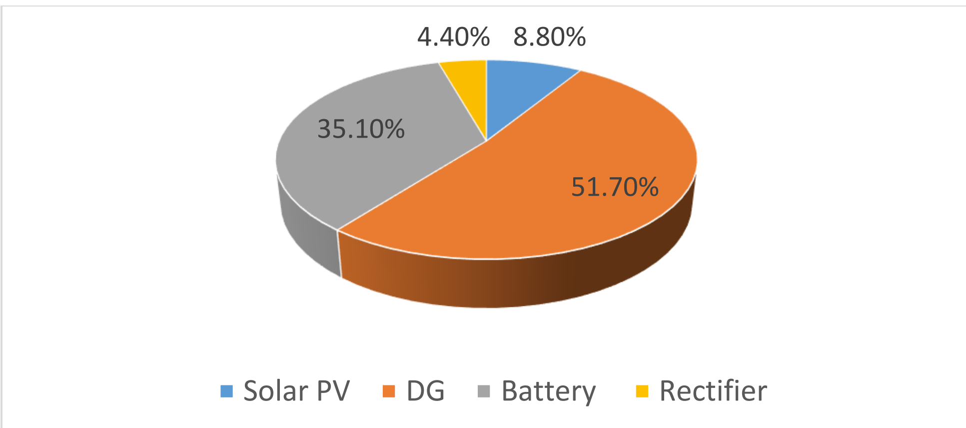

Figure 5.6: Share of OPEX between the components in the solar-diesel hybrid system for 5.68 kWh/m2/day

Replacement cost of some specific components like batteries and converter is calculated based on equation 4.13 - 4.15. The replacement cost for the batteries is computed as $165/year ($ 300 replacement cost × sinking fund factor of 0.141 based on a real interest of 9.69% and expected life of 5.65 years × 4 batteries). Similarly, the replacement cost for the inverter is $ 8/year ($300 replacement cost for half the size of 1kW × sinking fund factor of 0.0324 based on real interest rate of 9.69% and expected lifetime of 15 years). The addition of these costs gives an annual replacement cost of $ 173. Therefore, considering the cash flow summary in figure 5.3, a replacement cost of $ 932.25 ($165/years × 5.65 years) is paid every 5.65years for the batteries and a replacement cost of $120 will be paid in the 15th year for the rectifier.

The annual operating cost is therefore estimated from equation 4.18 as, $278 ($173 annual replacement cost + $ 114 OPEX - $9 SV). The cash flow shown in figure 5.3 shows that the operating cost of $278 is the same for each year for the project lifetime.

Figure 5.7 provides a graphical illustration of the variation of the operating cost and fuel cost with different solar radiation values. Since the energy contribution from solar PV increases with solar radiation rate, it is expected that the contribution from DG will reduce simultaneously. Likewise, a reduced use of DG will reduce the major portion of the operating cost which is the OPEX. Eventually, the operating cost reduces as the solar radiation values increase.

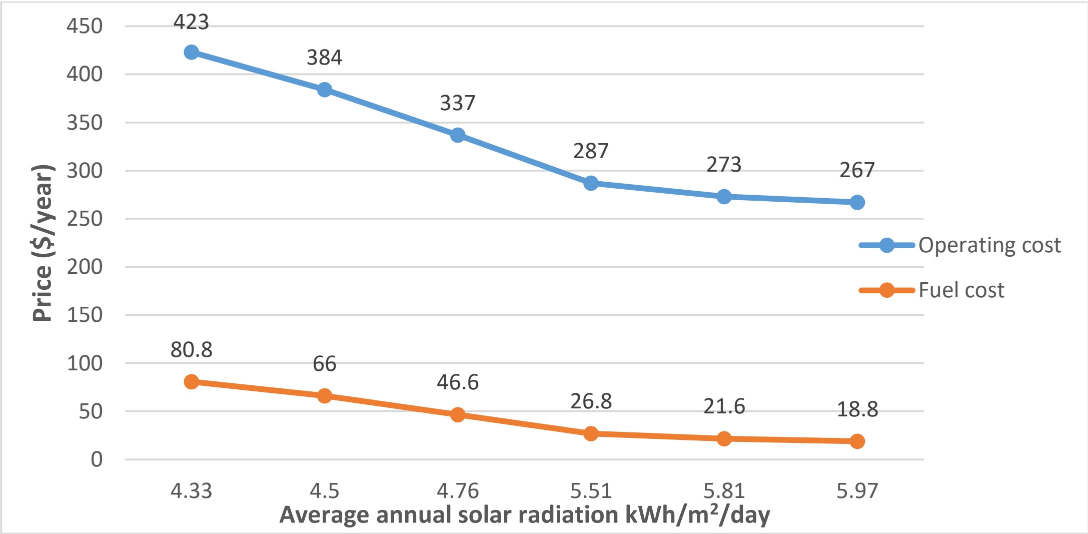

Figure 5.7: Variation of fuel cost and operating cost for different average annual solar radiation values

