Pan African University
Institute of Water and Energy Sciences

TECHNO-ECONOMIC ANALYSIS OF A HYBRID POWER SYSTEM FOR RURAL ELECTRIFICATION IN NIGER: CASE OF NGONGA ZARMA VILLAGE

MASTER'S THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE MASTERS DEGREE IN ENERGY: ENGINEERING TRACK

PRESENTED BY

Ms NANFUKA OLIVIA
Bsc Chemical Engineering

September, 2019

Pan African University
Institute of Water
and Energy Sciences

PAN-AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES

(Including CLIMATE CHANGE)

Master Dissertation

Submitted in Partial Fulfillment of the Requirements for the Award of Master Degree in
[**ENERGY ENGINEERING**]

Presented by

Olivia, NANFUKA

TECHNO-ECONOMIC ANALYSIS OF A HYBRID POWER SYSTEM FOR RURAL ELECTRIFICATION IN NIGER: CASE OF NGONGA ZARMA

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DISSERTATION APPROVAL PAGE

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DEDICATION

I dedicate this work to my beloved parents; thank you for being a great pillar in my life.

PAN AFRICA UNIVERSITY

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BIOGRAPHICAL SKETCH

Nanfuka Olivia was born and raised in Luteete located in Bamunanika town, Luweero District. She holds a BEng degree in Chemical Engineering from Ndejje University, Luweero, Uganda. She attended Gayaza High School for both her O and A level studies. She has previously worked as a shift superintendent for Extra Neutral Ethanol production in Bwendero Dairy Farm Limited. She has also undertaken part time work as a Teaching Assistant at the Department of Chemical Engineering, Ndejje University. In addition, her Master program included two six week internships at Atacama Consulting, Uganda and the Western Africa Science Center on Climate Change and Adapted Land Use (WASCAL), Ouagadougou.

ACKNOWLEDGEMENT

I would like to appreciate the support from the African Union through the African Union Commission, and all the partners (BMZ, KFW, GIZ, and University of Tlemcen) of the Pan African University Institute for Water and Energy Sciences, including Climate change (PAUWES) project. The financial support through the research grant and scholarship enabled me to finish my work, including the opportunity to pursue my masters at the Pan African University.

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

My appreciation goes out to Prof Rabbani Adamou for his advice and supervisory support through the research period. The entire staff at WASCAL center-Niger is fully appreciated for their availability and during my research stay at the institute. I also acknowledge the tremendous support from through translation and field support from Mr. Hassane Adamou, Mr. Abdou Moumouni, Mr. Hamidou Issoufou and Mr. Tahirou Garba whose generosity, hospitality and knowledge eased my stay in Ngonga Zarma village.

I also extend a note of thanks to all the staff at WASCAL Competence Center, Ouagadougou especially my internship supervisors Dr. Aymar Bossa and Dr. Yacouba Yiira for ensuring that we received fulfilling training on the essential technical tools for water, energy and climate modeling under the PAUWES-WASCAL Corporation program.

My profound gratefulness acknowledges the kindness Mr. Emmanuel Menya, Mr. Bouzed Himed Bouzed, who offered advice and training support during my work. I also appreciate the help of Mr. Henry Thomas Nelson and fellow course mates of energy class for assistance and encouragements, thus making this a journey worth taking.

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

I am grateful to the almighty God who for strength to walk this two-year journey in good health and abundance of joy and provision.

LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AEO	African Economic Outlook
ANPER	Agence Nigérienne pour la Promotion de l'Electrification Rural
CRF	Capital Recovery Factor
COE	Cost of Energy
DC	Direct Current
ECREE	ECOWAS Regional Centre for Renewable Energy and Energy Efficiency
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
GWh	Gigawatt hour
HOMER	Hybrid Optimization of Multiple Electric Renewables
HRES	Hybrid Renewable Energy System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelised Cost of Electricity
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MW	Megawatt
NASA	National Aeronautics and Space Administration
NIGELEC	Société Nigérienne d'Electricité
NPC	Net Present Cost

NREL	National Renewable Energy Laboratory
NESAP	Niger Solar Electricity Access Project
PV	Photovoltaics
RE	Renewable Energy
RES	Renewable Energy Sources
REN21	Renewable Energy Policy Network for the 21st century
RF	Recoverability Fraction
ROI	Return of Investment
SDGs	Sustainable Development Goals
SOC	State of Charge
SONICHAR	La Société nigérienne du charbon
SOMINA	La Société des mines d'Azelik
TOPSIS	Technic of Order Preference by Similarity Ideal Solution
WAPP	West African Power Pool

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ABSTRACT

Energy is significant in fuelling sustainable development for all by 2030, as is the current global agenda. Renewable energy sources (biomass, solar hydro and others) are defining the energy transition of the world today from the conventional sources (coal, oil, natural gas and others) to meet the climate goals as set in Paris Agreement. Niger is among the energy poor countries in the world today with most of the population in the rural areas having no access to electricity from the grid. The lack of electricity has greatly crippled the economic and social development of the villages. However, Niger is endowed with solar resource throughout the year which can be used to supply electricity to isolated communities in rural areas and can be coupled with the other available resources in the country using hybrid renewable energy systems. The study analyses the techno-economic feasibility of a hybrid system for electrification of rural communities in Niger with Ngonga Zarma village as a case study. The load demand of the community was 129.74 kWh for a community of 400 households. The micro-grid analysis tool homer pro was used to design and simulate the power system under two scenarios of grid and off grid connection. The grid connection scenario was found to be the possible way to electrify the community with a system configuration of 35kW Solar PV, 30 kW diesel genset and 16 batteries connected to the national grid of Niger. The system had a renewable energy fraction of 62.4% solar from a total electrical energy output of 93,865kWh/yr. The system had a net present cost of $221,153 with a Levelised cost of energy of 0.137$/kWh if sales to the grid are enabled. An increase of 18.3% is experienced when the sales to the grid are disabled from the system resulting in an increase of 113% in the LCOE of the system. The study further found that a solar PV-diesel hybrid system is the optimal system for powering villages in Niger but was particularly not feasible for Ngonga Zarma. The break-even grid extension distance being shorter than the recommended value. A sensitivity analysis revealed that a for a more reliable system, the electricity price increases and so does the optimal system change to the hybrid system of solar PV, diesel, battery with a grid connection. Increasing the maximum capacity shortage reduces the Levelised cost of the system by 10.23%. A further study should be done to consider the use of an electric system at Ngonga Zarma to electrify the surrounding villages and also irrigation.

Keywords; Renewable energy, HOMER PRO, hybrid electric systems, off-grid system, energy assessment

RESUME

L'énergie contribue de manière significative au développement durable pour tous d'ici 2030, comme il y contribue actuellement au niveau mondial. Les sources d’énergie renouvelables (biomasse, énergie solaire hydroélectrique et autres) définissent la transition énergétique du monde à partir des sources conventionnelles (charbon, pétrole, gaz naturel et autres) pour atteindre les objectifs climatiques fixés dans l’Accord de Paris. Le Niger fait partie des pays pauvres en énergie au monde avec la majeure partie de la population des zones rurales n’ayant pas accès à l’électricité du réseau. Le manque d'électricité a fortement handicapé le développement économique et social des villages. Cependant, le Niger est doté de ressources solaires tout au long de l'année pouvant être utilisées pour fournir de l'électricité à des communautés isolées dans les zones rurales. Cette peuvent être couplées aux autres ressources disponibles dans le pays en utilisant des systèmes hybrides d'énergie renouvelable. L'étude a analysé la faisabilité techno-économique d'un système hybride d'électrification de communautés rurales au Niger avec le village de Ngonga Zarma comme étude de cas. La demande de charge de la communauté était de 129,74 kWh pour une communauté de 403 ménages. L'outil d'analyse de micro-réseau Homer-pro a été utilisé pour concevoir et simuler le système d'alimentation selon deux scénarios de connexion réseau et hors réseau. Le scénario de connexion au réseau s'est avéré être le moyen possible d'électrifier la communauté avec une configuration système de 35 kW de PV solaire, un groupe électrogène diesel de 30 kW et 16 batteries connectées au réseau national du Niger. Le système présentait une fraction d’énergie renouvelable de 62,4% d’énergie solaire pour une production totale d’énergie électrique de 93 865 kWh / an. Le système présentait un coût actuel net de 221,153 dollars avec un coût d'énergie actualisé de 0,137 dollar / kWh si les ventes sur le réseau sont activées. Une augmentation de 18,3% est observée lorsque les ventes au réseau sont désactivées du système, ce qui entraîne une augmentation de 113% du LCOE du système. L'étude a également révélé qu'un système hybride solaire photovoltaïque-diesel était le système optimal pour alimenter les villages au Niger, mais qu'il était particulièrement impraticable pour Ngonga Zarma. La distance d'extension du seuil de rentabilité est inférieure à la valeur recommandée. Une analyse de sensibilité a révélé que, pour un système plus fiable, le prix de l’électricité augmentait, de même que le changement optimal du système en un système hybride composé de panneaux solaires photovoltaïques, de diesel et de batteries raccordées au réseau. L'augmentation de la pénurie de capacité maximale réduit le coût standardisé du système de 10,23%. Une autre étude

devrait être réalisée pour envisager l'utilisation d'un système électrique à Ngonga Zarma pour électrifier les villages environnants ainsi que pour l'irrigation.

1. INTRODUCTION

1.1. Background

Energy in various forms is essential for the support of livelihood, making it a driver for the economic advancement of a country. Economic opportunities in the world today, have significantly expanded, driven by the needs of the rising population. The global population is projected to reach 9 billion people by 2050 (OECD, 2011), further increasing the demand for food and energy from the rising standards of living to an extent driven by effects from climate change. Aside from population, transitioning to a carbon-free energy system requires new infrastructure contributing to the further increase in energy demand.

Conventional sources of energy currently dominate the total primary energy supply in the world, with a percentage share of 79.5% and renewables at 10.4% (REN21, 2017). The use of conventional energy sources has been found to release greenhouse gasses on combustion resulting in a rise in surface temperatures. Geopolitical conflicts have arisen in some African countries such as Nigeria, since conventional resources such as oil and natural gas are distributed in a few countries. Also, non-renewable energy resources are finite with some countries already cutting down on their production capacity, leading to volatility in fuel prices. For instance, coal and crude oil affect the security of supply for countries that are heavily dependent on oil including the importing countries. The world has looked to the use of alternative energy sources such as renewable energy sources (RES) and efforts to increase efficiency in energy use and production as a solution. The use of renewable energy sources also ensures the security of supply amidst fears of diminishing reserves of the conventional sources in the future and a lower environmental impact as compared to fossil fuels.

The global interest in RES has led to a continued reduction in the prices of their systems as evidenced by solar and wind technologies whose cost of energy is currently competing against that of fossil fuels, even though their subsidies are still in play. Despite the increment in energy demand, many people around the world are still without access to it with more than 500 million people in Africa not having access to electricity and many more without access to clean energy cooking. Nearly 80% of the people without access to power is from rural areas in the sub-Saharan, thus hindering the social-economic growth of rural communities (IEA, 2014). The electricity that is readily available and affordable can improve the livelihood of the rural areas through powering economic activities such as small scale businesses, lighting, and access to clean water through water pumping. Other advantages of rural electrification include education of the children in the communities, better health services, and communication in the region as that have been cut off from the rest of the areas of the countries — integration of renewable energy technologies in the energy mix curbing the challenges caused by rural-urban migration. Despite the incredible opportunities that come with rural electrification, an extension of electricity to rural areas in many developing countries has been affected by the high costs involved. Rural communities are isolated and mostly have a low willingness and ability to pay for electricity making it capital intensive and also hard as most of the population is sparsely distributed demanding for higher costs for connection of households.

Due to the low socio-economic development in the areas, there is a low energy demand and inadequate transmission lines making it uneconomical for governments to invest large sums of money which otherwise are important for the development of other sectors. A lack of access has increased poverty in rural areas. Developing economies have looked to distributed generation to lower the costs involved in the extension of electricity. A shift away from the centralized production of power has employed the use of RES due to their flexibility and less infrastructure needed that found in the project area with some connection to the grid and others as off-grid. Off-grid rural electric systems are becoming increasingly competitive for rural communities as they can support micro and small income generation leading to poverty reduction.

However, RES are facing drawbacks, such as their integration to the existing grid connections and variability in electricity generation. Renewable energy sources such as Wind and Solar PV are greatly affected by changes in weather patterns. The changes in weather patterns as a result of climate change result in the intermittency of power generated from wind and Solar PV. Another example is the decline in the performance of systems such as solar PV whose performance is predicted to decrease with an increase in the temperature of the area. In light of these challenges, hybrid renewable energy systems (HRES) can provide the solution to the difficulties by delivering energy to the communities depending on the locally available resources ensuring energy security for sustainable transformation. HRES refer to any energy system with more than one type of generator, usually a conventional generator and either small hydro, wind, PV (Cristian, Bizon, & Alexandru, 2017). HRES are becoming very important because of the opportunity they give to exploit the strength of two renewable sources. The systems are cost-effective, environmentally clean, and thus able to compete with centralized systems supplying power to rural areas.

1.2. Problem Statement

According to (Ministere De L'Energie Secretariat General, 2018), Niger is one of the developing countries in the world with national electricity access standing at only 12.3%. Niger, like most African countries, has considerably higher electricity access in the urban areas rated at 63.88%, but access is deficient in the rural communities estimated at 0.92%. The most significant portion of the national population is in rural communities. The energy demand for Niger is expected to continue increasing as Niger is among the African countries with a high population growth currently standing at 3% per year (Lighting Africa, 2017). There is a need to grow the economy of the country as World Bank has listed it according to a report released in 2016 that it was the second least developed country in the world. Some of the challenges listed include; low rate of industrialization, food insecurity, and weak education sector, among others.

The following challenges were identified in rural Niger, Dosso region which can significantly improve with an extension of electricity to the area and these include;

i. Due to the long dry seasons in the country and the extending desert, there is a lack of access to water as the people have to walk long distances to collect it. Diseases that arise from water harvested from open wells. Easy access to water can redefine the agricultural activities in the area through irrigation and readily available water for animal keeping.
ii. The region experiences hot seasons with temperatures that can peak at 30 degrees and more for most days throughout the year.
iii. Lack of a good communication process as there are no charging places for the phones
iv. Lack of enough businesses that can economically empower the area, and thus, many youths are left to migrate to the city, and others are left jobless and many homes struggling to meet their daily needs.

Niger has vast resources that can completely overhaul the state of the electricity sector in the country and thus improve the livelihood of the rural communities. The energy potential of Niger comprises of biomass, solar, hydro, and conventional sources such as coal, oil, uranium, and natural gas. Niger receives abundant sunshine as a country that is at the mouth of the Sahel with daily irradiation estimated at 5-7kWh/m^2 (IRENA, 2014). The use of solar PV can increase the electrification rate in the country and mainly for rural areas. The current economic situation in the country cannot secure the extension of the grid to the isolated communities as great resources are needed affecting the pricing of the electricity will be high. With solar and other renewable sources such as hydro, standalone systems can be designed to meet the energy needs of the communities at a lower cost and methods that are designed depending on the existing energy resources of the area. Numerous studies have been undertaken for HRES in different remote regions of the world, but less research has been conducted for the same in Niger. According to the current electrical situation in Niger, HRES systems will accelerate the government plans for electrification of rural areas and the spread of micro-grids to isolated communities in the country. This study aims to contribute knowledge to the techno-economic and social feasibility of HRES for the electrification of villages in the country. The study also hopes to design a system that will sustainably improve the lives of the people in the area.

1.3. Research Questions

The study serves to answer the following questions;

a) What is the energy demand of the village?
b) What are the local renewable energy resources that are to be considered for the design of a hybrid power system for the village?
c) What is the suitable hybrid power system that sustainably and optimally meets the energy needs of the community?
d) Is it profitable to consider grid or off-grid connection of the hybrid power system for the village under study?

1.4. Main Objective

The main objective of this study is to analyse techno-economic feasibility of a hybrid electric power system for electrification of rural communities in Niger's Dosso region.

Specific Objectives

- To determine the energy demand of Ngonga Zarma and establish her load demand curve
- To assess the relevant renewable energy sources for the proposed hybrid system based on the existing potential in the area.
- To model and simulate a hybrid system with various renewable energy technologies using HOMER Pro software
- To optimize the energy generation costs based on suitable renewable energy technologies

- To analyse the feasibility of connecting the system for either the on-grid/off grid hybrid system for the village.

1.5. Justification of the Study

The study is crucial as it will yield the following results;

i. The generated results will be used for the deployment of a project that can bring about socio-economic development of Ngonga Zarma community. The socio-economic benefits include but not limited to the following;
    - There will be an improvement in education as the students will no longer be limited to daytime study but can also be able to study in the night, helping them become well conversant with their classwork.
    - Creation of jobs in the area, especially in managing the hybrid system. Due to a lack of technically skilled people in rural areas, people can engage in cleaning and maintenance of the installed hybrid systems, especially in sanitation and manual labour.
    - The hybrid system will enable water pumping for both household use and irrigation, which can significantly improve the quality of life in the area. Through this, people will be able to grow their crops throughout the year with less adverse effects from the changes in the weather patterns.
    - For a hybrid electrification system to be sustainable in a rural area, the community is usually involved in the management of the system. Deployment of a hybrid electrification system in a rural community leads to training of the people in the area with skills that can improve their life such as business management and technical skills for proper maintenance of the power plant.
    - Electrification of the area leads to a thriving healthcare system that is operational 24h.

ii. The results from the analysis of the system can be used for conducting similar studies on different villages in the country, thus leading to the design of systems that are affordable and beneficial to the communities.

iii. The results attained from this study can be used to kick start a hybridization process for all the diesel-powered mini-grids in the country.

iv. Hybridized rural electrification systems in the country can reduce the emissions that result from conventional electrical, systems, especially the diesel mini-grids powering isolated areas in the country.

v. The results from the study can inform policy makers on the importance of grid connection systems and aid in the formation of policies such as net metering that can transform the future of mini-grids.

vi. The use of hybrid systems for the generation of electricity can improve the share of renewables in the energy mix of the country.

1.6. Hypothesis

A solar PV, battery electric system connected to the local grid can supply electricity to meet the needs of the community sustainably at a low cost.

A grid-connected 100% renewable electric system is a suitable electrification system for the community under study

1.7. Disposition

The thesis is made up of 5 chapters which are further described in Figure 1.

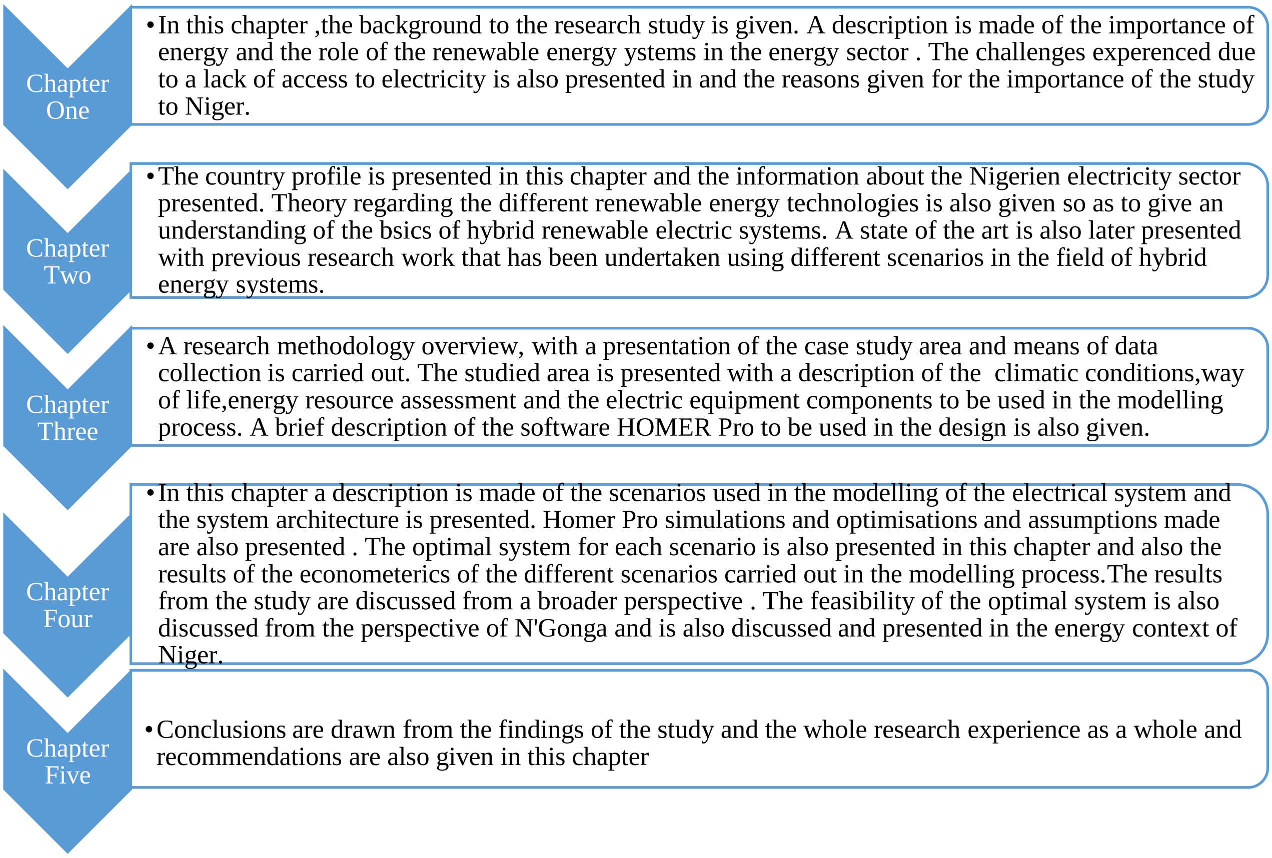

Figure 1.1: Disposition of the Master's Thesis document.