5.2.2.3 NPC

This is the present value of all costs incurred over the lifetime of the energy system. It is the sum of the entire cost and revenue. In this study, the costs include capital, replacement and the operational expenditure while the only revenue is the salvage value of the components. Each of these costs is composed of the capital recovery factor which is obtained as 0.107 based on equation 4.8. Therefore NPC at an average daily solar radiation of 5.68 kWh/m^2 can be mathematically obtained as $ 8,266 based on equation 4.8 and 4.19, which includes: capital costs of components ($ 5,665) + replacement costs ($ 1,622) + OPEX ($ 1067 = $ 852 O&M + $ 215 fuel cost) – Salvage value ($ 88).

Table 5.4: Classification of results based on the economic criteria (Total NPC in $)

BTS sites		**Hybrid configuration**				
Area	Average annual radiations (kWh/m^2/day)	PV/DG/Bat/Rec	PV/Bat	DG/Bat/Rec	DG/Rec	PV/DG/Rec
Ogbia	4.33	9,630	10,512	18,262	29,016	31,894
Umuoda	4.50	9,258	10,512	18,262	29,016	31,881
Lisa	4.76	8,821	10,512	18,262	29,016	31,709
Wase	5.51	8,349	10,512	18,262	29,016	31,646
Chibok	5.81	8,222	10,512	18,262	29,016	31,758
Bodinga	5.97	8,165	10,512	18,262	29,016	31,608

Note: *Values in blue colour represents the proposed hybrid configuration while the ones in red colour represents the current case (conventional power source for off-grid) in Nigeria*

Table 5.4 shows the important benefit of a solar PV/DG/battery configuration over the other possible power solutions. For all the solar radiation values, this configuration amounts to the least NPC. Deploying a solar PV/DG/battery HPS gives at least 47.3% reduction in NPC compared to a DG/battery system despite having a higher capital cost. NPC reduces even further as the average annual solar radiation increases. Once again, this is due to a reduction in the energy contribution from DG which consequently reduces the operating cost.

5.2.3 Environmental impact analysis

As stated in chapter 2, the important benefit of using renewable energy resources for power generation is that they are clean. However, solar-diesel hybrid power system which has the least carbon emission of all the configurations in table 5.5 cannot be referred to as a clean energy source because it has DG power system. In this study, the criteria used in measuring the level of environmental impact is the kilogram of carbon emissions which is also an objective function to be minimized.

Table 5.5: Classification of results according to environmental impact (CO_2 emissions kg/year)

BTS sites		**Hybrid configuration**				
Area	Average annual radiations (kWh/m^2/day)	PV/DG/Bat/Rec	PV/Bat	DG/Bat/Rec	DG/Rec	PV/DG/Rec
Ogbia	4.33	193	0	1,652	1,875	1,741
Umuoda	4.50	158	0	1,652	1,875	1,740
Lisa	4.76	112	0	1,652	1,875	1,729
Wase	5.51	64	0	1,652	1,875	1,725
Chibok	5.81	52	0	1,652	1,875	1,732
Bodinga	5.97	45	0	1,652	1,875	1,723

Note: *Values in blue colour represents the proposed hybrid configuration while the ones in red colour represents the current case (conventional power source for off-grid) in Nigeria.*

Table 5.5 shows the emissions for the different sites. Popularly used DG/battery source will emit 1,652 kg of CO_2 annually compared to solar/DG/Battery with a maximum of 193 kg of CO_2. This a very significant drop in carbon emission. The addition of batteries to the HPS also helps to considerably reduce the dependence on fuel which cuts the carbon emissions. About 1,548 kg of CO_2 per year was saved by adding batteries to a solar PV/DG only system at low radiation and up to 1,678 kg of CO_2 per year at higher radiation. Figure 5.8 shows the influence of solar radiation on the diesel consumption per site. In general, as the average solar radiation values increase from the south up north, the carbon emissions from the sites reduces as a result of a decrease in the energy contribution from DG and fuel usage. This supports the findings in the work done by Kareem and Abdul-Hussain [20].

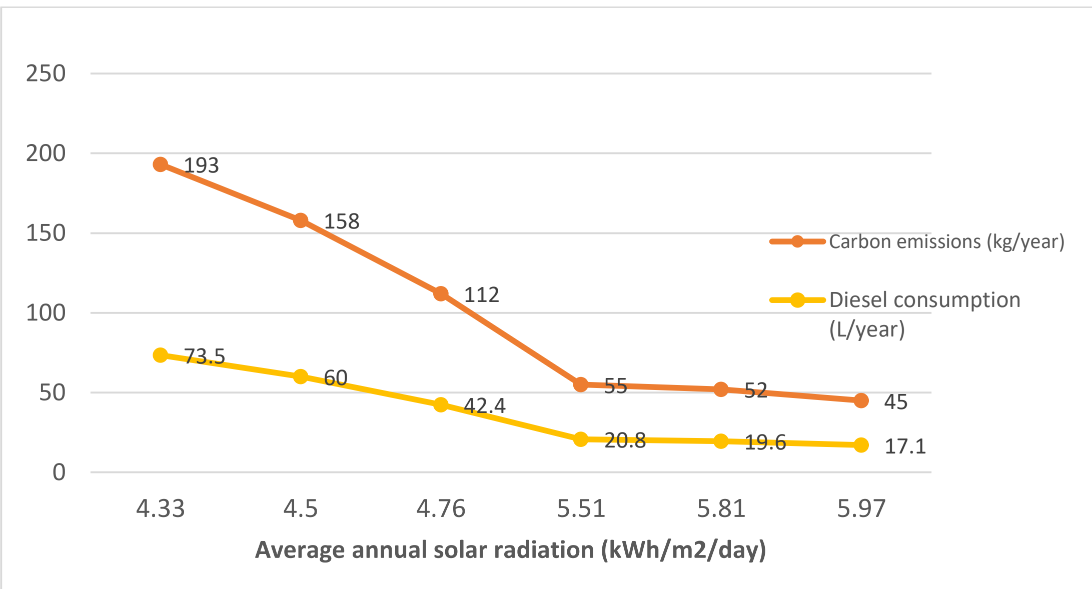

Figure 5.8: Variation of diesel consumption and carbon emission for different annual average solar radiation values

5.2.4 Sensitivity analysis for fuel price

Apart from the effect of average annual solar radiation variation, the effect of a variation in fuel cost was also studied in the sensitivity analysis. This is because the price of diesel varies across Nigeria and as a result it is anticipated that diesel price could influence the optimal solution for some locations. Diesel prices such as; $0.8, $0.9, $1, $1.2 per L have been considered as sensitivity variables in HOMER simulation. The optimal system type (OST), which is solar PV/DG/battery, remains the same regardless of the fuel price. Figure 5.9 shows that an increase in fuel price will consequently increase the NPC for all the BTS locations.