1.8. Scope of the Study;

The study mainly focused on designing a suitable electrification solution for Ngonga Zarma. The system design was based on the existing energy resource potential of Ngonga Zarma Village. HOMER Pro was used for the design because it simulates combinations of different energy resources in a time step of one minute to an hour and then optimizes the options to give a low-cost solution. A sensitivity analysis was carried to cater for uncertainties in system variables.

Despite the fact that the research was to design a system that meets the energy needs of the community, the deferrable load for water pumping was not included in this research. The environmental criteria concentrated on the emissions in the form of CO_2 despite the existence of other pollutants.

2. LITERATURE REVIEW

2.1 Introduction

In this chapter, both the theory and empirical research about hybrid renewable electric systems is presented. The theory regarding electrical systems that make up hybrid renewable energy systems is given. Also, a review is provided on the econometrics that is important in assessing the feasibility of an electrical system. The chapter also includes current information regarding energy production, electricity sector, and the historical energy context of Niger, including an energy resource assessment of the country at large.

2.1. Context

Niger is located in the western region of Africa, with a population of 19.9 million people (Open Capital Advisors, 2017). The country is landlocked bordered by Algeria and Libya in the North, Mali and Burkina Faso in the West, Nigeria and Benin in the South and Chad in the South with a population density of 12 people per km^2 as shown in Figure 2.1.

Figure 2.1 Map showing Niger and the neighboring countries

Source: Google Imagery

2.1.1. Demographics

The country's population mainly located in rural areas contributing a percent share of more than 80% of the total population and only 16% located in urban areas with an overall annual population growth of 3.8 % (IDEA, 2018). Females dominate the population of the country with a percent share of 50.21% of the total. The region of Zinder according to the (Institut National De La Statistique Du Niger, 2016) was found to be the most populous region in the country at 20.9% percent share of the population with Dosso taking a share of 11.9%. Niamey takes up a 5.8% share of the people and is found to be among the most densely occupied regions in the country with a population density of 4567.4 habitats/km^2. This population distribution is because of the economic activities that see a migration of the people to the capital for better employment opportunities and livelihood. However, most of the people, as noted earlier, live in rural areas with close to 22% of the populace in the region residing in rural areas, as shown in Figure 2.2.

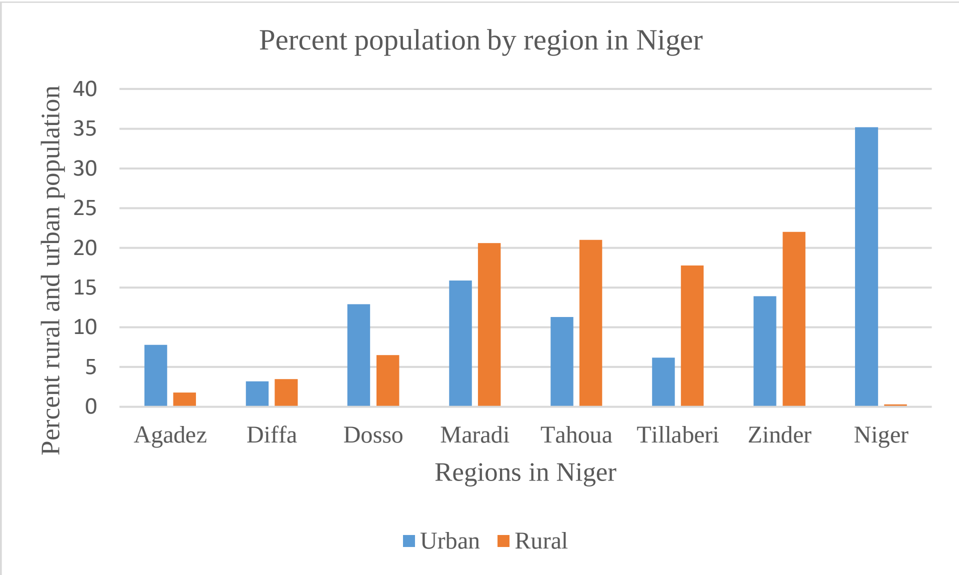

Figure 2.2: Percent population by region of Niger

Source: (Institut National De La Statistique Du Niger, 2016)

The population distribution in the country clearly shows the importance of the rural areas, and the significant impact that changes in the livelihood of the rural areas will bring to the people of Niger. The population in most African countries today is mainly young, and Niger is among the countries with a high percentage of the population being considered young. Half of the people in Niger are young, with most of them being 15 years and 2.7% of the population being older adults. The people of Niger are reliant on Agriculture as a source of income for the families

According to Figure 2.3 below, shows the reliance of the community on agriculture. The families mostly engage in grain farming such as maize, sorghum, and millet. The cereals harvested are stored in granaries so that families can survive the long dry season

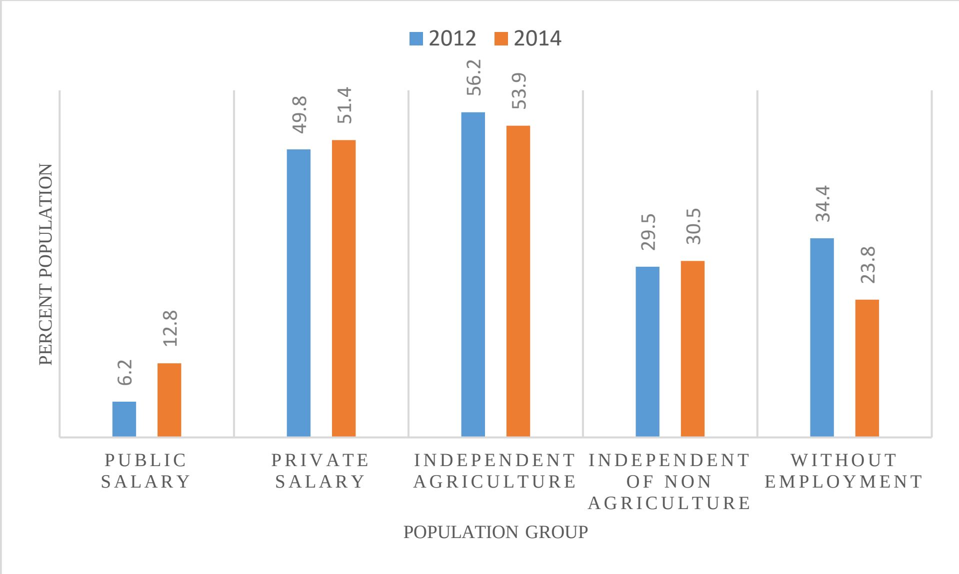

Figure 2.3: Percentage of Population with employment

Source :(Institut National De La Statistique Du Niger, 2016)

According to Institut National De La Statistique Du Niger, (2016), 95.8% of the population uses solid biomass for cooking for a study taken in 2015. The mainly used cooking method is wood relying on the use of inefficient cook stoves.

2.1.2. Climate

Niger experiences three climate zones from the North to the South of the country. The Sudanian zone is limited to the North by a line that is 15^0 West and 14^o east. The region is the most watered part of the country receiving 600 mm of water per year. The moisture increases in the South-Western area (Gaya) at 870 mm with Savannah vegetation and cultivation of crops such as millet, sorghum, maize, and peanuts. Niger experiences a subtropical climate which is hot and dry, especially in the northern part of the country. The southern part experiences a tropical environment around the Niger Basin. The rainfall season falls between July to September with the rainfall quantity falling between a range of 0-400 mm.

2.1.3. Economy

Agriculture mainly dominates the economy of Niger with subsistence crops of primary interest to the population in Figure 2.4. Other areas of interest include livestock and trade in uranium being that Niger has one of the largest uranium deposits in the world and the currently taking the most substantial portion of exports out of the country.

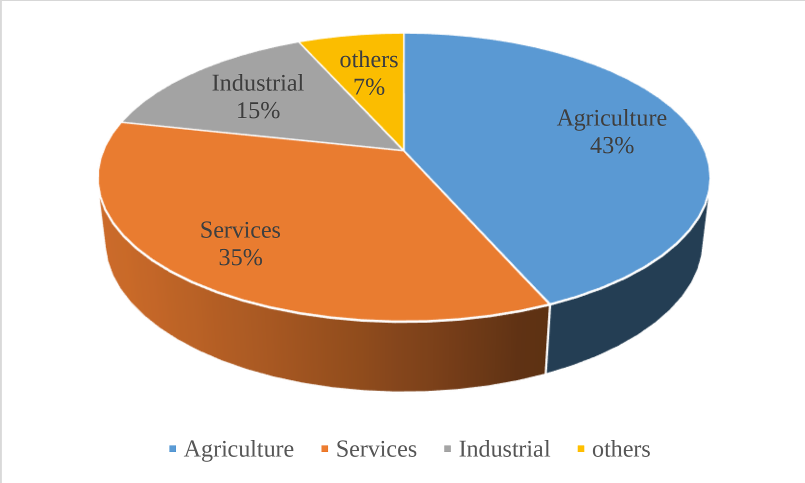

Figure 2.4: GDP structure of Niger, 2018

Source: AEO, 2018

With a GDP per capita of 368 dollars, Niger is among the least developed countries around the globe. However, the economy has been growing at a steady rate since the discovery of oil at the Algerian border. Uranium and oil are among the critical exports of Niger. Exports from uranium are vital to the economy of Niger with the country among the top four producers of Uranium in the world (Institut National De La Statistique Du Niger, 2016).

2.2. Energy Situation in Niger

According to Gado (2015), Niger has vast energy resources that can completely change its current energy situation. The country possesses extensive, conventional sources of energy and also a lot of renewable energy potential.

2.2.1. Conventional energy resources

Niger has proven reserves of oil, coal, and uranium, as shown in Table 2.1.

Table 2.1: Conventional energy sources of Niger

Resources	Reserves
Uranium	450000 tonnes
Mineral Coal	90 million tonnes
Crude Oil	1.18billion
Natural Gas	18.6 billion m^3

Source: (Institut National De La Statistique Du Niger, 2016)

The energy resources are located in the Northern part of the country in the Agadez region. Uranium mined in the country is for export to other countries. Some of the crude oil that is produced is for shipping and the remainder fed as raw material to the 20,000 barrels per day refinery located in Zinder. The crude is transported to Zinder through a pipeline to produce products such as gasoline, diesel oil, and Liquefied Petroleum Gas (LPG).

2.2.2. Renewable Energy Resources

Niger has vast renewable energy resources with a potential that comprises biomass, Solar, hydro, and conventional sources such as coal, oil, uranium, and natural gas. The country envisions 100% access to energy in 2030, with rural access at 30% and overall access of 65% , increase the share of renewables in the generation of electricity to 57% by 2030 excluding the imported electric power and also reduce the percentage of traditional biomass in the energy mix by 2020 from 87 67% (ECREEE, 2015).

2.2.2.1. Solar Energy;

Niger receives abundant sunshine as a country that is at the mouth of the Sahel with daily Irradiation estimated at 5-7 kwh/m^2 and 7 to 10 hours of sun per km^2 (UNEP,2017) and is possible throughout the region as shown by the map Figure 2.5.

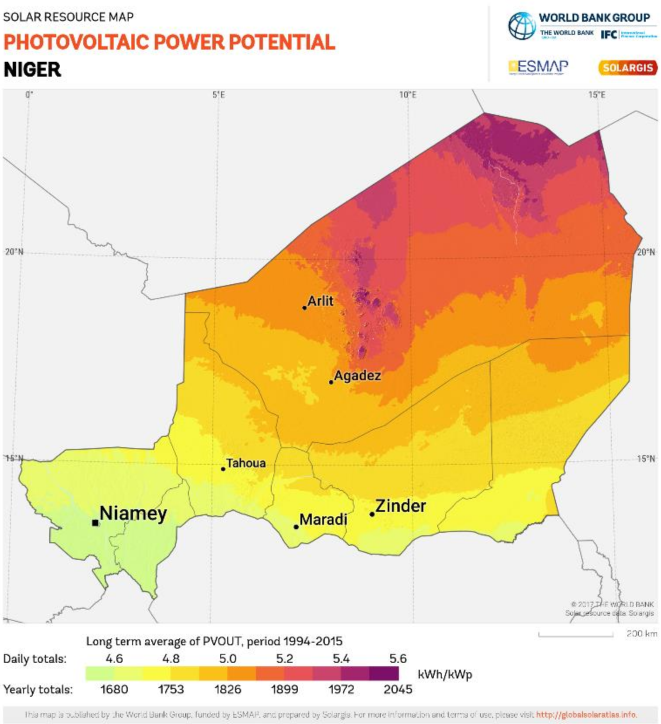

Figure 2.5: Solar photovoltaic potential of Niger
Source: SOLAR-GIS

The solar potential in Niger is feasible for solar PV and use in solar thermal applications. The immense potential has mostly gone to waste with only 10% harnessed per day, yet the potential can roughly cover the annual energy needs of Niger (Dankassoua, Madougou, & Yahaya, 2017).

The harnessing of solar energy in Niger faces a challenge of the dust in most parts of the country, reduces the performance of the solar PV modules. Solar technology in the form of photovoltaic has found considerable use in the country for the following applications;

- Street lighting in the urban centers with areas such as Niamey already benefiting from this.
- Use on the solar fridges to sustain health centers that carry out vaccinations, which dramatically improve the health off the communities.
- Solar water pumping in many rural areas
- Solar home systems for those not connected to the grid.
- Supply of power to masts for telecom companies.

2.2.2.2. Biomass

Niger has been massively hit by desertification with the extension of the desert that is in the North of the country. However, there has been considerable usage contributing a share of more than 70% of the total primary energy supply (IRENA, 2014), as shown in Figure 2.6. The country, according to (IRENA, 2014), has estimated wood productivity of 0.1-0.5 m^3/ha per annum even though the state generally does not have enough information that can ably predict the total potential of the resource. The existing forest cover occupies only 2% of the land area of the country of which 600,000ha are for natural forests, and 11000000 ha are for marginal forests (IRENA, 2014). Biomass, though profoundly affected by the dry climate, is harnessed as a source for thermal energy. Rural areas use the traditional biomass and modern technologies such as biogas cannot be used due to challenges of water as the most significant part of the country is dry and is at high risk to climate change due to its position in the Sahel region. Due to the uncontrolled harvesting and use of wood to growing energy demand, biomass use is not sustainable(Gado, 2015).

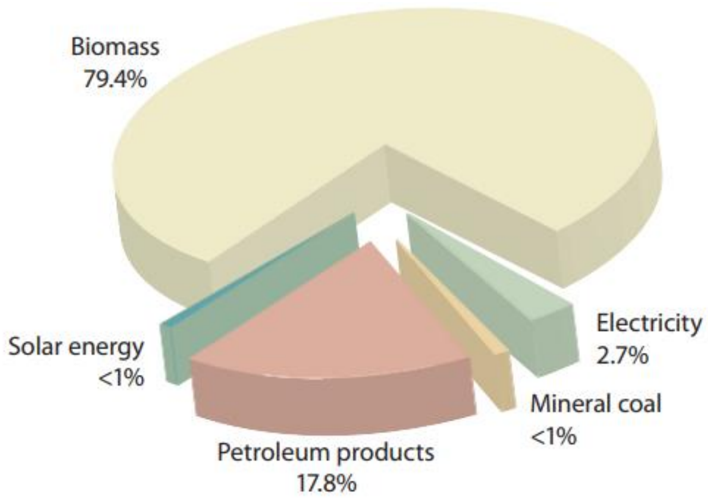

Figure 2.6: Total Primary Energy Supply of Niger

Source;(Gado, 2015)

2.2.2.3. Wind Energy

The country has favorable wind speeds ranging from 2 to 6 m/s at the height of 10 m through the best rates estimated in the Northern part of the country which is sparsely populated and thus an electrification project involving wind energy would be costly. Moderate wind speeds less than 4 m/s have been recorded to be found in the South-Eastern part of the country which is only in favor of pumping water for the communities.

Figure 2.7 shows the wind speeds of different cities in particular regions of the country that can be harnessed.

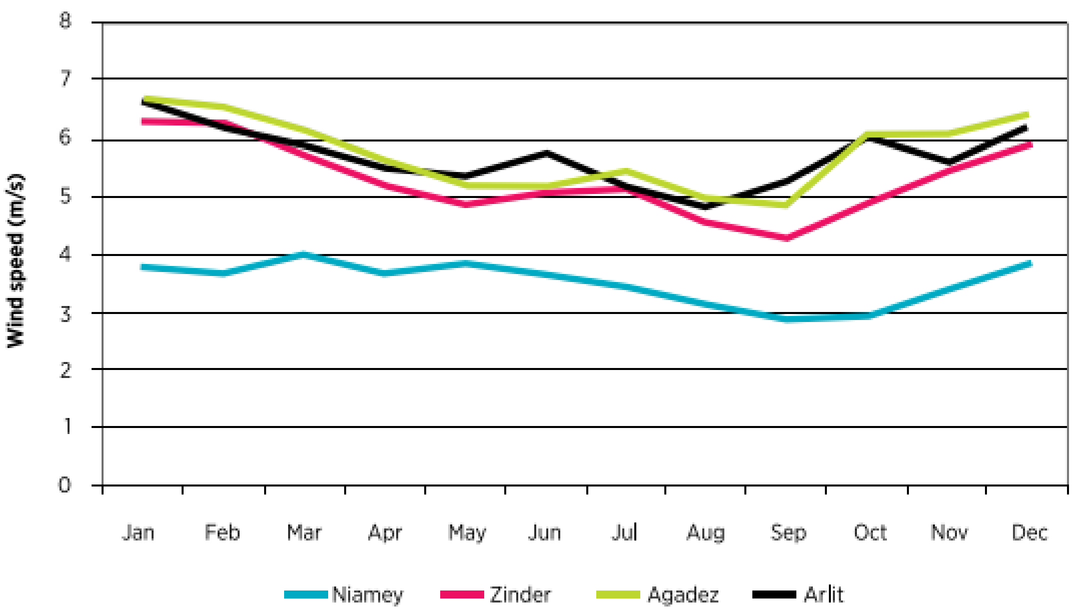

Figure 2.7: Wind speeds of four areas in Niger

Source:(IRENA, 2014)

2.2.2.4. Hydro energy

According to ECOWAS, 2006, Niger has been estimated to have a potential of 400 MW of which close to half of this potential has been harnessed. The country to date has three hydropower stations plans located on River Niger, and these include Kandadj with a potential of 125 MW, 122 MW in Gambua on River Niger and 26MW in Dyodyonga (UNEP, 2017). The country has an estimated potential of 8 MW at the tributaries of River Niger Figure (2.8), and these are Mekrou, Tapoa, Gorouol, and Sirba. The potential can be harnessed for rural electrification as they do not require dams (IRENA, 2014).