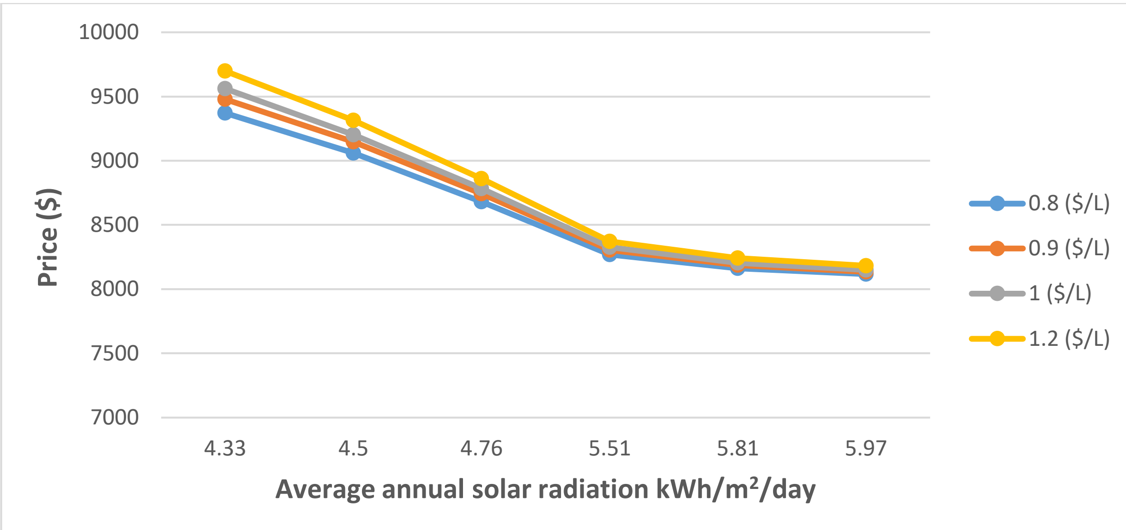

Figure 5.9: Sensitivity analysis for NPC ($) variation with fuel prices ($/L)

5.3 Discussions

An in-depth analysis of results obtained from the simulation emphasizes the following key findings: (i) solar PV/diesel generator/batteries is superior to the other four configurations possible in meeting the objectives of this study; (ii) the inclusion of solar PV to the traditional DG/battery system increases the initial capital cost of the system, but significantly reduces the net present cost in the long run; (iii) the use of solar PV system reduces the environmental impact caused by the hybrid system significantly, and (iv) as the energy contribution from solar PV in the electrical output increases, the operational expenditure of the entire system and kg of carbon dioxide gas released reduces significantly.

5.3.1 Justification for the proposed hybrid power solution for Nigerian BTS

Solar energy has been established to be a readily available resource in every part of Nigeria, especially for telecommunication application. Furthermore, its ability to provide energy anywhere it is needed and modular technology makes it a more viable option for BTS than other renewable energy resources. The results of this study have shown that the penetration of solar radiation in the different locations boosts the renewable fraction in the energy mix which is highly desired for a remote based BTS in Nigeria.

Alsharif *et al.* [19] compared the economic feasibility of using solar PV/DG hybrid system in Malaysia and Germany. The study showed that the net present cost of deploying the power solution in Germany is approximately double the cost for Malaysia, even though the price of solar PV system is much cheaper in Germany. This is because the average solar radiation in Germany is 58.8% that of Malaysia. Therefore, the energy contribution from a solar power system in Malaysia reaches up to 43% thus reducing the operating cost incurred with the use of a DG. This result provides a logical support for the adoption of a hybridized solar PV/DG/battery power system in Nigeria because it receives a higher average solar radiation than Malaysia and Germany. To deploy a similar hybrid system in Nigeria, the energy contribution from solar power system is expected to be far more than the diesel generator which will reduce the operating cost of the hybrid system and pollution level even further. This has been proven in this study.

Based on these important observations, we can rightly say that it is undesirable for Nigerian mobile network operators to continue with diesel generators.

Chapter 6: CONCLUSION AND RECOMMENDATIONS

Outline

6.0 Introduction

This section gives an overview of this study and concludes with the relevance of the thesis. Recommendations were also added to show important aspects which could add to the current study.

6.1 Conclusion

Nigerian mobile network operators need a reliable, cost effective and environmentally friendly power solution for off-grid BTS, especially in rural areas. This would help them deploy telecommunication infrastructures in remote locations in order to connect with their potential customers. Through this study, a hybrid power system comprising solar PV/DG/battery has been shown to be the most suitable power solution compared to other possible configurations considered in meeting the load demands of a rural micro BTS in Nigeria.

HOMER simulation tool was used to model and optimize an off-grid solar PV/DG/battery hybrid power system for Nigeria and to evaluate the performance of this system under six different annual average solar radiation values. The annual average solar radiation values represent actual rural locations for the BTS in the six geopolitical zones of Nigeria, namely; Umuoda (South-East), Ogbia (South-South), Wase (North-central), Lisa (South-West), Chibok (North-East) and Bodinga (North-West).

The optimal system configuration from HOMER that would effectively power a peak load demand of 145 W was the same for all solar radiation values indicating that the component sizes [1 kW solar PV, 0.5 kW DG, 4 units of 6V (360 Ah) batteries in series and 0.5 kW rectifier] are the same for all the locations considered. The optimal configuration was compared with the conventional power source.

The economic benefit of the optimal configuration was revealed by a 47.3% decrease in the net present cost of running the system for 25 years compared to the conventional DG/battery system which currently exists in most off-grid areas. Furthermore, solar energy makes up at least 87% of the total energy produced by the hybrid power system. In some sites, a diesel generator may not be needed until June to September, when the clearness index drops. This offers an important environmental benefit because the consumption of diesel fuel is significantly reduced at the base stations. This helps to avoid the periodic maintenance of the diesel generator and its associated operating costs.

In summary, this study has shown the importance of a hybridized solar PV/DG/battery power system in addressing a pressing need in the Nigerian telecommunication sector. Although, the aim of this study is not to show the most viable site for the proposed hybrid power solution, however, the results obtained can be used by the Nigerian Communication Commission (NCC) in developing a framework or guide for the establishment of green mobile telecommunication stations in Nigeria based on anticipated financial demands.

6.2 Recommendation

The economic inputs used in this study, which includes; capital costs of components, replacement costs, maintenance costs and real interest rate, have been obtained from recent literature sources and based on a comparison with current market prices. Therefore, it is recommended that these values be tested in real life situation as a continuation of this work.

Also, to further examine the financial demands of the proposed hybrid solution, this study recommends that a reliable software tool such as RETScreen be used in a future work.

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APPENDICES

This section is divided into two subsections; (i) Appendix A, and (ii) Appendix B. Appendix A provides additional tables for the optimization results while Appendix B provides the pictorial illustrations of the annual electrical energy output per site.

(i) Appendix A

Table 1A: Optimization results for Ogbia site (4.33 kWh/m^2/day)

Configuration	Initial capital	Operating cost	Total NPC	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	423	9,630	0.810	0.87	73
PV/battery	8,400	226	10,512	0.884	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,929	31,894	2.682	0.48	661

Table 2A: Optimization results for Lisa site (4.5 kWh/m^2/day)

Configuration	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	384	9,258	0.778	0.90	73
PV/battery	8,400	226	10,512	0.884	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,928	31,881	2.680	0.49	661

Table 3A: Optimization results for Umuoda site (4.76 kWh/m^2/day)

Configuration	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	337	8,821	0.742	0.93	42
PV/battery	8,400	226	10,512	0.884	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,910	31,709	2.666	0.51	657

Table 4A: Optimization results for Wase site (5.51 kWh/m^2/day)

Configuration	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	287	8,349	0.702	0.96	24
PV/battery	8,400	226	10,512	0.884	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,903	31,646	2.661	0.55	655

Table 5A: Optimization results for Chibok site (5.81 kWh/m^2/day)

Configuration	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	273	8,222	0.691	0.97	20
PV/battery	8,400	226	10,512	0.884	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,915	31,758	2.670	0.56	658

Table 6A: Optimization results for Bodinga site (5.97 kWh/m^2/day)

Configuration	Initial capital ($)	Operating cost ($/year)	Total NPC ($)	Cost of energy ($/kWh)	RF	Diesel fuel (L)
PV/DG/battery	5,665	267	8,165	0.686	0.98	17
PV/battery	8,400	221	8,465	0.712	1.00	-
DG/battery	1,665	1,772	18,262	1.535	0.00	627
DG only	465	3,049	29,016	2.439	0.00	712
PV/DG only	4,465	2,899	31,608	2.657	0.57	654