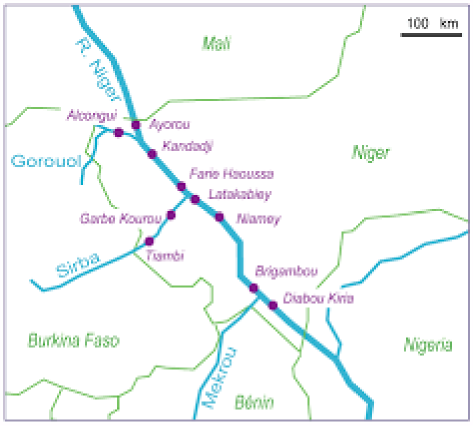

Figure 2.8: Tributaries of River Niger

Source: (IRENA, 2014)

2.3. Energy supply

According to Ministere De L'Energie Secretariat General(2018), the primary energy supply of Niger stood at 3079.56 ktoe dominated by biomass followed by petrol product. Coal is used in the production of electricity while biomass is a significant household resource in rural areas as it is affordable by the communities. Despite the fact that Niger has a low biomass cover, the country's final energy consumption is dominated by biomass at 80.23% as shown in Figure 2.9. The use of other sources of energy, such as coal and solar is rather negligible. The total final energy consumption is 2899 ktoe.

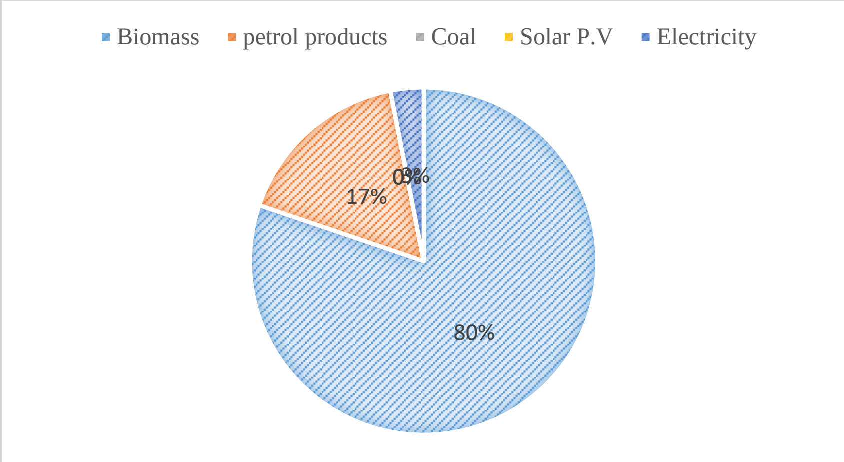

Figure 2.9: Final Energy supply of Niger, 2018

Source: (Ministere De L'Energie Secretariat General, 2018)

A comparison between the trend in population and the final energy use showed that increment in populace resulted into an increase in the last energy use due to the large share of biomass in the household energy mix that contributes 80% of the final energy consumed Figure 2.10. According to the last energy use in the country has not changed much, just like in other developing countries whose energy use is mainly dependent on biomass.

The final energy consumption of Niger is mostly dominated by households, which is the same for most of the countries on the continent, followed by the transport sector at 14.04% of the total energy supply.

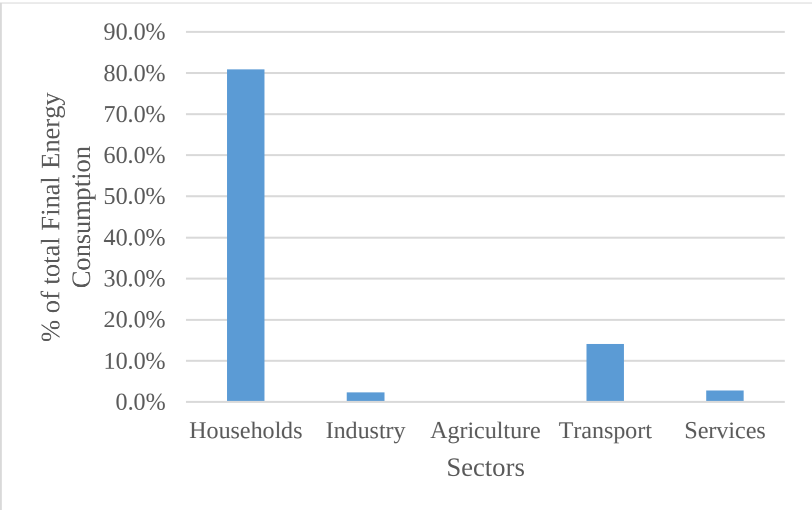

Figure 2.10: Final energy consumption in Niger by sector

Source: (Ministere De L'Energie Secretariat General, 2018)

However, according to Figure 2.10 showed that a period between 2012 and 2015, the final energy use surpassed population growth due to an increase in the petroleum products that were being used in the country.

2.4. Electricity Sector in Niger

2.4.1. Electricity Supply

Sociéte Nigerienne d'Electricité (NIGELEC) is the state-owned company that is in charge of increasing access to On-grid electricity in the country. Before the electricity act of May 2016, NIGELEC was in charge of generation, transmission, and supply of power in the country. To increase efforts in improving electricity access in the country in both rural and urban areas, the government liberalized the sector involving the public sector. The Act further introduced the *Autorité de Régulation du Secteur de l'Energie as Niger* (Energy Sector Regulatory Authority of Niger) and *Agence Nigérienne pour la Promotion de l'Electrification Rural* (ANPER) which is in charge of increasing access to electricity to rural communities (WORLD BANK, 2018).

Niger has an on grid electricity capacity of less than 175 MW generated by NIGELEC and other private companies (IRENA, 2014). NIGELEC produces 83 MW from a thermal power station, and the rest of the capacity is provided by Nigerien Anou Araren Coal Company (SONICHAR), AGGREKO with a thermal power plant of capacity 15 MW. There exists independent power producers who contribute a total of 38 MW with SORAZ generating 23 MW and SOMINA providing the rest of the capacity (IRENA, 2014).

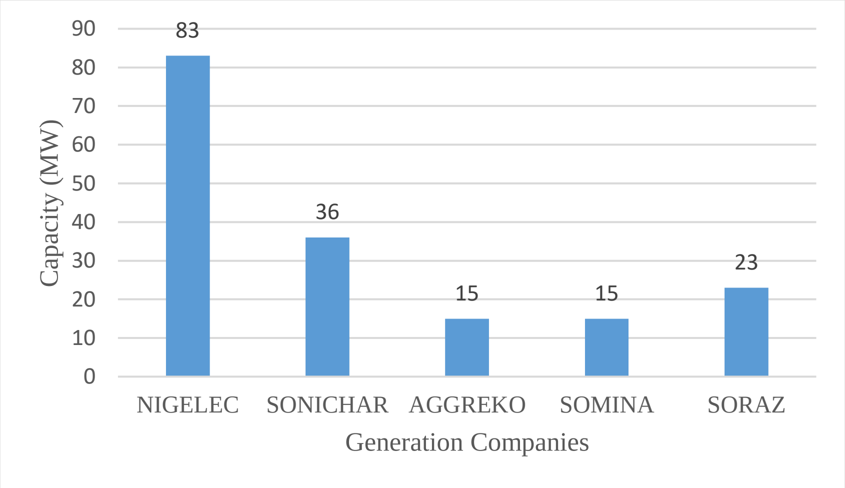

Figure 2.11: Electricity generation capacity in Niger.
Source; (IRENA, 2014)

According to the electricity produced in Niger stood at 551.63 GWh in 2017 and an 8.41% increment in the imported electricity at 845.19 GWh. The increase in imported power is evidence of increasing electricity demand in the country. Niger imports electricity from Nigeria at a low wholesale price of $0.04 per kWh, making it cheaper than the power produced in the country. Niger then further sells both the imported and locally generated electricity at a tariff of $0.158 per kWh. However, the growing demand in Nigeria and political insecurity undermine the reliability of the system. Another issue is that the existing lines cannot carry the required transmission capacity to Niger, and there is a need to replace the current lines with higher voltage lines.

2.4.1.1. Grid Electricity

Only 11% of the population has access to the grid and only covering a small piece of the expense of land that Niger occupies (Open Capital Advisors, 2017). The situation is as a result of the concentration of the people in the South and South West of the country with many sparsely populated in other regions of the country. According to World Bank, (2018), Niger has four grid networks that are interlinked with Nigeria's grid and through this the country imports electricity at a lower cost to meet the electricity deficit in the country. The other grid line is connected to SONICHAR in addition to different isolated mini-grids supplying areas that are far away from the grid.

Table 2.2: Table showing the interconnection voltage lines currently existing in Niger

Interconnection line	Voltage (kV)	Capacity (MW)
Birnin'Kebbi-Niamey	132	120
Katsina-Gazaoua	132	60
Damasak-Diffa	33	5
Kamba-Gaya	33	5

Source: (Institut National De La Statistique Du Niger, 2016)

However, due to the rising electricity demand, the grid lines cannot supply the required power for an extension to other areas in the country due to limited capacity and also the increase in demand in Nigeria.

NIGELEC has smaller decentralized electric generation systems powered by small diesel generators that provide power for a few hours to the isolated areas. NIGELEC currently boasts of 218,000 customers connected to the grid however electricity supply system has been characterized by frequent blackouts (Societé Nigerienne d'electricité NIGELEC, 2017).

The country through NIGELEC strategic plan 2016-2027 and donors has plans to increase production with plans dominated by investment in thermal power plants and the rest being solar. Increase in interconnection through the construction of grid lines in the framework of West African Power Pool (WAPP) connecting Niger to neighboring countries such as Burkina Faso, Benin, among others.

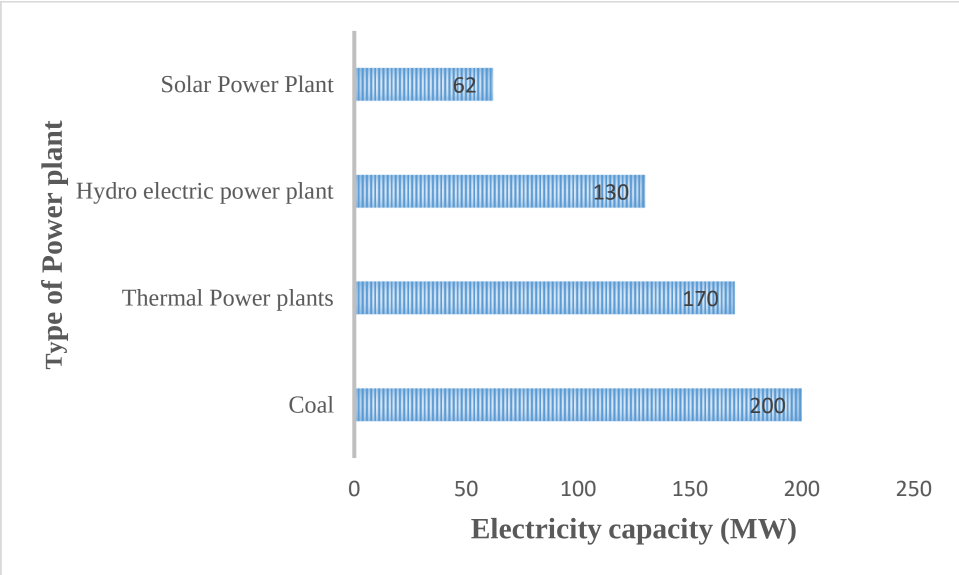

Figure 2.12: The type of plants that are under the plan for construction

Source; (Open Capital Advisors, 2017)

The solar power plants in the program include a 20 MW in Gusselbody, 20 MW in Goroubanda, 10 MW in Maradi, 7 MW in Malbaza and 5 MW in Zinder. Among the thermal power plants planned include a 60 MW in Zinder, 12MW in Maradi, 18 MW in Malbaza and 80 MW in Goroubanda (Open Capital Advisors, 2017).

According to Societé Nigerienne d'electricité NIGELEC, (2016), interconnection and extension plans for the national grid include;

i. The 330 KV from Birnin-Kebbi to Niamey of 265 km, Zabour to Malanville at a distance of 120 km and another stretch from Niamey to the border of Burkina Faso with a distance of 470 km(WAPP project)
ii. Rehabilitation of the 132 kV line from Birnin-Kebbi to Niamey
iii. Project for construction of a 132 kV line from Maradi to Malbaza distance of 200 km and also one from SORAZ to Zinder with a distance of 54 km.
iv. Project to extend and strengthen distribution lines in the areas of Goure, Tchintabaradem, Ouallam, and Lossa

According to consultations made by Open Capital Advisors, (2017), the National utility NIGELEC is also considering connecting of some mini-grids to the national grid as a means of increasing generation capacity, reliability, and reduction of costs currently incurred by the mini grids.

2.4.1.2. Off-Grid Electricity

Off-grid electricity in the country is in the form of home systems powered by solar and the mini-grid that was mainly fueled by diesel engines but have now extended to the use of solar and when coupled together result into hybrid systems. The country has 80 diesel powered mini-grids that are spread out to isolated communities. These mini-grids have been found to run on losses due to the high operating cost as due to increasing diesel prices in the country and electricity from them cannot be afforded by the residents of the community.

The solar PV market in Niger is quite vibrant due to the readily available sun throughout the year. According to Raach,(2014), the solar PV market in Niger was estimated at 565 kWp with telecommunication companies taking the largest share at 48% for installation of telecommunication musts in urban and rural areas.

2.4.2. Electricity Consumption

The country was listed as one of the lowest energy consumers in the world, with a rate of 43 kwh that is lower than the average for Africa (IRENA, 2014). The deficient per capita consumption makes Niger among the least electricity consumers compared to the world average of over 2770 kWh and the African average of 575 kWh (Open Capital Advisors, 2017). However, power consumption has been increasing at a rate of 8.0% from the turn of the millennium (Ministere De L’Energie Secretariat General, 2018). The electricity consumption in the year 2017 was 1066 GWh, which was an increment from the previous year of 1033 GWh (Ministere De L’Energie Secretariat General, 2018). The households and the other spread consume 50% of the produced electricity out between services sector and industry as shown in Figure 2.13. In the Agricultural sector, electricity is deployed to pump water for irrigation.

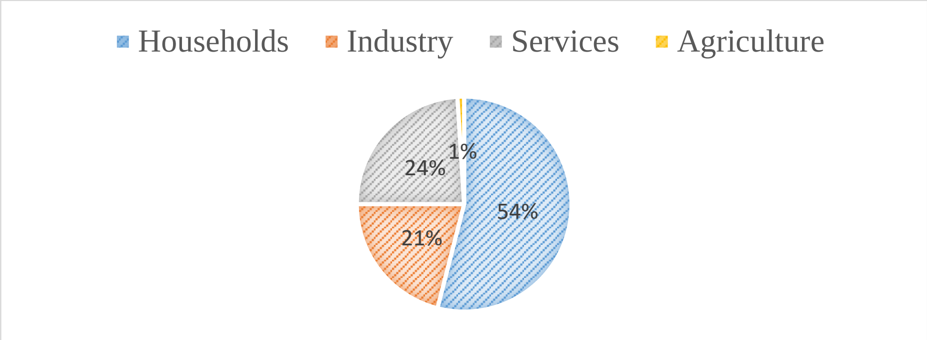

Figure 2.13: Electricity consumption by sector

Source: (Ministere De L'Energie Secretariat General, 2018).

To make electricity more affordable, the government introduced tariff classes through which consumers get price subsidies. One of these is the social tariff where a consumer of 3 kWh of electricity is awarded the first 50 kWh at a subsidized price of 0.11kWh.

2.4.3. Access to electricity;

Due to the unique nature of the organization of the country, with many people leaving in the Southern part of the land results in unequal access to electricity in the regions in the country. Due to initiatives and funding from different organizations such as World Bank, the government of Niger has taken considerable effort to increase the electricity access in the country over time focussing on rural areas in different regions in the country. The national electricity coverage rate has increased by 10.64% since 2012 despite the effort to extend the grid and also increase generation. There was no sizeable increment in the coverage over years with sparsely populated areas such as Agadez and Diffa have higher electricity access rates due to the isolated mini-grids spread out in the regions.

According to the Ministere De L'Energie Secretariat General, (2018) report, electricity access rate stayed stagnant in most of the regions of the country except Agadez and Niamey. With Niamey alone seeing an increment of over 50% from 2012 as shown in Figure 2.14.

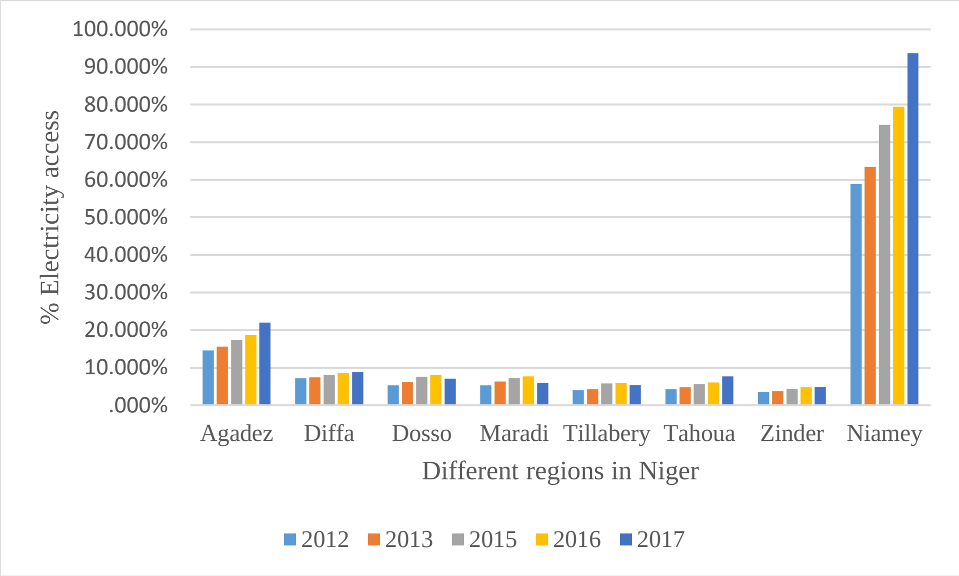

Figure 2.14: Electricity access rate trend of Niger from 2012 to 2017

Source: (Ministere De L'Energie Secretariat General, 2018)

However, Dosso region as depicted in Figure (2.14), is among the areas which have seen a considerable increment in the number of villages that have been electrified, unlike Niamey and Agadez whose rate has remained the same due to earlier efforts for electrification.

The electricity Access program of the Nigerian Government;

The ministry of Energy has a long term strategy of increasing electricity access that is;

I. 85% through densification and extension of the NIGELEC network
II. 5% through decentralized mini-grids
III. 10% through distributed systems such as solar kits.

Increase electricity generation capacity to 850MW with renewables contributing a share of 30% of the total generation and 85% of the total produced from National energy resources in the country.

2.5. Solar Energy Technology and Systems

2.5.1. Solar Energy Technology

The use of solar energy in the world to provide power for both heating and lighting has grown tremendously due to the availability of the solar resource in most of the areas in the world. Solar PV technologies use solar cells to harness the energy from the sun to produce electricity through the photovoltaic effect. Solar cells packed in modules or arrays are responsible for converting energy that is embedded in the ray of light emitted from the sun into useful energy. Solar cells can be classified into three groups according to the maturity of the technology according to Figure (2.15). However, the leading technologies on the market today are the wafer based cells made (Monocrystalline and Polycrystalline) from crystalline Silicon and the thin film cell technologies.

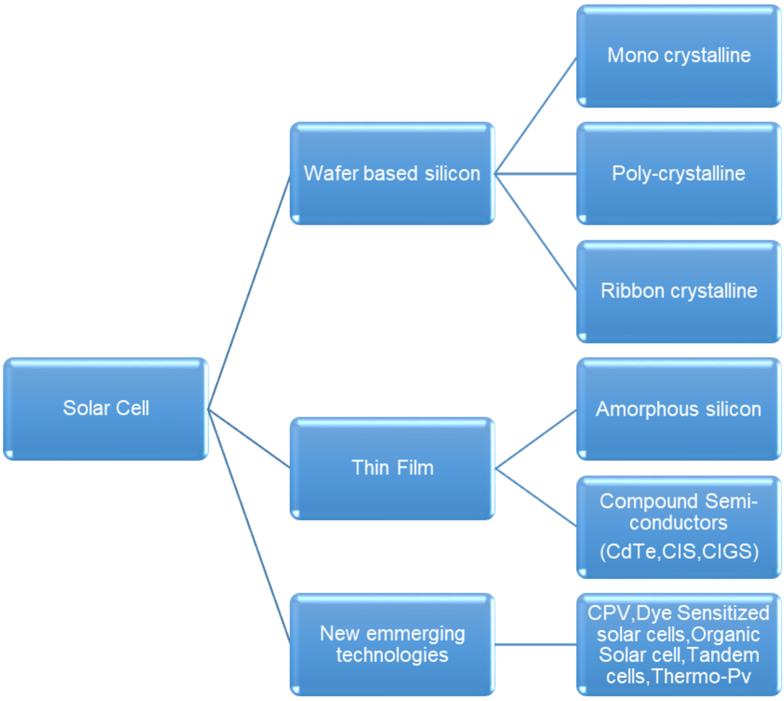

Figure 2.15: Classification of Solar cells

Source:(Mohanty, Muneer, & Kolhe, 2016)

According to Mohanty et al. (2016), Mono/Single crystalline silicon cells have an efficiency between 14-20% while the polycrystalline silicon cells have a much lower capability making them less costly and thus more abundant on the market. According to IEA, (2014), the efficiencies of PV technologies are steadily rising with younger technologies having higher efficiencies than older ones as shown in Figure 2.16.