(ii) Appendix B

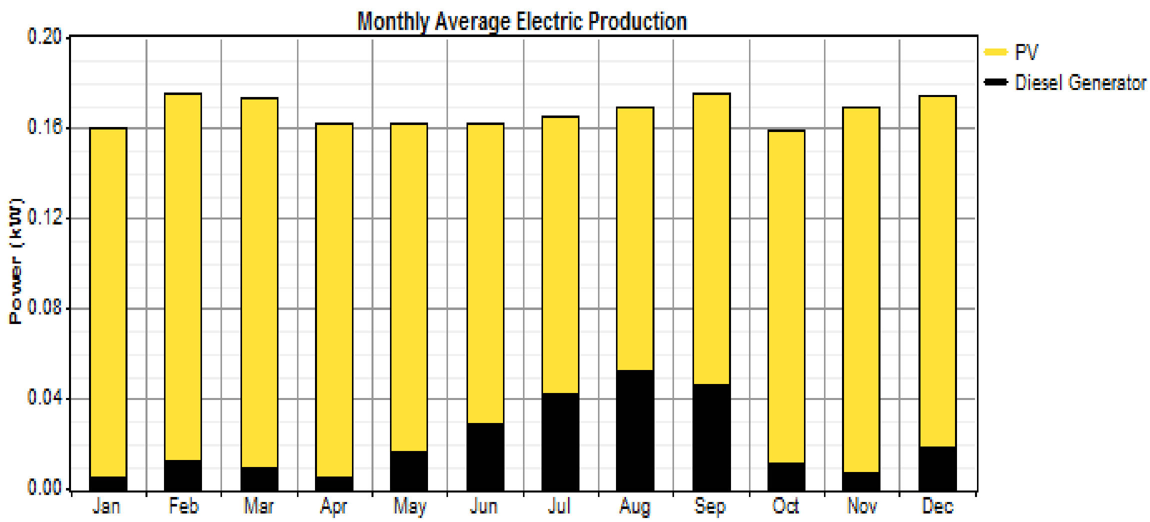

Figure 1B: Annual electric energy output for Ogbia site (4.33 kWh/m^2/day)

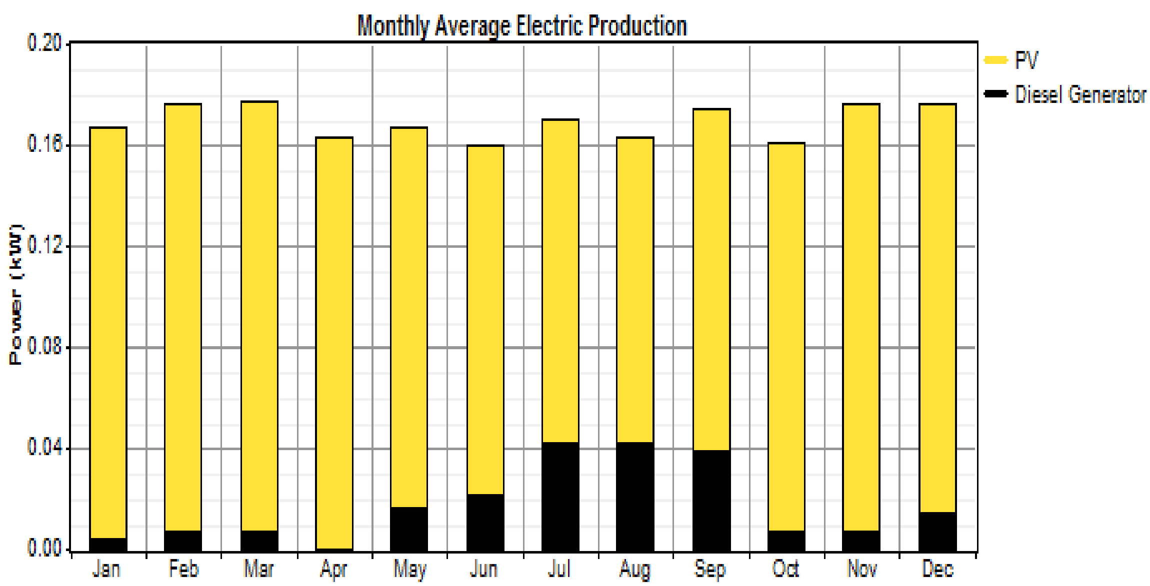

Figure 2B: Annual electric energy output for Lisa site (4.5 kWh/m^2/day)

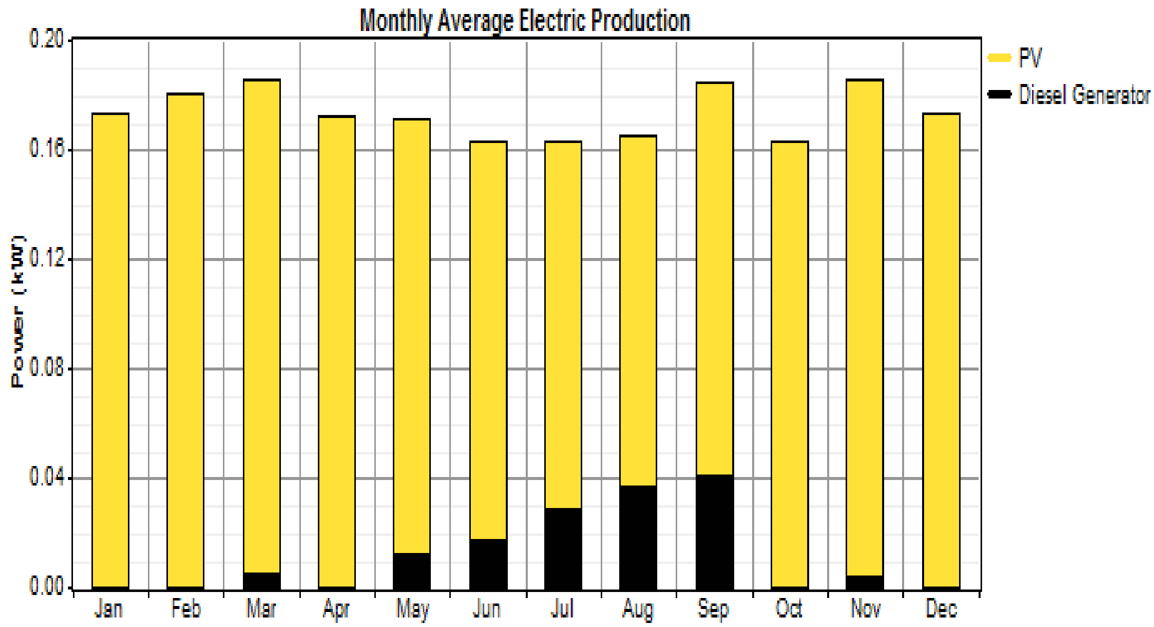

Figure 3B: Annual electric energy output for Umuoda site (4.76 kWh/m^2/day)

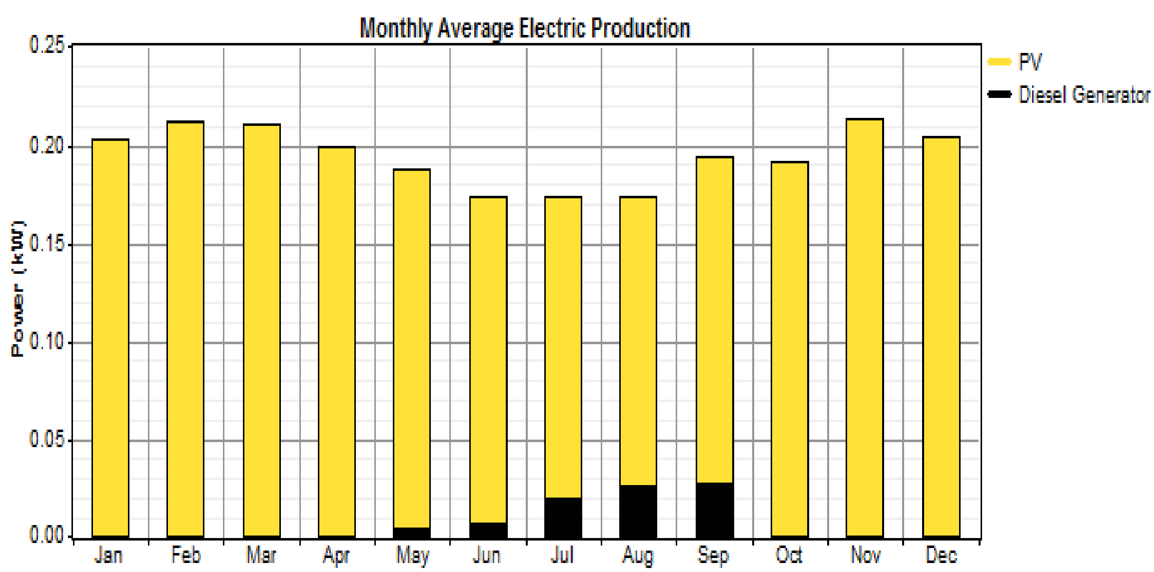

Figure 4B: Annual electric energy output for Wase site (5.51 kWh/m^2/day)