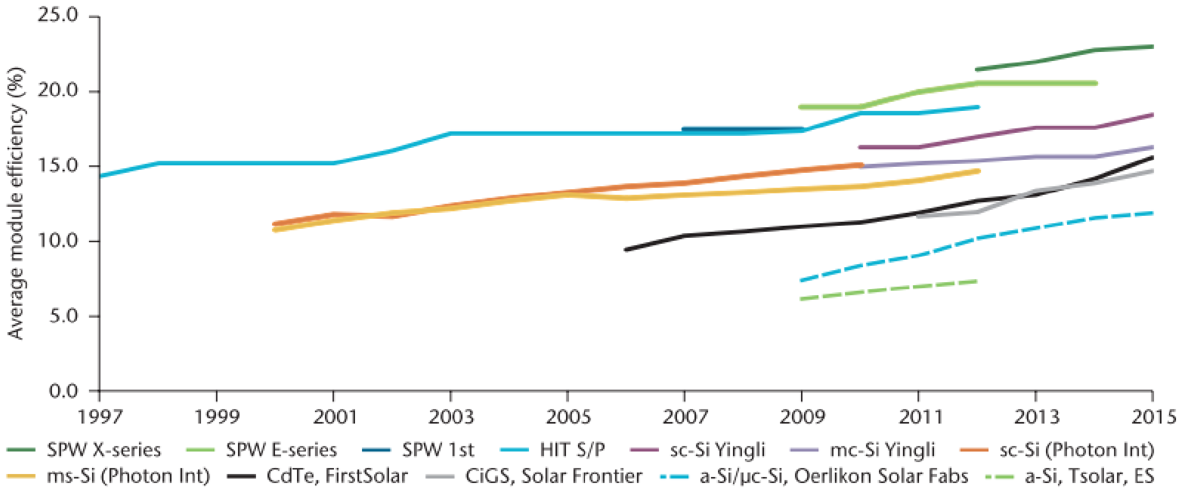

Figure 2.16: Efficiency trend of PV technologies to 2015

Source:(IEA, 2014)

When solar cells are connected in series to increase their voltage, they form a solar PV module. PV modules connected in series are called a string. If the modules are physically identical and exposed to the same conditions, then the output voltage of string is the voltage of an individual module multiplied by the number of modules. When modules are connected in parallel, they increase the power rating of the system and is called an array, as shown in Figure (2.17).

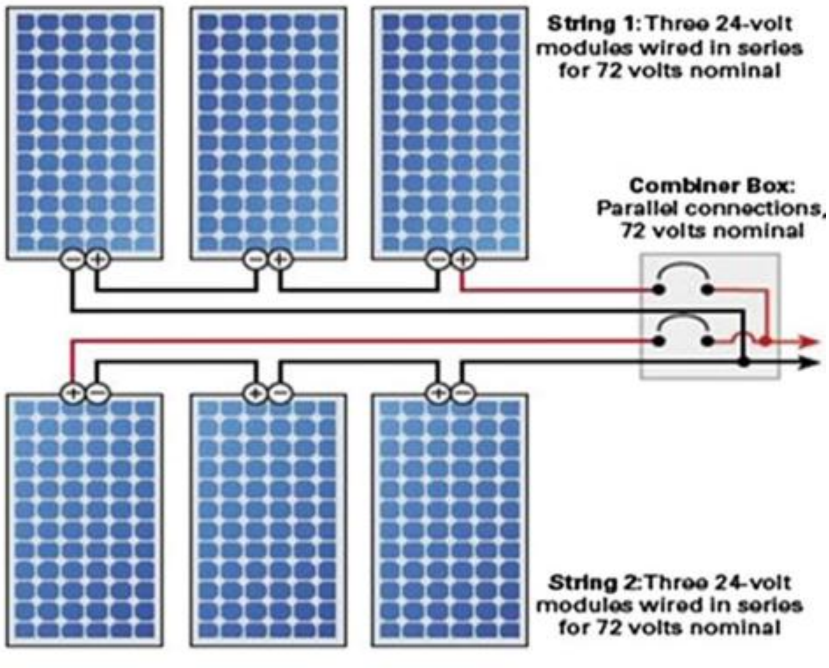

Figure 2.17: Connection of PV modules to form an array

Source: Mason et al. 2008

A single diode circuit model (Figure 2.18) is the most commonly used model to predict the performance of a PV cell. The model comprises of a single current source without resistance is called the ideal single diode model. A shunt resistance (Ru_{sh}) is added to create a real situation involving a load and the resistance (R_s) in the wiring.

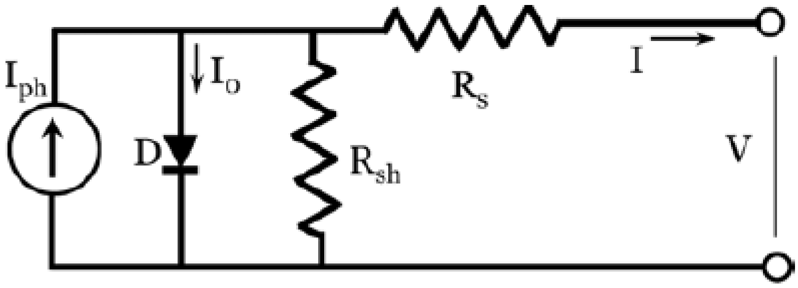

Figure 2.18: Single Diode Model

Thus the generated current of the circuit without a shunt resistor can be calculated using the equation (2.1).

$$I = I_{ph} - I_0\left(exp\left(\frac{qV}{kT}\right) - 1\right) \tag{2.1}$$

With a shunt resistor the equation is as follows;

$$I = I_{ph} - I_0\left(\exp\left(\frac{V + R_s I}{A}\right) - 1\right) - \frac{V + R_s I}{R_{sh}} \tag{2.2}$$

$$A = \frac{N_s n k T_c}{q} \tag{2.3}$$

where;

I_{ph} is the photocurrent which depends on solar radiation and cell temperature

I_o is the inverse saturation current which depends on the temperature

V is output voltage,

R_s is series resistance,

k is the Boltzmann constant,

q is electron charge (1.6×10^{-19}C),

Tc is the cell temperature,

n is the usual ideality factor,

N_s is the number of cells in series.

The irradiation that is incident on a Solar PV module is the normal and diffuse irradiation that is dependent on the position of the sun and time of the year. The irradiation is calculated by equation (2.4).

$$I_t = I_b R_{sh} + I_d R_d + (I_b + I_d) R_r \qquad (2.4)$$

where;

I_b and I_d are normal and diffuse irradiation and, R_r and R_d are the tilt diffuse and tilt factors of reflected solar irradiations. The hourly solar power output of a module is equal to equation (2.5).

$$P_{sj} = I_{TJ} \eta A_{pv} \qquad (2.5)$$

Where;

Apv is the area of the module on to which the solar irradiation is incident, I_{TJ} is the solar irradiation incident on the panel/array area, and η is the efficiency of the panel. The power produced by the PV is the product of the current and voltage. The power output of a PV module is dependent on both the resistance of the load and irradiance.

$$P_{SJ} = P_{STC} G_C \left(\frac{1 + K(T_C - T_{STC})}{G_{STC}} \right) \qquad (2.6)$$

where;

G_C is the light intensity at a working point

P_{SJ} is the hourly output from the Solar PV module

P_{STC} is the rated power of the Solar PV generator.

T_{STC} Is 25^0C

G_{STC} is $1kW/m^2$

P_{STC} is the rated photovoltaic generated power

T_C is the surface temperature of a battery

K is a temperature parameter.

The parameters used to characterize a solar PV module are the short circuit and open circuit voltage, fill factor and the maximum power point that is when the product of V_{mp} (Voltage when Power is at maximum) and I_{mp} (Current when power is at maximum) is at a peak. Solar PV cells are connected in series inside the module (stretching the power curve along the V_{oc} line) though rare they can also be connected in parallel extending the curve along the Isc line in Figure 2.19.

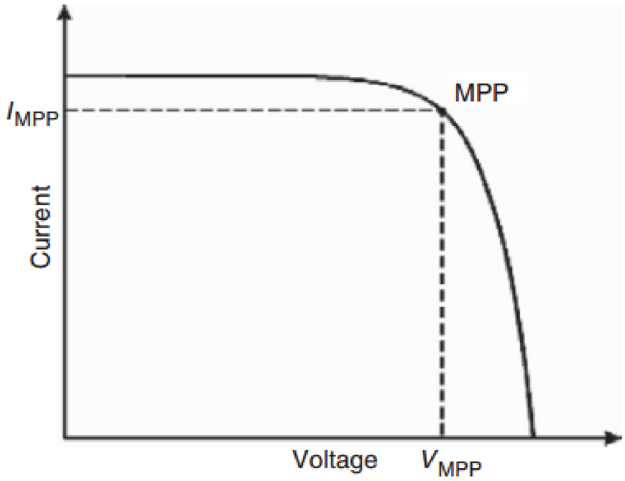

Figure 2.19: The Maximum power point of a solar cell

The equation can determine the *Vmp*;

$$Vmp = Voc - \frac{kT}{q} \ln\left[\frac{Vmp}{nkT/q} + 1\right] \quad (2.7)$$

The fill factor is a measure of the junction quality and the series resistance, and the closer the value is to unity, the higher the quality of the module. The fill factor compares the maximum power that can be produced to the theoretical power.

$$Ff = (Vmp * Imp) \;/\; (Voc * Isc) \quad (2.8)$$

The following equation defines the module efficiency;

$$\eta = \frac{FF*Voc*Isc}{Pin} \quad (2.9)$$

where P_{in} is the power that is incident on the solar PV when there is solar radiation.

2.5.2. PV System Components:

A connected PV system mainly has the following components that are the solar PV array, charge controller, inverter, and with or without a battery system. The components of the system (Figure 2.20) vary depending on the type of connected load, whether DC or AC current power them.

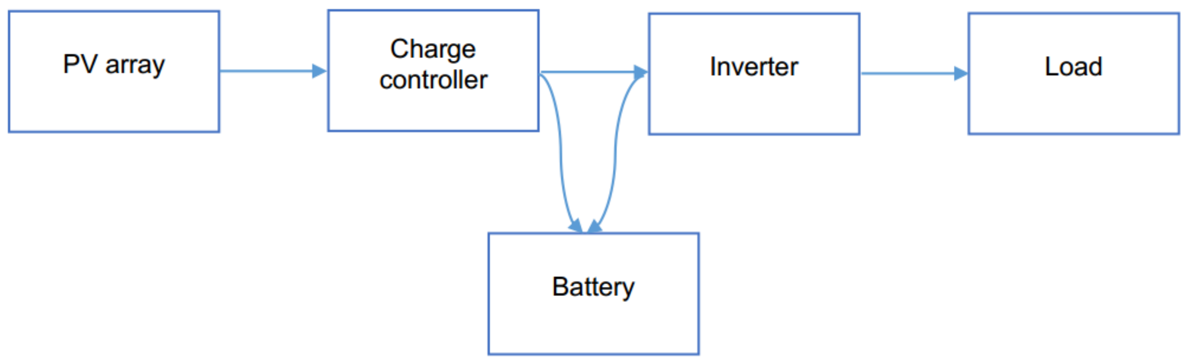

Figure 2.20: Components that make up a Solar PV system

Solar PV system supplying D.C loads differ from that of AC loads because they do not require an inverter but do have a DC to DC converter for the supply of the right voltage to the loads. Another less complicated system is that of a grid-connected system which may not require energy storage as the PV system can be used to provide energy during the day and use grid electricity in the night. The choice of components can vary depending on the decision of the energy source to use.

2.5.2.1. Maximum power point tracker (MPPT)

Using an MPPT increases the amount of energy that can be transferred from the array to the electrical load. The system is primarily used to change the PV output voltage to supply maximum power to the demand. According to Aswathanarayana et al. (2010), states that an MPPT is not an actual component of the PV system, but attached to the DC-DC Converter, inverter or charge controller. The search for a charge controller should ensure that they have the MPP Tracker. These type of controllers are more expensive than the normal, but the increment in power generation per day does offset the cost.

Algorithms are used to search for the maximum power point of the solar PV module on the power curve. The P-V and I-V characteristics of the panel are affected by the irradiance and temperature, thus shifting the MPP (maximum power point). MPPT categories most widely used consist of two groups that is, the direct and indirect MPPT. The indirect MPPT involves the use of algorithms to locate the MPP while the direct MPPT uses collected current -voltage data to check the MPP of the system.

2.5.2.2. Charge Controllers

Charge controllers are in the PV system are used to connect or disconnect the battery when it reaches the set charge capacity. Overcharging and deep discharging are conditions that are detrimental to the health of the battery, and through the charge controller, the life of the battery can be lengthened. The system employs the use of blocking diodes connected in series to avoid the discharge of the batteries through PV cells in the night when there is no sun to generate energy and also the deep discharging to loads in case of long periods of no energy generation(Louie, 2018). They also prevent the battery from being damaged in case of short circuits in the connections in the PV cells.

According to Louie, (2018), the charge controller is also essential in regulating the magnitude of the AC voltage maintaining an excellent quality electricity service and also increasing the life span of other components that are connected on the system. The types of charge controllers used in Solar PV systems include; Series charge controller, shunt charge controllers, and DC-DC controllers.

2.5.2.3. Battery

Energy storage is essential because of the intermittency of renewable energy systems such as solar which is only available during the day time when the sun is shining or for wind when it is not available. Many rural electrification projects in all sizes to extend electricity to rural areas have significantly been successful due to the presence of energy storage technologies, mainly batteries. The most widely spread energy storage technology are batteries due to affordability in cost and the maturity of the technology as compared to the other technologies such as fuel cell systems. Batteries are deployed in electrical systems mainly to balance the supply and consumption of electricity a vital feature when it comes to renewable energy systems which experience intermittency in a generation. The batteries of the system can be affected by temperatures and are recommended to keep them at 25◦C thus should be maintained in a housing unit whose temperatures do not vary a lot over time.

The most widely deployed batteries in electrical systems are the lead-acid batteries and lithium-ion batteries. The most commonly used lead-acid batteries are the sealed and flooded lead-acid batteries. Lead acid batteries can also be identified according to the nature of their plates;

The flat plate battery usually has characteristics of 1000 cycles and a daily depth of discharge of 25 ^{o}C; tubular plate lead-acid batteries to have a higher cycle life between 3000-4000, and depth of discharge of 20%. However, the self-discharge rate of the tubular batteries is higher as compared to the flat plate batteries and the rod plate batteries whose superior characteristics make them more expensive for off-grid electric systems.

The most important criteria according to C. . Nayar & Islam,(2011) when choosing a battery for an electric system, the following characteristics should be prioritized life span of the battery, maintenance costs, capital costs, efficiency of the battery, low self-discharge, low charging and discharging current and long duration of charge and discharge. Complete discharge of batteries and incomplete charging are among the worst criteria that reduce the life span of a batter, especially Lead-acid batteries that widely deployed for rural electrification (C. . Nayar & Islam, 2011).

Modeling of the battery Bank

To properly size a battery bank, parameters such as the battery life, depth of discharge, state of charge, and temperature correction and battery capacity among others have to be provided.
Battery Capacity can be modeled using equation (2.10);

$$Brc = {}^{EcDs}\Big/_{((DODmax)\eta t)} \tag{2.10}$$

Where the E_c refers to the load in Ampere-hours Ah), D_s refers to the battery autonomy days, DODmax refers to the maximum depth of discharge (Usually maintained at 80% for most of the deep cycle batteries) and the η_t is the temperature correction factor that is assigned. When the amount of power being produced from the hybrid renewable energy system is higher than the load demand, the extra power produced is used to charge the battery.

It is also essential to understand the behavior of the battery at a specific time during the charging cycle, and the equation of models this behavior;

$$E_B(t) = E_B t - 1)(1 - \sigma) + \left(\frac{E_{GA}\,(t) - E_L(t)}{\eta_{inv}}\right)\eta_{bat} \tag{2.11}$$

Where E_B and $E_B(t-1)$ represent the charge quantities of the battery at the time (*t*) and (*t*-1), $E_{GA}(t)$ is the total energy generated by the renewable energy source after the losses in the charge controller to the battery after losses in the charge controller,$E_L(t)$ is the load demand the system is supplying at the time (*t*) and $\eta_{inv} and\ \eta_{bat}$ Represent the efficiencies of the battery and inverter while the σ is the self-discharge rate of the battery bank. The charge capacity of the battery falls within the following constraints were the E_{Bmin} and E_{Bmax} are the minimum and maximum charge quantities of the battery bank.

$$E_{Bmin} \leq E_B \leq E_{Bmax} \tag{2.12}$$

According to Dawoud, Lin, & Okba, (2018), the state of charge can be used to optimize the HRES, and the following equation is deployed for use;

$$SOC_{(t)} = SOC_{(t-1)} * \left(1 - \frac{\sigma.\Delta t}{24}\right) + \frac{I_{bat}\,(t-1)*D_t*\eta_{bat}}{C\prime_{bat}} \tag{2.13}$$

In designing solar home systems, to determine the batteries connected in series and parallel Equations (2.14) and (2.15) are used.

$$Number\ of\ Series\ Batteries = \frac{NV_{BB}}{NV_B} \quad (2.14)$$

$$Number\ of\ Parallel\ Batteries = \frac{C_{BB}}{C_B} \quad (2.15)$$

Where;

NV_{BB} is the battery bank Nominal voltage

NV_B is the battery Nominal voltage

C_{BB} is the battery bank Capacity

C_B is the battery Capacity

2.5.2.4. Inverter

Inverters are Solar PV system components that convert DC power into AC. The process of conversion of power from AC to DC is called rectification and is performed by a rectifier. Most of the inverters currently deployed in solar systems are bi-directional and can operate in both the inversion and rectification modes. Inverters are critical components of a Solar PV system as most of the loads that are powered by the system are AC while Solar PV modules generate DC electricity. The inverter uses a set of switches that are simultaneously switched on and off using a Pulse Width Modulation to convert the constant DC voltage into a sinusoidal voltage of AC as shown in Figure (2.24) (Louie, 2018).

The inverter must match with the system current and the voltage of the system's input side, and with the grid voltage and frequency on the output side. Inverters more frequently connected to electrification systems vary between the voltages of 12 and 240 voltage levels DC depending on the required power level. A safety margin is required for an inverter to be able to meet the peak power demand. The size of inverters varies from a couple of hundred watts to hundreds of kilowatts. However, since the PV system does not always generate up to the full expected, the inverter is usually sized less than the system. In smaller systems such as standalone systems, one inverter can be used to supply power to the connected load, as shown in Figure (2.22).

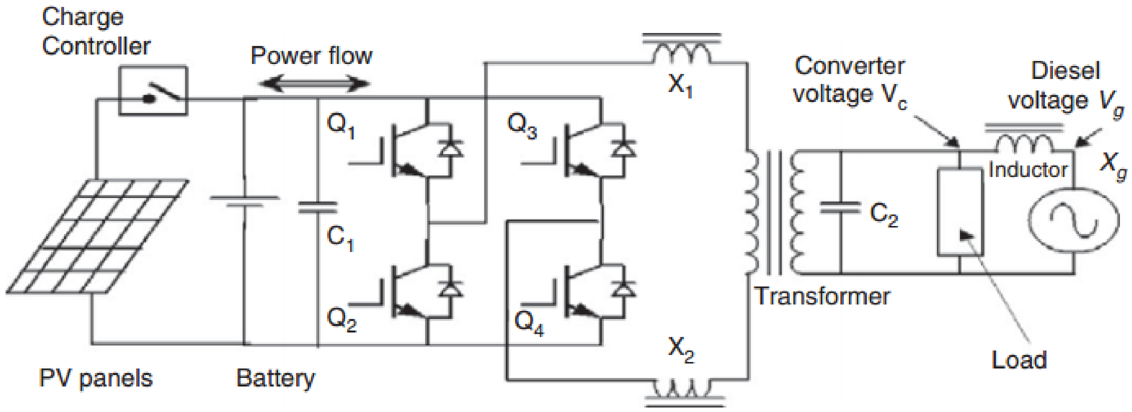

Figure 2.21: Inverter connected in a hybrid system of Solar PV, Battery and Diesel Generator

Source:(C Nayar & Islam, 2011)

In a hybrid system of Solar PV, battery, and a diesel generator, the inverter can be connected in parallel to the generator to supply power to the load, and when the inverter system is down, the generator can supply the load. Large Solar PV systems do require the use of many inverters and many system topologies are deployed to ensure maximum efficiency of the system and reduction of costs. The grid-tied inverter supplies AC electricity after conversion at the same frequency as the grid electricity a function specific to a particular type of inverter. Module inverters are connected per PV module, string inverters where a single inverter is connected to a string of modules and multi string inverters where more than one strings are attached to an inverter.