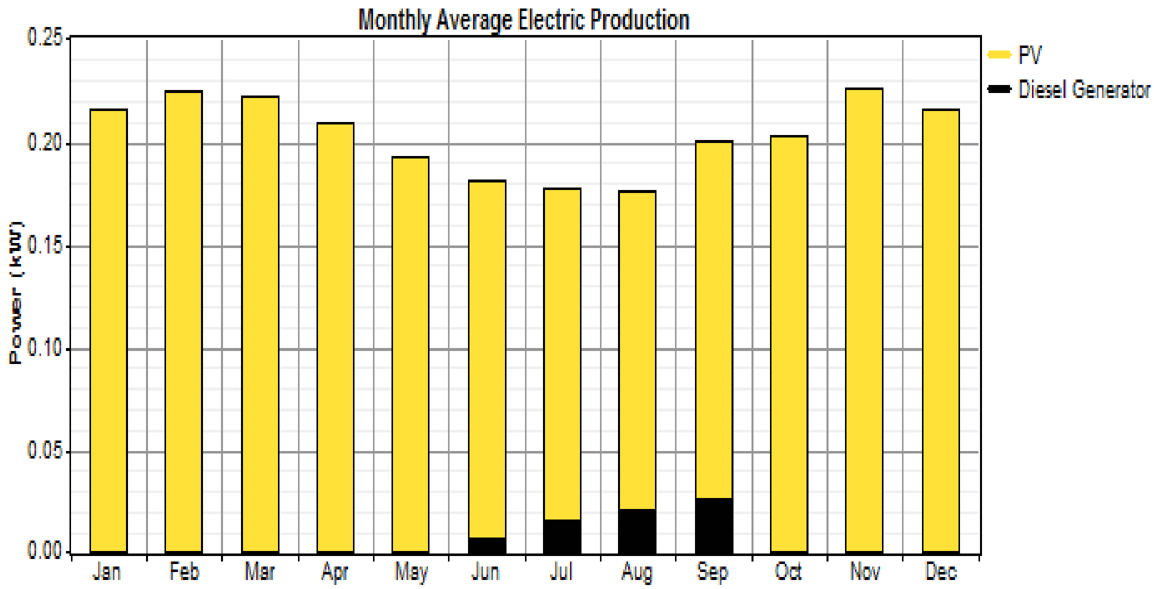

Figure 4B: Annual electric energy output for Chibok site (5.81 kWh/m^2/day)

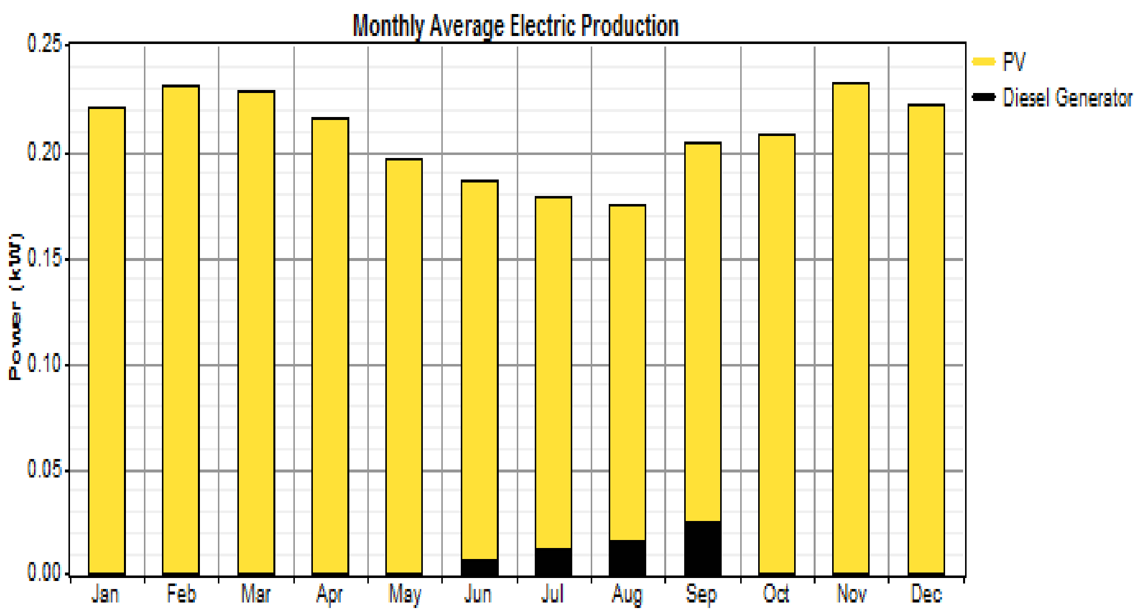

Figure 6B: Annual electric energy output for Ogbia site (5.97 kWh/m^2/day)