2.5.2.5. DC-DC Converters;

The converters are mainly used to boost the smaller DC voltage from a PV panel or battery bank to a larger voltage for distribution carrying out a step up function. The converters can also be used to decrease the voltage from distribution down to a consumer's house for connection to DC appliances carrying out a step-down function. The work done by converters can be compared to the transformers connected in AC circuits.

2.6. Diesel Generator

The diesel generator before the advent of Solar systems was among the key energy sources in the villages and the reliable choice during a blackout or load shedding in developing countries. The energy source comprises a reciprocating engine which is slightly different from the type deployed in power plants. The frequency of use of diesel gensets has reduced mainly because of the efforts to improve electricity access and the gradual decrease in the prices of solar PV systems increasing their affordability to households and businesses.

The genset system has three main components that are; the diesel engine, synchronous A.C generator, and the control system. The genset is deployed in many of the HRES, to maintain the stability of the voltage amidst the variability in the solar PV resource and Wind energy. Without a genset in place, the hybrid system will be liable to intermittencies in the generation capacity of the system. Also, it has also been deployed in systems with batteries to provide a backup energy generator in case the battery does not supply the load, especially during the days of Autonomy.

Diesel gensets provide energy on demand as compared to the renewable energy systems as it is not subject to seasonal and daily variability. The output from the system is determined by the load demand meeting the needs of the community that is if there is enough fuel for this demand. Unlike the renewable energy sources, the use of a diesel generator as an energy source is characterized by the operation due to the daily purchase of fuel determined by the existing demand and maintenance costs on top of the capital costs. Diesel gensets have been highlighted to have disadvantages such as noise pollution, the release of CO_2 and other gases to the atmosphere and also the insecurity in the supply of the fuel to be used primarily for areas that inaccessible due to infrastructural challenges.

According to Deshmukh & Deshmukh, (2008), the Gen set needs to be designed such that the rated capacity supplies the maximum load. The efficiency of the genset varies with the electric demand that is connected to the system. The study Muselli, Notton, & Louche, (1999) also further recommends that the installed genset system should not produce a current that is greater than as shown in the equation (2.16)

$$Capacity\ Tor/5 \qquad 2.16$$

The efficiency of the generator is the product of the efficiency of the thermal/ and the future of energy.

Deshmukh & Deshmukh,(2006) Further states that when a generator is used to 70% to 90% of the advised load capacity, then it is performing well economically. Thus the overall efficiency of the diesel generator is given by Equation 2.17

$$\eta_{overall} = \eta_{\,thermal\ brake} * \eta_{generator} \qquad 2.17$$

Whereby the $\eta_{thermal\ brake}$ refers to the thermal brake efficiency of the diesel system.

Genets come when they are available in a different capacity, making it easy for planning and installation and also operated on demand without waiting time. However, gensets require operating costs in terms of fuel, which may escalate if no fuel supply is closest to the location of the plant. Diesel gensets have many parts that may require repair and replacement.

During modeling, the fuel consumption of the diesel generator can be modeled depending on the output power

2.7. Hybrid Power Systems

A hybrid power generation system is a system combing two or more energy sources, operated jointly, including (but not necessarily) a storage unit and connected to a local AC distribution network (mini-grid). Hybrid systems are essential for providing electricity to rural areas to provide power for needs such as lighting, pumping, refrigeration, radio, and televisions, among others for houses or communities. In order to construct a system that is cheap, reliable, and affordable, it is essential to design an optimal one. During the design process, it is critical to consider the location of the community to be electrified to find either an isolated or grid connected system as shown in Figure 2.22. The type of loads to be provided for in the community is relevant to ensure the reliability of the supplied electricity

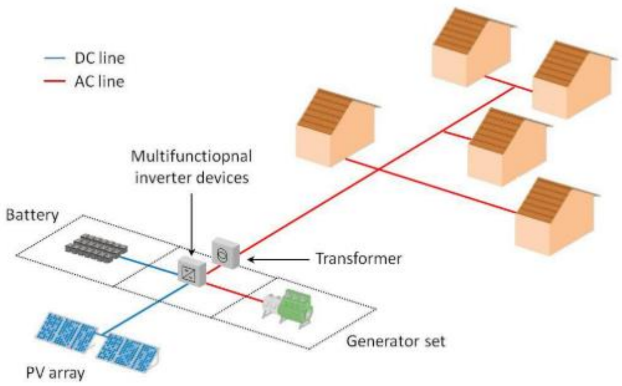

Figure 2.22 Solar PV, Battery and Generator set hybrid system

Source: (Gregoire Lena, 2013)

A hybrid system can be a combination of one or more renewable energy sources coupled together or a combination of a renewable energy source with another source that is conventional Azoumah et al., (2011).

2.7.1. Types/Forms of hybrid energy systems

2.7.1.1. Conventional based hybrid energy system

This type of hybrid system has the renewable energy system couple with usually a diesel-powered generator or with any other traditional source of fuel. They are used when there has already been a diesel generator powering a community and are used to increase the renewable energy fraction in the production of electricity. More often they are deployed to cut down on the costs of generation of power, which is always expensive due to the high operating costs in terms of fuel and maintenance of the parts of the diesel generator. Hybridization of existing diesel generators usually results in a decrease in the price of energy to the residents due to a reduction in the operating costs and also increases reliability mainly in areas that have limited access to trading centres that sell fuel. An energy storage system may or may not be added depending on the reason for the installation of the system.

2.7.1.2. Renewable Energy-based hybrid energy system.

Solar-PV, Wind, Biomass energy resources are coupled together to generate reliable power for a community. Energy storage in the form of batteries added to the system depending on the chosen system that is if a system will be either off-grid or on the grid. The advantages of the different renewable energy resources such as solar which is always available during the day except on cloudy days are used to complement other sources such as Wind which can blow in the night and even on the overcast days. Biomass is mainly considered if there is a considerable amount of the resource that can sustainably power a gasification plant or provide biofuel to power a generator. Thus the system is coupled with either solar or Wind. However, agricultural residues have been considered in this regard due to their availability.

Because, different energy sources produce a different type of power say; Solar PV generates DC power while wind energy system generates AC power, the system configuration of a hybrid renewable energy system is heavily dependent on the available renewable energy resources in the area under study. The energy resources that are to be considered in the design also dictate the type and number of components to be added to the system. The efficiency and cost of the system much depend on the choice of a coupling system for the added elements.

2.7.2. Configuration of the hybrid energy systems

According to hybrid electric systems can be connected in the following ways that is; Series hybrid systems connection or Parallel hybrid systems connection or Switch hybrid connection

2.7.2.1. Series hybrid energy systems

In the series connection, all the power generators of the hybrid system feed the DC power in a battery, thus requiring a charge controller/battery charger for all the connected energy sources. The load is connected to the DC bus through an inverter Figure (2.24). To ensure a reliable supply of power to the connected loads, the inverter and the diesel generator are designed to provide power to the peak load. The subsequent rectification and inversion of the power generated by the diesel generator increase losses in the system, thus lowering the overall efficiency.

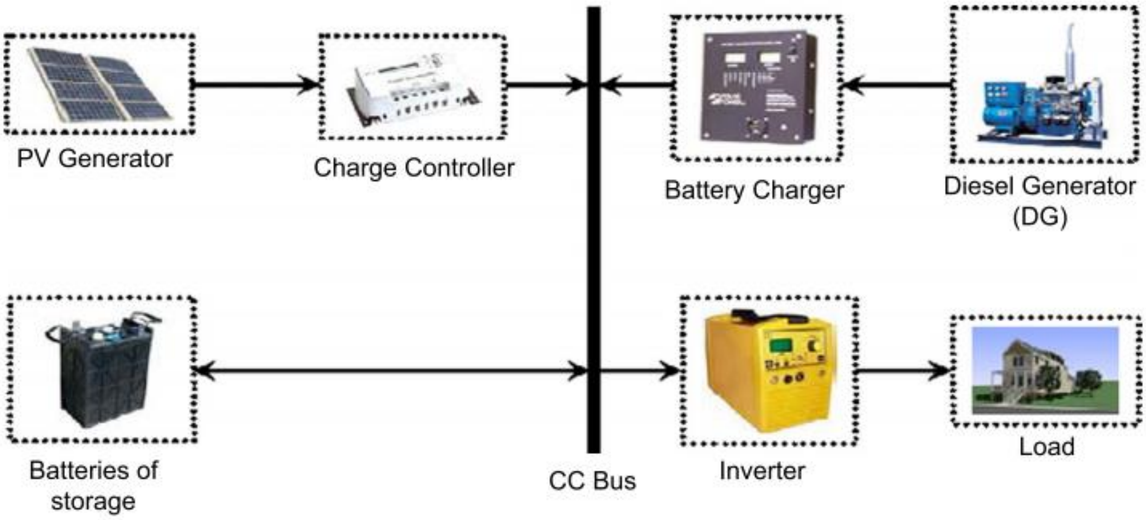

Figure 2.23 Series hybrid Solar PV, battery and diesel generator

Source: Azoumah et al.,, (2011)

According to Azoumah et al.(2011), some of the highlighted disadvantages include a reduction in the lifetime of the battery bank due to the increase in the cycling of the battery bank, larger battery bank and a failure in the inverter affects the supply system to the load.

2.7.2.2. Switched Hybrid Energy system;

In this type of configuration, the A.C load is either supplied by a switchover from the inverter or the engine-driven generator. The Battery bank is charged by both the PV generator and the engine drove generator. During a period of low demand, the load is supplied by the PV generator and the battery. One of the cited disadvantages by Azoumah et al., (2011), is the interruption in power that is experienced during the switch over to the diesel generator. The system has better efficiency than the series hybrid energy system

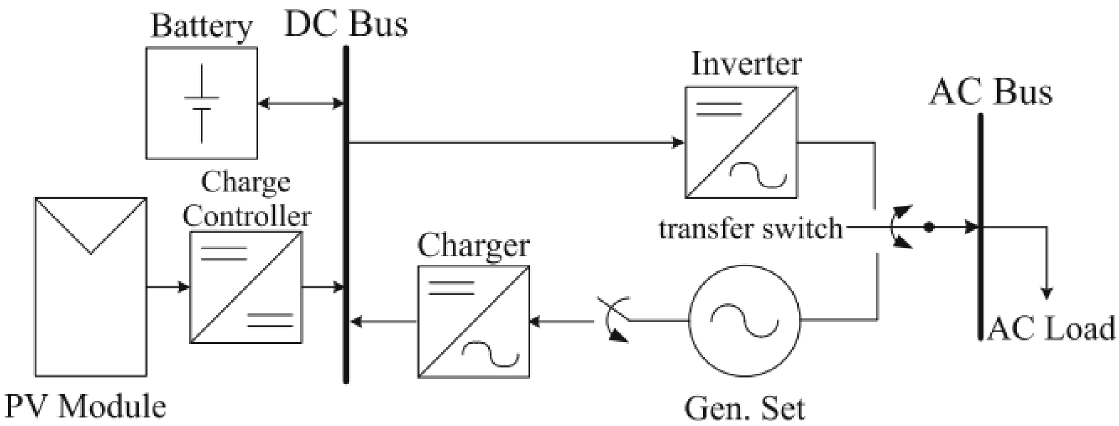

Figure 2.24 Switched hybrid Solar PV, battery, and engine drove Generator

Source: (Louie, 2018)

2.7.2.3. Parallel hybrid energy system

This type of system connection can be connected as either AC or DC coupling. In this type of system, different energy sources that are connected to the system can be able to supply the load differently. The connection of the energy systems does not depend on whether there is a low load or it's the peak load. The different energy generators and loads are connected to a DC/AC bus using the right power electronics and through the correct circuitry

A bi-directional inverter is used to ensure the supply of power to meet the AC load demand and also the battery bank can be charged by the diesel or other fuel type generator shown in Figure (2.28). Through this topology, AC load demand can be powered by both the fuel-fired generator and the other connected energy source.

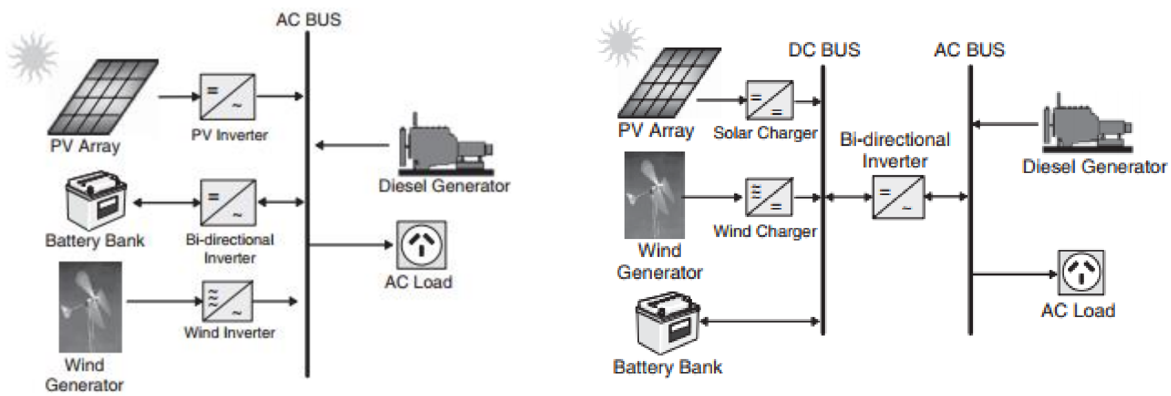

Figure 2.25 DC and AC Bus coupling in parallel Hybrid energy system

Source: C. V. Nayar, Islam, Dehbonei, Tan, & Sharma, (2011)

2.7.3. HOMER Pro

HOMER is an abbreviation for Hybrid Optimization of Multiple Electric Renewables. The tool developed by the National Renewable Energy Laboratory (NREL) is useful in handling various renewable energy technologies such as PV, wind, hydro, fuel cells coupled with the use of a generator or the use of a battery or hydrogen for energy storage. The software entails a possibility to connect the different sources and loads to either a DC or AC bus. HOMER can also simulate a grid-connected system while indicating the availability of the grid in hours of the year and the percentage of power blackouts. HOMER is a time step simulator which is used as an optimization tool for deciding the system configuration. It is used in both developing as well as developed countries to analyse the off-grid electrification issues. Homer involves three stages, as shown in Figure 2.31 that is a simulation, optimization, and sensitivity analysis to carry out techno-economic feasibility of a system and has thus been described as flexible and effective Figure (2.29). (Eltamaly & Mohamed, 2018).

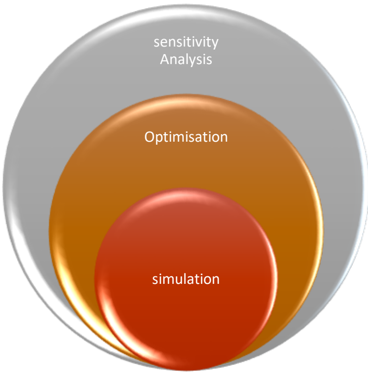

Figure 2.26 Layers in solving Problems with Homer

Source; (capacity4development.eu, 2016)

It can be used for both off-grid and on-grid system configurations. The input data into the software involves the resource data, load data, components of the system among others and yields the cost of energy, net present value, IRR and can be used for all forms of renewable energy as is shown in the Table 2.3;

Table 2.3: Type of result expected from Homer

Type of result	Explanation
System configuration	Overview and simulation of all possible arrangements as specified by the user
Component size	Size of components depending on the system configuration
Initial capital costs	Initial capital costs [$]
Operating costs	Operating costs per year [$/yr]
NPC	Total net present cost [$]
COE	Cost of energy [$/kWh]
RE-Fraction	Renewable fraction on energy generation [%]
Diesel consumption	Diesel consumption of the generators per year [l/yr]

Source; (GIZ, 2016)

A graph depicts the various ranges of the most cost-effective systems over the given operating period, based on the selected criteria. Detailed results can be output for each of the individual simulated systems (graphs, tables, scatter plot, print-out).

2.7.4. State of the Art

Hybrid systems have been of great interest to the developing world due to the ease in which they can be implemented in areas that are far from the grid such as Islands and isolated areas. Integration of renewable energy resources with conventional sources reduced the cost of energy of the electric systems making them cheaper than the use of one resource Al-falahi, Jayasinghe, & Enshaei,(2017). According to Bahramara, Moghaddam, & Haghifam, (2016), most of the research has been done in Asia a continent that holds half of the population of the world is followed by Africa (Bahramara et al., 2016). The work further suggests that the reason for a extensive work in the area is because of the great efforts that have been taken to improve access in the regions to achieve sustainable development goal (SDG) seven.

The design of hybrid systems involves combining two electric systems making it a complicated process, especially if the modeler desires a design that is optimized to give the lowest cost of energy. Different tools have been used to analyze the HRES and most widely used technologies include RETScreen, Hybrid2, and HOMER Pro, among others, have been used to analyze different configurations of the system. Bahramara et al., (2016) described HOMER Pro as a powerful tool for analysis of HRES with most of the common systems used being wind, solar PV, small hydropower, among others. The modelled systems can be either off-grid or on grid technologies, with each having its advantages and disadvantages. The designed system uses data such as metrological data, load profile, economical, and technical data to find the right system for the area.

Empirical work has been done regarding the use of two or more hybrid electric systems around in communities around the world. Most of the modelled systems have used either solar PV, wind, biomass, diesel generator and energy storage with either battery or the more recent technologies such as fuel cells. Anand Singh, Prashant Baredar, (2015) optimized a system using a solar, fuel cell, biomass for an energy center in the Indian state of Madya Pradesh. The research found the cost of energy to be 15.604 Rs/kWh and the system producing 36kwh/year of the unmet electrical. Al-badi & Bourdoucen, (2009), performed a feasibility study for the hybridization of an existing diesel system without the inclusion of a battery for a rural area in Oman, finding that the project was economical for high wind speeds above 5 m/s. Also,Shezan & Narottam, (2017) performed the optimization of an HRES of wind and diesel generator for a rural area using HOMER Pro. The system designed to provide electricity to rural communities in Indonesia with a peak load of 8.7kW, resulting in a reduction of 32.45% in net present cost and CO2 emissions.

Ya and Lilienthal, (2017) hybridized the existing diesel micro-grid in a rural village in Central Myanmar. The system had a Levelised Cost of Energy at 0.339$ which was less than the previous tariff for the old system at 1.48$/month for just a lamp and T.V. Halabi et al, 2017 performed a study focused on the performance of two installed decentralized electrification systems in the area of Sabah in Malaysia. The results from the study further supported the idea that hybridization of rural electrification systems reduces the pricing of the system and the 100% renewable system was found to be performing well mainly in the environmental criteria but had a higher cost of energy

Aside from the research performed on the hybridization of existing diesel systems, considerable research has been done to compare the most suitable system for electrification of regions or areas with a high number of renewable energy resources. The electric systems combine more than one energy source with some using newer energy storage systems such as fuel cells.

Ghenai and Bettayeb, (2019), designed a Solar PV, diesel generator, and Fuel cell hybrid system for electricity production in buildings for heating and cooling needs. The optimized system had a high renewable fraction of 66.1% and a cost of 92$ per MWh with most of the energy being provided by Solar PV. Cristian et al., (2017), performed a comparative study to determine the most suitable combination of energy sources to provide electricity to a load demand of 218kW in Ramnicu Valcea County.

According to the net present cost, a combination of PV panel and Wind turbine were found to be the optimal system for the micro-grid design and recommended for the investor. (Sawle, Gupta, & Bohre, 2018) Carried out research with the primary objective of the study being to design a rural electrification system that is economically feasible and sustainable for electrification of rural areas in Southern India. HOMER Pro was used to optimize the system with solar, wind, hydro and battery being the most cost-effective system for the area. Muh & Tabet, 2019 also carried out a study to compare the most sustainable system to electrify the communities that had no access to electricity in the Southern region of Cameroon.

Ngan and Tan, (2012), explored the possibility of using PV, Wind, and Diesel system for the electrification of the Southern city in Malaysia, Johor Bahru. HOMER Pro was used to optimize the electrification system of a building in the city. The study found that the diesel system gave the least cost of energy though had the highest carbon emissions to the environment. The hybrid systems with the integration of Wind and diesel enabled the system to reduce the reliance on diesel for electricity production because the resource is readily available.

Hybrid electric systems can be either off or connected to the grid. According to Bahramara et al., (2016), most of the hybrid systems designed are off-grid, and only a few cases do they consider grid connection for the components. During attachment of hybrid systems to the network, two modes are mainly considered. Many of the systems carry out a comparison between the cost of extension of the grid and that of installation off-grid systems where system designers use the cost per km for the area that needs electricity. Another mode is the comparison of off-grid systems with an option of selling power back to the grid through a grid feed-in point.

Bastholm & Fiedler, (2020) compared the viability of connecting a PV-diesel hybrid system to the national grid in Tanzania. A comparative analysis carried out in HOMER Pro gave results that showed that if there are many blackouts attached to the existing network, then it is viable to consider the connection of the off-grid PV diesel hybrid system to the national grid (Chedid, Baydoun, Eid, Tarhini, & Ghajar, 2015). The study optimized the hybrid system of PV-biomass-diesel for electrification of Jawani, Teezpur district, India. A grid and off-grid connection were carried out. With an LCOE of 0.091, the cost of a connected grid system was less than that which was off-grid with an LCOE of 0.45$/kWh.

Camblong et al., (2009), studied the feasibility of using a hybrid system of Solar PV and other resources for an unreliable grid. The paper was used to consider the possibility of using a hybrid system of Solar PV and other resources for an unreliable grid network. With the presence of incentives, the payback period is seven years and an IRR of 13%. Chandrakar, Yadav, Sahu, & Soni, 2013 studied the performance of a hybrid energy system comprising of solar PV and a generator powered by either diesel or biofuel through a 'flexy-approach.' The study further cited a fraction of 30% solar penetration as a feasible solution for the community.

Identification of the Knowledge Gap

Numerous studies conducted for HRES in different remote areas in the world, but less research has been conducted for the remote regions in Niger. According to the current electrical situation in Niger, HRES systems will enable the government plans for electrification of rural areas and the spread of micro-grids to isolated communities in the country.

Most of the work performed, considers systems that are not grid connected. An off and on-grid analysis was carried out in this research to find the least cost option to electrify the community better yet the most sustainable option. This study aims to contribute knowledge to the techno-economic and social feasibility of HRES for the electrification of villages in the country. The study also hopes to design a system that will sustainably improve the lives of the people in that community.

2.7.5. Economic Analysis of the system;

According to Al-falahi et al., (2017), the most important parameters used in the estimation of the project cost and prediction of the economic performance of the system are; Levelised cost of energy, discounted payback period, Net present cost and the payback period.

2.7.5.1. Levelised cost of energy;

For a system to be installed, it is crucial to know the price of a unit of electricity generated over its lifetime that will pay for the invested capital, the ongoing costs during operation and the return on investment at the end of the project. The LCOE is a tool used in comparing several renewable energy systems that are under consideration for installation among the many alternatives available, especially with the HRES. The revised cost of energy is determined by a division of the life cycle cost of production of electricity by the total energy produced during the lifetime of the project. Due to the difference that exists in magnitude of the project, the LCOE is determined by Equation 2.18.

$$LCOE = \frac{TLCC}{\sum_{t=1}^{T} \frac{Ep}{(1+r)^t}} \qquad 2.18$$

Whereby *TLCC is* the total life cycle cost, *Ep* is the electric energy produced throughout the lifetime of the project whereas t is the lifetime of the project and the r is the discount rate of the project.

2.7.5.2. The net present cost of the system;

The NPC is the most used criterion currently by mini-grid developers to either select or reject an energy technology. The net present cost is a summation of the present value of all expenses that are related to the project during the period of interest, and these costs include; capital cost, non-operation and maintenance costs, energy costs such as fuel, replacement costs, emission penalties, and others minus the revenues earned during its lifetime. The revenues include the salvage value and also grid sales value if the system is connected to the grid. If several energy technologies are being considered, then the technology with the lowest NPC will be selected. The following Equation 2.19 calculates NPC.

$$NPC = \frac{C_{ann,tot}}{CRF_{i,Rproj}} \qquad 2.19$$

Whereby $C_{ann,tot}$ is the total annualized cost, CRF is the Capital Recovery Factor, i is the annual real interest rate and *Rproj* being the Project lifetime.

CRF is given by the Equation (2.20)

$$CRF_{i,N} = \frac{i(1+i)^N}{[i(1+i)-1]} \qquad (2.20)$$

Where;

i is the interest rate

N is the number of years

2.7.5.3. Payback Period

The payback calculates the period it will take the cash flow of the HRES to equal the initial investment cost. The payback method can further be detailed into a simple payback period method or the discounted payback method.

2.7.5.4. Simple payback Method

Eltamaly and Mohamed, (2018) lists the method for calculation of the simple payback as Equation (2.21)

$$Simple\ Payback = \sum_{t=1}^{T}(Annual\ energy\ cost\ saving - \ Annual\ operating\ cost) \tag{2.21}$$

Where;

T is the number of years it takes for the sum of all the net cost savings to equal the initial investment cost, and t is the first year of the project.

2.7.5.5. Discounted Payback time;

The method is used to calculate how much the discounted net cost savings will take to pay back the initial investment Nigussie et al.,,(2017). This method differs from the simple payback because it includes the discount rate of the investor.

$$Discounted\ Payback = \sum_{t=1}^{T}\frac{(Annual\ energy\ cost\ saving - \ Annual\ operating\ cost)}{(1+r)^t} \tag{2.22}$$

Where;

r is the discount rate is the first project year, and T is the number of years it takes the discounted net cost savings to equal the initial investment.

2.7.5.6. Present Value Method;

The present value method uses the Present worth of a future transaction made during the projects lifetime, mainly cash flows. The project with the highest cash flow gets to be selected and accepted for investment (Eltamaly & Mohamed, 2018).

$$Present\ Value = \frac{Future\ value}{(1+r)^t} \tag{2.23}$$

Where;

r is the discount rate of the project, *t* is the year of cash flow value under consideration, and Future value is the cash flow under consideration.

2.7.5.7. Net Present Value (NPV)

The NPV method can be used to examine the costs and revenues of the project together. The process is recommended for use on projects that are mutually exclusive and also as a second method that can be used to validate a primary purpose. For an HRES project with one primary capital source then (Eltamaly and Mohamed, 2018) give Equation (2.24) for calculation of NPV.

$$NPV = \sum_{t=1}^{T} \left(\frac{1+a}{1+r}\right)^{t} * S - C_{WECS} \qquad (2.24)$$

Where;

$\sum_{t=1}^{T} \left(\frac{1+a}{1+r}\right)^{t}$ Is the present worth of a series of regular future payments made by the system

Cwecs is the primary capital source and is the discount rate.

2.7.5.8. IRR (Internal Rate of Return)

The IRR is the discount rate for investment with future cash flows that make NPV equal to zero. The IRR can be used to decide on whether to proceed or reject a particular project using a specific acceptable minimum IRR value. However, IRR is not recommended for choosing between mutually exclusive projects but for single projects (Short, Packey, & Holt, 1995).

$$0 = NPV \qquad (2.25)$$

2.7.5.9. Annualized system cost;

Annualization transforms a series of future cash flows into equivalent annual streams thus the annualized system cost refers to the sum of the annualized value (capital, replacement, and maintenance) of all the system components (Nigussie et al., 2017). The total annualized cost refers to the annualized value of the entire NPC. Thus the annualized cost is given by Equation (2.26) (Homer Energy, n.d.)

$$C_{ann} = CRF_{i,Rproj} \times C_{NPC}$$

Where;

C_{ann} is the annualized cost

CRF is the Capital Recovery Factor

$Rproj$ is the project lifetime

i is the annual real discount rate

3. METHODOLOGY

Introduction

This chapter presents in detail the data collection methods and the tools used for the analysis of the collected data during the study. Firstly, a description of the techniques for data collection is presented methods used to collect data are described. A presentation about the way of life in the case study area is given. The energy situation and the climatic condition is described, including economic activities in the community. Secondly, a description of the software tool used to model and optimize the hybrid system (HOMER Pro). A report is also given on the energy resources found in the community that can sustainably be harnessed for electricity production. The chapter further introduces the chosen components for modeling in HOMER Pro including the financial costs of the equipment to be used in the design of the system

3.1. Data Collection

3.1.1. Literature study

A literature study was undertaken to understand the energy situation in Niger. Some of the documents that were reviewed include reports from different agencies of the government in the energy sector. Agencies that were approached for documentation included NIGELEC reports, ANPER reports, and also the reports released by the National Statistics Institute, including World Bank report concerning the NESAP project with the Nigerian Electricity agencies. Through these reports, a clear picture was drawn concerning electricity access in Niger and also recent developments in the country to improve energy infrastructure.

Published articles were also studied to give an in-depth understanding of the subject of study. Also, books and a critical summary of work that has been realized in the area of research were used to understand the information that needs to be collected for designing of the system and also to use in the questionnaires.

3.1.2. Primary Data Collection

3.1.2.1. Questionnaire

Case study research is commonly used as a research methodology in different fields of study to give a representation of a problem in a larger area of study. In a bid to find suitable electrification systems for rural areas, intense research expressed in different case study areas has been done to give recommendations for various countries around the world. The six primary sources of information used in a case study are documentation, archival records, interviews (including questionnaires), direct observations, participant observations, and physical artifacts. According to Louie, (2018), there are four methods for load estimation that are currently in use today for projects around the world. These methods are; the bottom-up approach, survey method, regression and data-driven method, common in areas that have been previously powered by a diesel generator and are to be hybridized to reduce the running cost and improve the renewable energy fraction. However, Louie, (2018) further emphasizes that the survey method is the most common approach due to the lower costs involved though despite the popularity, the results if not fully assessed can contain a high percentage of errors.

In this study, questionnaires were used to carry out a survey of Ngonga Zarma community to collect primary data on appliances currently in use in the community, duration of use and the existing electrical solutions in the community. The questionnaires were to also determine the general energy needs of the Ngonga Zarma and the current supply systems for energy in the village. From the literature study, the village was found to contain 403 households. The households found in Ngonga Zarma community are not so distinct from each other. Thus, data that has been collected for one house can be ably applied to the other families. Of the 403 existing homes, one hundred households were sampled for the survey. A sampling of the houses to be assessed was done under the guidance of the commune Secretary-General, who is well versed with all community members.

To ensure the reliability of the results collected from the survey, local teachers from the community secondary school fluent in French were recruited to help in the conduction of the study with the local language as the medium of communication. The hired teachers underwent a 3hr training on the different sections in the questionnaire, including the dos and do nots during the entire process, not forgetting the expected type of result at the end of the survey. After training, teachers were distributed to different parts of the community to ensure full coverage in terms of area of the community. The second batch of questionnaires was directed to business communities to understand the energy needs and how access to reliable electricity would affect them. Ten questionnaires were used to collect information from the existing businesses in the community. GPS coordinates of key features in the village, such as the existing dry wells, high electricity consumption institutions were collected for mapping. The coordinates were also used to map potential customers in the community.

3.1.2.2. Face to face interview

Aside from the questionnaires, interviews were done to get further details and a collective understanding that would lay a background for interpretation of the survey results. The people who were interviewed under the study included; the Village chief, solar technician, Secretary General of the commune and some of the residents of the community. A short stay in the village was undertaken to understand the way of life in the community and observe the different activities that were done by the people throughout the day during the week and the weekend. The stay lasted three days and two nights and preceded other visits.

During this stay a walk was taken around the village in the night to observe how the village looked in the night and during the day, a walk was taken to the market place to find the economic activities in the area. Through this observatory study, information regarding the key trade commodities was undertaken, a ready supply of solar appliances in the market place. Through this study, critical areas for productive use of energy were identified, the prices of fuel in the local market and other business activities present in the area. Through the conducted interviews, information regarding constraints to the expansion of businesses and also access to electricity was shared.

3.2. Case study Area;

Ngonga Zarma village located in Ngonga commune found in the Department of Boboye, Dosso region as shown in Figure 3.1

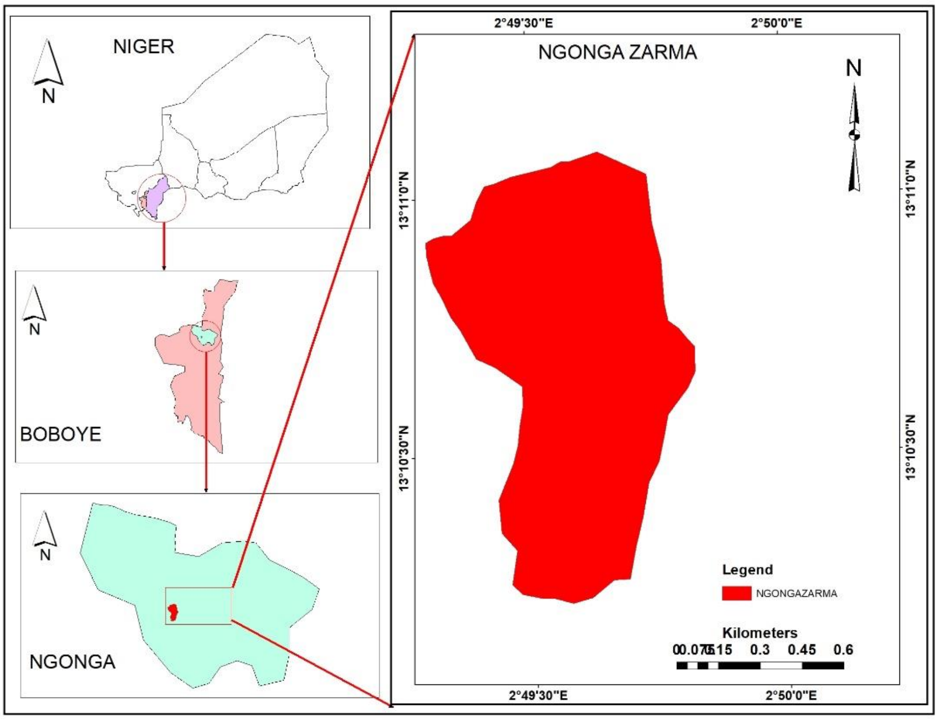

Figure 3.1: Map of Ngonga Zarma

Source: [Own map], (Niger country shape file from https://www.diva-gis.org/)

The village is located 9 km from the main highway from Niamey through Tilaberri to Dosso town. Access to the community is through a stonny murram road from the main road. The way through is characterized by portholes that are flooded with sand making it difficult for smaller cars to travel through, especially at a distance of 1km from the village. The villages surrounding Ngonga Zarma include Perth, These, Boulakorgui, Sodobey, Naoudawo, and Heda Fakara. The main languages spoken in the area are Hausa and Djerme as shown in Figure 3.2. The villages are quite important because all these communities have no access to electricity and a mini grid in the area could further deeply enrich them.

Figure 3.2: Neighbouring villages of Ngonga Zarma

Source: www.openstreetmap.org

The community is most densely populated (Figure 3.3) with households built firmly to each other. Most of the houses in the Ngonga Zarma are made of straw and banco. Only a few homes are made of concrete with iron sheets for roofing with most of them having two rooms. In light of this, a few selected houses can give a true representation of the energy needs of the community.

Figure 3.3 Spatial image of Ngonga Zarma village

Source: Google Earth

3.2.1. Demographics;

The Village has a population of 3624 people of which 1861 are males and the rest female. Therefore the males take the largest portion of the people in the community as shown in the Figure 3.4.

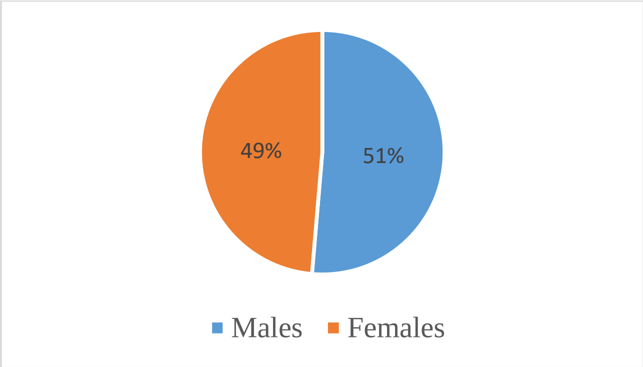

Figure 3.4 Population of Ngonga Zarma

Both the male and female population are dominated by young people from the age of 40, which is evidence of the fact that the African continent has the most youthful population in the world.

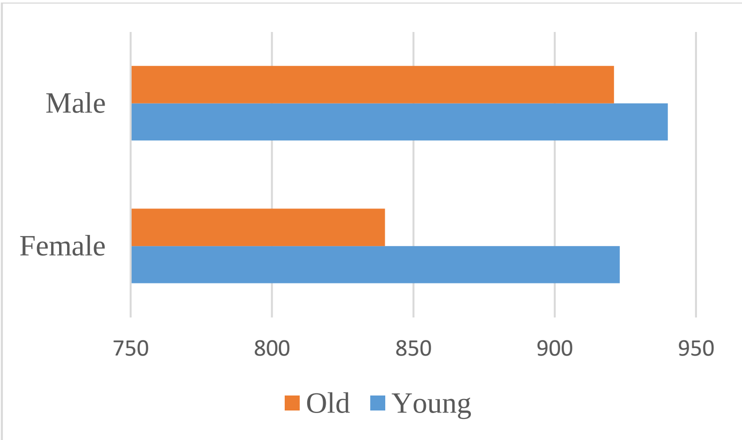

Figure 3.5: Population distribution by age in Ngonga Zarma

According to the way of life of the village, it is evident that the women are responsible for activities such as fetching of water from the well. The community has quite several water sources which include four water wells which are evenly distributed in Ngonga Zarma. However, the wells depict a tedious activity for those involved as long ropes are used to draw water from a depth of 8m and above. Enlarging the existing solar pumping station and introducing a proper financing scheme would ease the burden of water collection on the women.

3.2.2. Economic activities in the village

The village has a nursery, primary, Arabic and French school, and secondary school but the literacy rate is still low. The schools have no electricity system in place, which significantly affects the quality of education given to the students. The main economic activity in the community is farming and cattle keeping. The community is known for trading in cattle with a vibrant market day every Saturday, cattle trading being the dominant activity. The type of animals reared in the area apart from cows include goats and sheep. The trade sees many traders with some from as far as Nigeria and Benin who are looking for cheaper animals. Other activities include trading in grains such as millet, sorghum with the community having four functional grain mills. Due to the long dry season that is experienced by the country at large, farmer own granaries were they keep their harvest for use during the time of scarcity. With this, the trade in grains goes on throughout the dry season.

The community has a few shops aside from grain mills that sell ice and coffee and other household products. Despite trading in ice, the population does not have refrigerators thus relies on the ice brought from Margou, the nearest village with electricity. Other commodities include the sale of airtime, petrol and also the charging of phones using solar. The community has a 15kW solar-powered water system that sells water at the cost of 25fcfa (0.042$). However, despite the subsidized fee, people still prefer the free water from the well even though it is a lot of hard work to fetch it. A more extensive system is currently being planned in the community with a direct connection to some households however a better financing model should be introduced to make the water more affordable under the climatic condition of Ngonga Zarma Village

Located in the Southern part of Niger, Ngonga Zarma like the rest of the region experiences a semi-arid tropical climate. The region is also found in the Sahel climatic zone of the country experiencing a climate that can favor both animal rearing and crop farming. The weather is characterized by a wet and long dry season. The wet season extends from June to September and the dry season from October to May.

3.2.2.1. Temperature;

The region experiences high-temperature conditions with an annual average temperature of 28.5^{o} with the hottest months being April, May, and March. Ngonga Zarma, according to the RETScreen Expert online version NASA database, experiences the lowest temperature conditions from November to January in Figure 3.6.

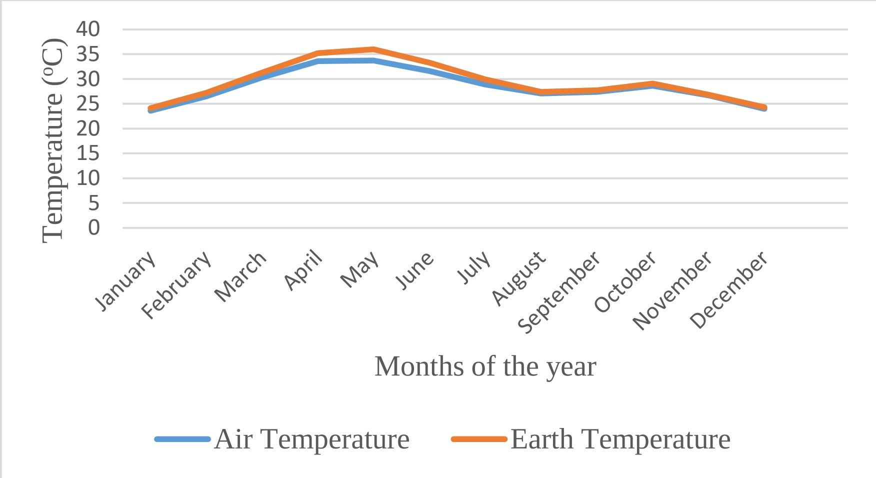

Figure 3.6: Annual Earth and air temperature of Ngonga Zarma

Source: NASA RETScreen database

3.2.2.2. Rainfall

The region like the rest of the country has one rainy season with peak precipitation of 545mm^2 experienced during August. The days of rain vary from 6 days in June to 7 in August with 12 days as the peak in July as shown in Figure 3.7. The rainfall received during this period is essential for farming and also for cooling the heat due to high temperatures to within a favorable range for both the installed energy system and even for the wellbeing of the people.

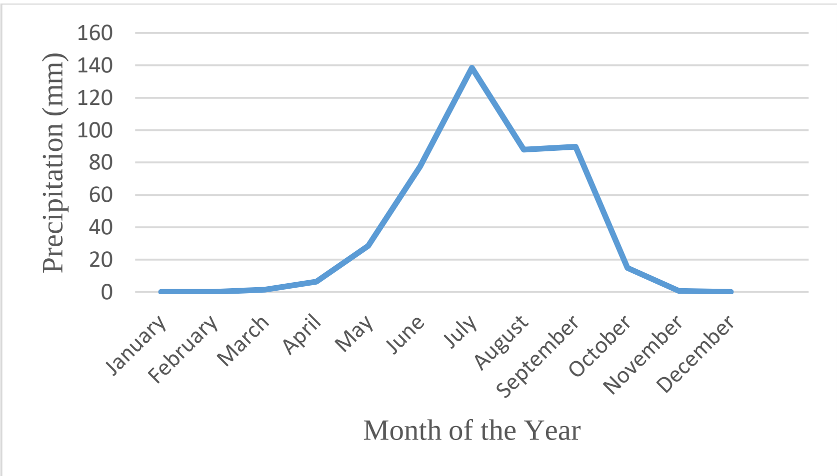

Figure 3.7: Rainfall trend throughout the year of Ngonga Zarma
Source: NASA RETScreen Expert

3.2.3. Energy Access in the Village;

3.2.3.1. Energy for cooking

The community mainly relies on wood for their cooking needs while using inefficient cook stoves. All the surveyed households in the community indicated the use of wood for cooking a resource that is unsustainable due to the dry climatic condition of the area and the low biomass cover in the area. The use of firewood means that women and girls have to walk long distances to collect wood for household use.

3.2.3.2. Electricity access

3.2.3.2.1. Electricity needs

During the survey, a need was found for electrification in the community. Some of the observed needs for electricity in the community include water pumping for irrigation, an extension of the existing small solar powered system. Figure 3.8 shows some of the expected high consumption areas such as the current health Centre, grain mill, old water supply system, and the existing schools in the community.

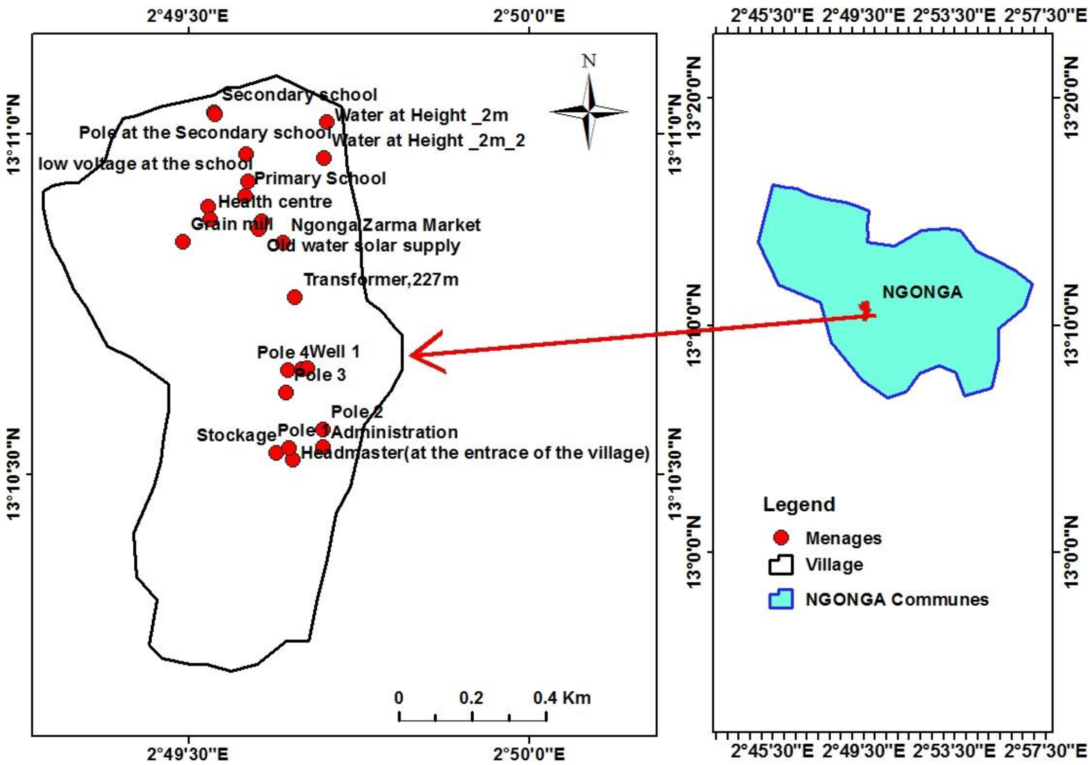

Figure 3.8: Map of Ngonga Zarma showing key features in the community

Source: [Own map]

3.2.3.2.2. Access to electricity from the grid.

Ngonga Zarma village has no access to electricity with previous plans to electrify the village having failed. The community under an earlier project to electrify the village, was deployed and installed pylons for extension of electricity but four years later the community has no power. This situation has been attributed to the fact that grid connection lines from the national grid cannot supply stable power to the community. Niger relies on electricity that is imported from Nigeria, but with time, the increasing electricity demand has seen shortfalls in this supply and reliability. The existing transmission lines in capacity and quality cannot carry the needed capacity to cover Ngonga Zarma and the surrounding villages. Connection of new communities on the current lines requires an upgrade of the existing lines and an increase in the generated electricity in the country to supply the communities with stable and reliable electricity. The interconnected lines could not provide enough electricity to power other neighboring villages such as Nioumey Kougourou Zarma 2.5Km and Boulakorgui 3.5 km from Ngonga Zarma. Ngonga Zarma is located 9km from the main highway in Margou village.

Figure 3.9: Map showing the distance of Ngonga Zarma from the main road

Source: Google Earth

Despite the existing shortfall in electricity, some of the surveyed households have solar home systems ranging from 20W to 100W shown in Figure 3.10. The solar home systems are used to charge solar lamps and telephones. The lamps provide light in the night though a walk through the night in the village revealed that only a few homes have access to these lamps with the community being deafeningly quiet and dark. Most of the solar systems in place are owned by existing small business owners and mainly households whose relations worked either in the city or neighboring countries.

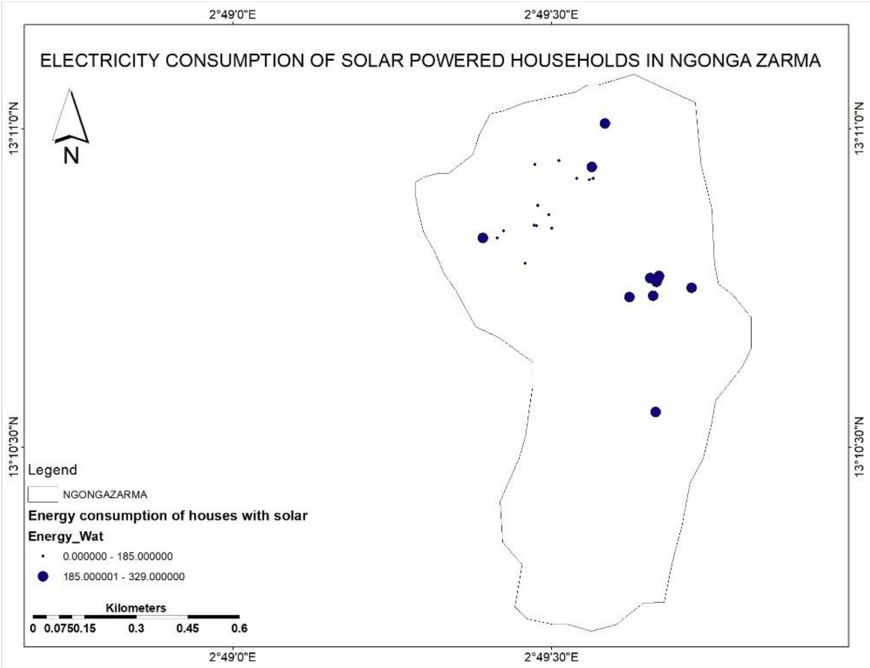

Figure 3.10 Map showing the houses with solar home systems and their average daily consumption
Source: [Own map]

Families without solar home systems mainly relied on primary batteries to power torch lamps and small radios for information. These batteries can be bought from the nearby small shops or market; however for better quality batteries, Margou village at the main highway was the place where they are purchased including ice for cooling. From the surveyed households, it was found that a majority of the sampled households do not own solar home systems shown in Figure 3.11.

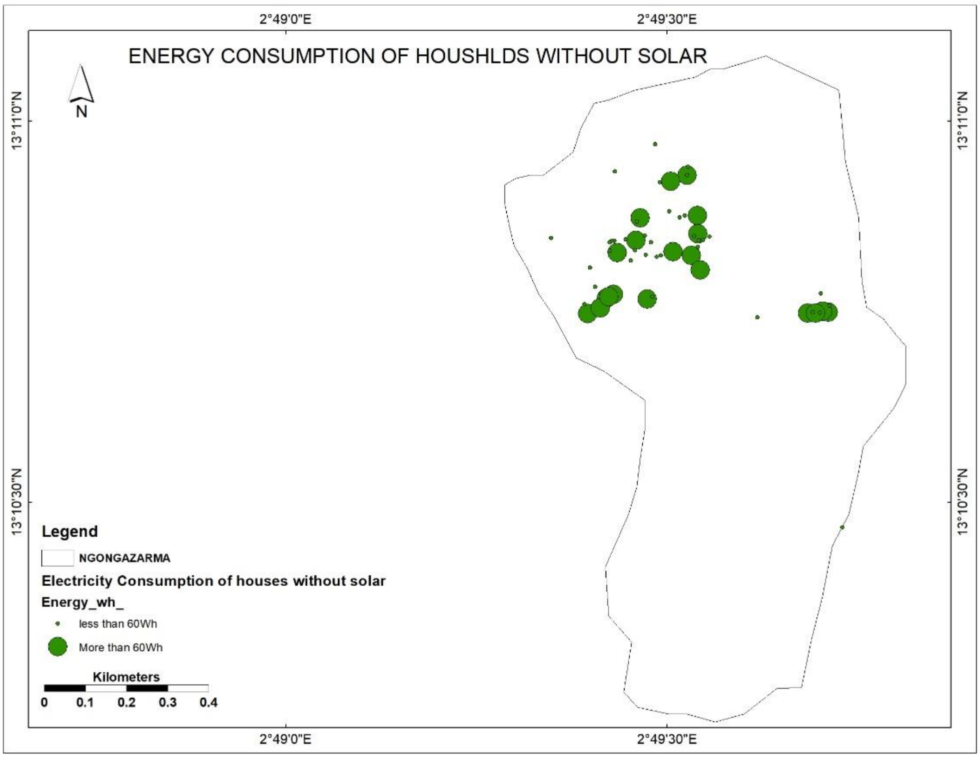

Figure 3.11: Map showing houses in Ngonga Zarma without solar home systems plus their electricity consumption.
Source: [Own Map]

3.2.3.3. Load profile of the community

3.2.3.3.1. Institutional Load Profile;

The institutions considered in this study include Mosque, Secondary school, Primary school, Nursery school, and the Health Center as shown in appendix A and B.1. The main groups with high demand are the Health center, Secondary school, and the Mosque. A peak is realized at 8 pm mainly for lighting and also midday when fans are switched on for cooling.

3.2.3.3.2. Administration load profile;

The main load of the administration building and the village store is the fan switched on at midday and further used for later afternoon work as shown in appendix A.1. Due to the nature of work performed by the administration unit, a computer system was planned for in the model. The structures are found in an open area without trees to provide any form of shading, thus making it very hot during the dry season.

3.2.3.3.3. Household Load

The household load was estimated using the assumption that not all households in the village will be electrified in the first year or the following years. From the results of the survey, it was found that 75% percent were willing to pay for electricity. Thus from the 403 households, the system was designed for 302 households as the rest of the 15% were assumed to either stay powered with solar home systems and others unable to pay electricity monthly including the connection cost. The households to be connected were further divided into two different types; type one who are low consumers of electricity and type two who are high consumers of electricity. From the survey results, most of the respondents were willing to pay for electricity at a fee less than the NIGELEC grid price. These respondents were taken as low consumers while the rest who were willing to pay the grid price and more were taken as higher consumers of electricity and grouped as household type two. Thus, 255 households were calculated under group one and 45 households under group two.

Household type one

This category comprises of an estimation of houses which from the survey can only pay electricity at a price lower than the national grid price. In the case of electrification, it was assumed that the houses would try to maintain a lower electricity consumption. The electricity load was limited to a minimal; providing only lighting and radio to stay informed. The houses were assumed to have two rooms and also in need of only one electrical outlet. The profile is seen to have two peaks from 6 am and at 8:00 pm when most of the residents were at home and resting after a day’s work. During the period of stay in the community, it was observed that the residents woke up quite early for the early Morning Prayer to start the day explaining the first-morning peak before setting off to the field see Appendix B.2.

Household type two

In this category are households that during the survey were considering paying the price for grid electricity and more. An assumption was made to find these households as large consumers of electricity. The load profile contains two peaks in the wee hours of the morning and at 8 pm. An increase in the demand is seen at 3 pm during the hours when residents of the village are coming back from the field see Appendix B.2.

3.2.3.3.4. Commercial load

The community, according to the interview with the community leaders, is still backward concerning any commercial activities aside from trading in animals and grain see Appendix B.1. The village, according to the discussion has ten major businesses of which 4 are grain mills and the rest being small shops and kiosks for serving coffee. A peak in demand is observed at midday due to grain mills that have started work, and then the demand decreases along the day as the mills are switched off and the business such as kiosks and shops start providing recreation service to the community through radio and television for the evening.

3.2.4. Energy resource assessment and components selection in Homer Pro.

Hybrid electric systems are a combination of different components that are used to harness power from various energy sources. The parts are distinct from each other, and combining them in a single system increases the number of variables to be considered for evaluation to give an optimal design. Modelling of hybrid electric systems is a complex process that requires calculations of energy balances in a time step and then determines the cheaper system for installation. Different software tools are used to aid in decision making; however, for this study, HOMER Pro was chosen to perform the analysis of the system. HOMER Pro requires energy resources potential of an area for modelling

3.2.4.1. Energy Resources Assessment

3.2.4.1.1. Wind Resource;

Ngonga Zarma receives an annual average resource of wind at a speed of 2.94m/s height of 50 m according to the NASA database in HOMER Pro as shown in Figure 3.12. The lack of enough data on the variation of wind speeds in the country more specifically in the southern part has made it un-favorable to consider electrification using Wind resource in the region and Niger at large. Moreover, for an electrification project powered by Wind resource to be feasible, should have an annual average wind resource of 6m/s. Thus the use of Wind as a renewable energy resource shall not be considered in this research. However, the wind can be harnessed for pumping of water just like other communities that are faced with severe water scarcity.

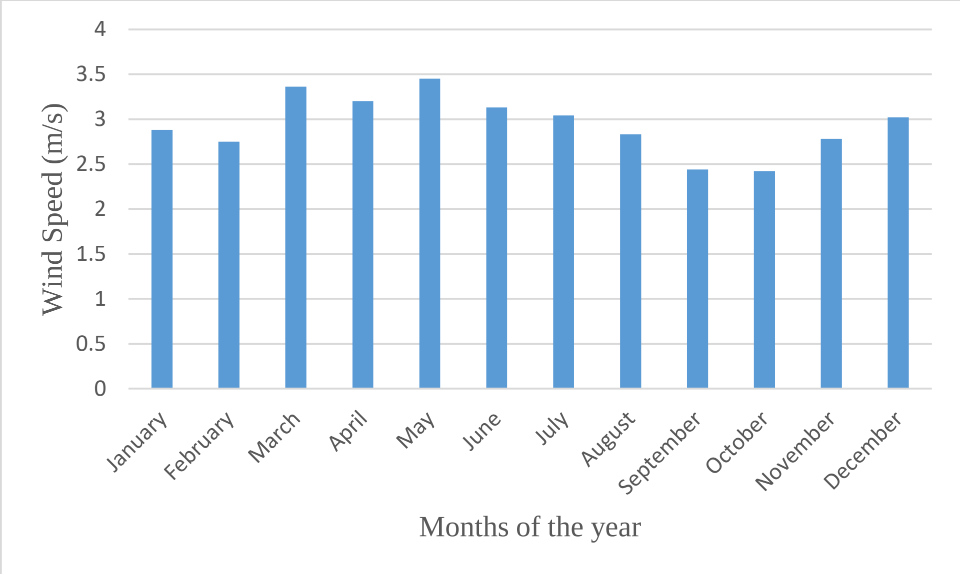

Figure 3.12: Wind speed received in Ngonga Zarma

3.2.4.1.2. Solar Resource Assessment;

Found in the Dosso region, a solar resource of Ngonga Zarma used was from NASA database found in HOMER Pro software. The website provides data for over 22 years; from 1983 to 2005. The scaled annual average was found to be 6.17kWh/m^2/day. The highest daily irradiation during the year is April and May which are also essentially among the hottest days in Niger as shown in Figure 3.13. The clearness index of the area varies between 0.646 as the highest experienced during the dry season and 0.64. However, the lowest clearness index is 0.542 in August. The region experiences peak rainfall during August during this time there is an overcast due to heavy rain clouds hence a lower clearness index and daily radiation of 5.7kWh/m^2/day.

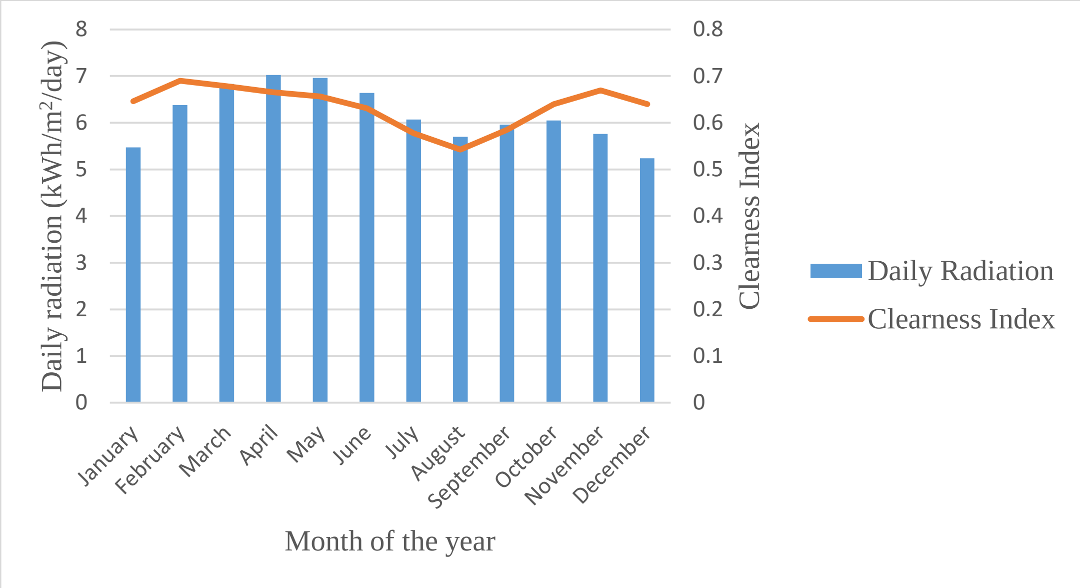

Figure 3.13: Daily radiation of Ngonga Zarma community
Source: NASA Database Homer Pro

Adaramola, Paul, & Oyewola, (2014), defines the clearness index as a fraction of the total radiation that is incident to the planet earth from the atmosphere to that measured at a particular location on the planet. Clearness index is essential in providing information about the weather conditions for a specific place or region to properly size the solar PV system with an appropriate power bank. Another aspect that the index helps in predicting is the availability of solar radiation in an area. A region such as Dosso and Niger at large is dry and receives the sun for most days throughout the year, thus knowing the clearness index planning for a reliable system even in the short wet season. According to IQBAL, (1980), highlighted that for massively overcast weather, the clearness index value is below 0.4(K_T<0.4) and K_T in the range of 0.4 and 0.6 is partly cloudy. A K_T above or equal to 0.7 was found to predict clear weather for the place under study. Throughout the year, Niger experiences a solar resource with a clearness index above 0.6, showing that the installation of a PV system in the area will thrive and provide close to the predicted amount of energy.

3.2.4.1.3. Diesel Fuel

During the field visit to Niamey, the price of diesel was observed at 1.03$ at the exchange rate (1$ =585 FCFA). According to Knoema, (2019), the cost of diesel according to their exchange rate maintained between 0.0.48 in 2000 to 0.88 in 2016. During this period, the price rose to a maximum of 1.16$. However, for rural areas and during the time of scarcity (as a result of geopolitical conflicts and struggling economy), that is far from the capital city, the diesel prices increase. In order to carry out a sensitivity analysis, different values of the fuel prices were selected for study. The current diesel price of 1.03$ was chosen and other costs between 0.8$ and 1.3$. An increment of 0.06$ maintained during the simulation. 1.5 $ was selected to represent periods of extreme scarcity of diesel, a situation that is terrible for communities such as Ngonga Zarma.

3.2.4.2. Hybrid Energy system components;

3.2.4.2.1. Diesel Generator

The minimum load ratio is the percentage of the total load of the system below which the generator is switched off so as not to support the connected electric load. If the connected load is below the minimum load ratio, the generator runs at a high load and the extra power produced is either used to charge the battery or dumped. When other energy sources in the system are powering the load, the generator is switched off. The diesel generator chosen for modeling of the hybrid energy system is a Generac 30kW. The power factor of the generator is 80% as shown in Table 3.1. The generator was added to the HOMER Pro library and later chosen because of its availability on the Nigerien market. Ownership of diesel generators in Niger is a requirement because of the frequent blackouts day and night that affect the running of businesses, including the need for cooling. The situation is the same for both the urban areas and rural though the load shedding period for rural communities is longer. Other system constraints considered include; the discount rate of the project at 4.5%, inflation rate at 2.4%, System fixed costs at 1500 and operating costs at 800 dollars per year.

Table 3.1: Design Parameters for the Diesel Generator

Parameter	Units	Value
Capital cost	$/kW	666.67
Replacement cost	$/kW	666.67
Operation and maintenance cost	$/h	0.6
Operational lifetime	Hours	20,000
Fuel curve intercept	l/h	0.538
Fuel curve slope	l/h/kW	0.303
Fuel Price	$	1.03

3.2.4.2.2. Battery

The battery is essential in a hybrid system as it provides electricity at a lower cost than the diesel generator during the time solar PV is unavailable. The Battery Model 6CS25P from Surette was chosen for modeling of the system and the details are enlisted in Table 3.2. The number of batteries considered in the optimization study were determined by HOMER Pro optimizer, which decided on the total number needed.

Table 3.2: Design parameters for the Batteries

Parameter	Units	Value
Nominal Voltage	Volt	6
Nominal Capacity	kWh	6.91
Round trip efficiency	%	80
Maximum capacity	Ah	1156
Minimum state of charge	%	40
Capital cost (1)	$	1200
Replacement cost (1)	$	1200
Operation and maintenance cost	$/year	15
Maximum charge current	A	279
Maximum discharge current	A	279

3.2.4.2.3. Solar PV Module

Canadian Solar 250CS6P-250P was used in the study because it is cheaper and widely preferred in previous research concerning a similar area with specifications as shown in Table 3.3. The component was chosen to be the main electricity generator due to the abundant sunshine received in the country. Tracking system was not considered in this research because of the terrain of Ngonga Zarma. As described before, Ngonga Zarma sits on flat ground with very few trees scattered over the expanse of land; thus losses due to shading are not considered. With the right angle of inclination, the modules do receive sunshine throughout the day.

Table 3.3: Design parameters for the Solar PV Modules

Parameter	**Units**	**Value**
Capital cost	$/kW	1400
Replacement cost	$/kW	1400
Operation and maintenance cost	$/kW	5.5
Operating Temperature	Hours	43
Derating factor	Percent	85
Nameplate Voltage	Volts	37.8
Efficiency	%	13

3.2.4.2.4. Converter

The model designed in Homer Pro consists of both DC and AC power generators connected to an AC only load. A converter is therefore needed to convert DC power to AC to supply the load and vice versa to charge the battery. A bi-directional inverter was chosen for the micro-grid, and HOMER Pro software used for optimization of the size. A grid connection study was carried out for one of the scenarios, and thus a grid-tied converter of Schneider Electric Conext XW model with specifications in Table 3.4 is chosen.

Table 3.4: Design parameters for the Converter

Parameter	**Units**	**Value**
Capital cost	$/kW	600
Replacement cost	$/kW	600
Operation and maintenance cost	$/year	0/year
Operational lifetime	years	10
Efficiency-Rectifier	%	93
Efficiency-Inverter	%	92.70

3.2.4.2.5. Controller setup;

The dispatch strategy chosen for the design of the system was Homer load following approach mainly because of the decision to maintain low costs of operation. Ngonga Zarma community located far from the capital, and because of this, it is essential to minimize the amount of fuel used by the generator, further reducing the operation costs. In this control strategy, the diesel generator is continuously switched on and off during the operation. A 10% operating reserve is chosen because Ngonga Zarma is not expected to have high variability in the load as the people maintain a similar routine and the demand too is not likely to change a lot in five years. Also, the area has many sunshine hours with less overcast days as seen from the clearness index given earlier on in the chapter thus assuming that the amount of radiation per day is maintained the same for the more significant part of the year. The capacity shortage is chosen to be 3% because the power supply from the grid is not reliable not forgetting that the primary resource; solar PV, faces intermittency looking at the wet season experienced by the Niger.

4. CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Introduction

The chapter presents the findings of the load assessment performed on Ngonga Zarma village and the load curve of the community. Two scenarios for electrification were chosen for analysis to determine the low-cost option for providing adequate power to the community. A presentation is given about the system configurations and assumptions taken during simulation in HOMER Pro.

4.2. Load profile of the community;

Ngonga Zarma has two demand peaks experienced at 6:00 am and 8:00 pm as shown in Figure 4.1. The peak load demand of the village is 22.94 kW at a time when most of the residents are back home. The differences in seasonality that is winter or summer were not considered in this research. Electricity during this time is mainly consumed for lighting, radio, and cooling. Most of the residents wake up between 5 am and 6 am for prayers and then leave for their fields to work. Electricity consumed early morning is to provide lighting during early morning prayers mainly. Results from the survey showed that there was no difference between the weekdays and weekends as most of the residents worked the whole week except on Saturday when there was a market day in the community.

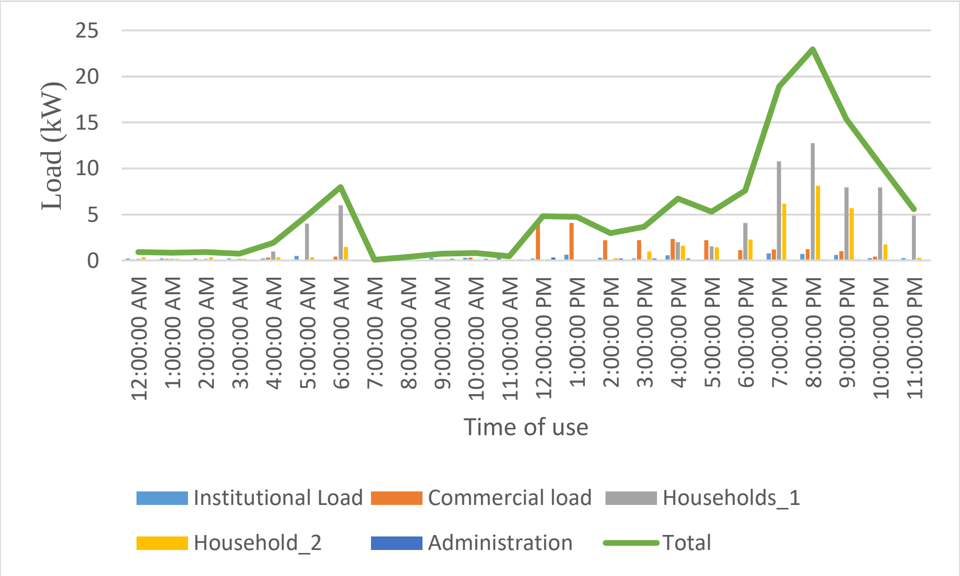

Figure 4.1: Load profile of Ngonga Zarma Village

4.3. Modelling and Simulation results from Homer Pro;

Two scenarios were modelled for the electrification of the Ngonga Zarma community, which are an off-grid and on-grid connection. In the off-grid context, the system was designed to be a standalone system with batteries for storage and the energy generation sources as solar PV and the diesel generator in Figure (4.2). The grid connection system had a similar model but with the local grid connection attached as another energy generation sources and also to enable the sale of excess electricity as a means of stabilizing the system.

The advanced grid module was added to represent both the reliable and unreliable supply of electricity. Through this mode, the break-even distance for connection of the rural community to the national grid was explored.

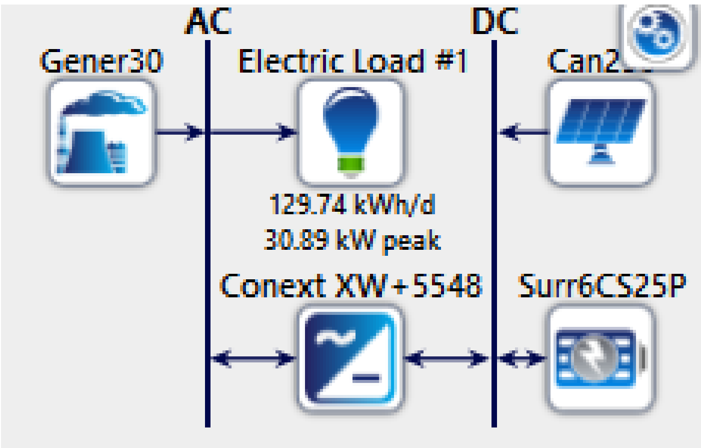

Figure 4.2: System configuration for the off-grid scenario
Source; HOMER Pro 3.13.1

4.3.1. Off-grid electrification Scenario for Ngonga Zarma Community

In this scenario, it was assumed that the community would generate and consume its power without sharing to the national grid network. Due to the extensive use of AC power-consuming appliances, the electric load is connected to the AC bus with the diesel generator. A bi-direction converter is used to convert electricity from the DC bus to AC power. Solar PV generates electricity in DC form, which charges the battery, therefore, a connection to the DC bus. Three hundred seventy seven simulations were run in HOMER Pro, of which 277 were found feasible and the rest infeasible. Of the infeasible solutions, 112 were eliminated because of the capacity constraint of 3% and the others were omitted due to reasons such as the lack of generation sources, among others. HOMER Pro presented the five optimal solutions in different categories for assessment as shown in Table 4.1.

Table 4.1: System components and their sizes

System Configuration		Size of Solar PV (kW)	Size of Diesel Generator (kW)	Size of Converter (kW)	Size of Batteries (Unit)
Solar PV, diesel and battery	A	35		27.4	56
Solar PV and battery	B	35	30	27.6	80
Diesel and Battery	C		30	6.68	8
Solar PV and Diesel generator	D	34.3	30	8.81	
Diesel Generator	E		30		

The system comprising of Solar PV, diesel generator and battery (A) stood out as the optimal system with a capacity of 35kW of solar and a battery bank size of 56. The string size of batteries was 8 with seven strings connected in parallel. The system also comprises of 27.4kW size of a converter with 42.9 hours of autonomy. The solar PV and battery system (B) presented the same capacity for components as system A but a slightly bigger converter size of 27.6 kW. The diesel generator only, system configuration (E) was considered as the most expensive option for electricity generation. Five categorized optimal system configurations were shown in the software from system A to E.

4.3.1.1. Cost analysis of the systems;

High capital costs are characteristic of renewable energy systems because of the upfront costs of equipment that need to install before the production of electricity. Most of the renewable energy sources have high costs of the balance of system equipment often required for stabilization of the system. The RES often need equipment installed over a large piece of land to harness the energy, especially solar and wind systems, thus quite essential to establish an optimal system for a particular location. The costs of the system configurations are broken down into different classes from capital costs to salvage value.

System configurations that comprised of Solar PV gave a relatively high initial capital cost as compared to those using a diesel genset for electricity production Figure 4.3. Capital costs for system A were $154,121 as compared to those of system E at $21,500. The high initial costs are mainly due to the balance of the system equipment apart from the solar panels. Despite the reduction in the pricing of solar modules, most of the balance of system equipment is still expensive and not as affordable as the modules. The balance of the system costs for systems that have solar includes converter and battery costs whereby the price varies according to the size of the capacity of the system. System B has a high number of batteries at 80 in amount more than system A at 56. The replacement costs for system B due to the set battery life that increases the costs depending on the battery bank size.

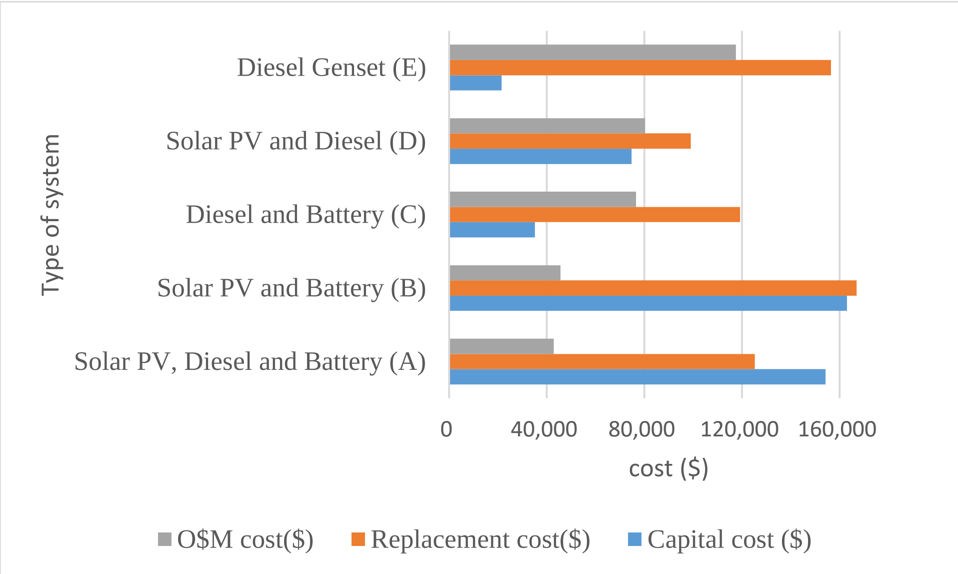

Figure 4.3: Capital costs of different system configurations

Systems with the diesel genset have high O&M costs due to continuous expenses incurred in lubrication among others. The diesel generator, especially in system E and system D, has extended operating hours, which lead to the wear and tear of the generator requiring lubricants and also having more break downs that need to be repaired. Thus the more hours a diesel genset has to run, the higher the operation and maintenance costs. System (E) at $117,532 has the highest costs as compared to the other configurations.

Overall, systems that have a diesel generator have more top operation and maintenance expenditure as compared to solar PV systems. System (B), has the highest salvage value at the end of the project life due to the minimum running time awarded to the genset. System (E) has the lowest salvage value, which can be attributed to the wear and tear from the continuous operation of the generator, which reduces the quality of the equipment at the end of the project. Figure (4.4) shows a plot of the salvage value of different system types and their running hours. From the result, it is noted that systems that have a long period of operation of the diesel generator have a low salvage value as compared to those with either low to non-operating hours.

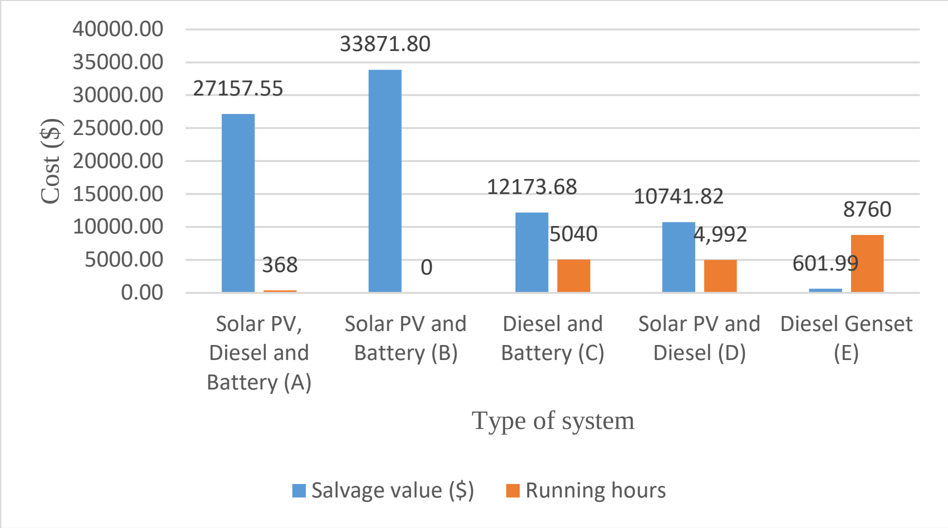

Figure 4.4: Variation of the salvage value with the running hours of the diesel generator system

4.3.1.1.1. <u>Fuel costs;</u>

Fuel costs are essential expenses during the lifetime of the system because they are determined by the amount of electricity produced, which depends on the demand of the community. System (E) has the highest fuel costs at $675,984.84 in Figure 4.5. System (C) and (D) have closer fuel costs due to the high percentage of energy generated from the diesel generator. In both systems, the diesel generator has a high run time of more than 4000 hours a year. The diesel generator either provides electricity during the night for system D or during the day for system C.

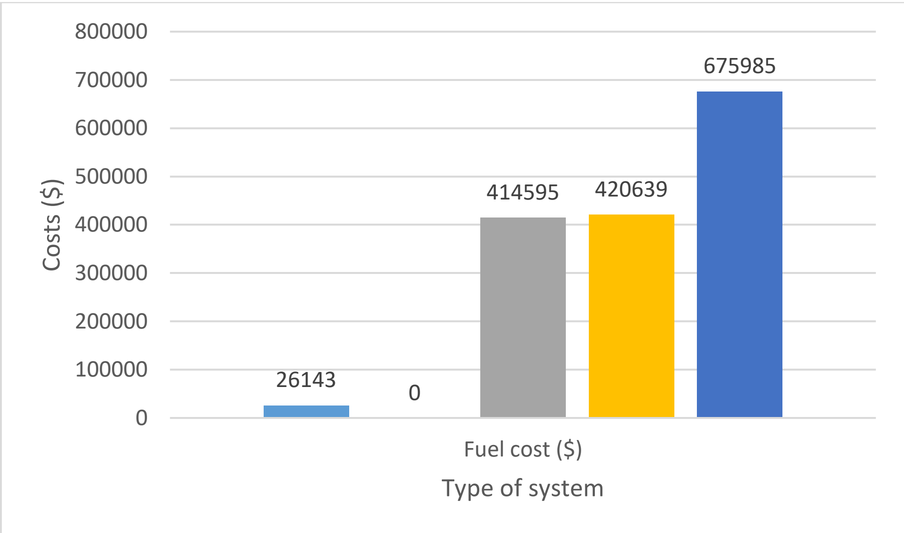

Figure 4.5: Fuel costs per system type

4.3.1.1.2. <u>Net present Cost;</u>

System (E), has the highest Net Present Cost (NPC) attributed to high fuel costs and O&M costs as compared to system A. The high costs are due to the high percentage of electricity generated from the diesel generator. System A, has higher initial costs attributed to the batteries, diesel, and solar PV modules but has the lowest net present cost at $321,249 better than system B. However, it should be noted that systems A and B have net capital cost that are considerably lower than the rest of the systems such as system E in Figure (4.6).

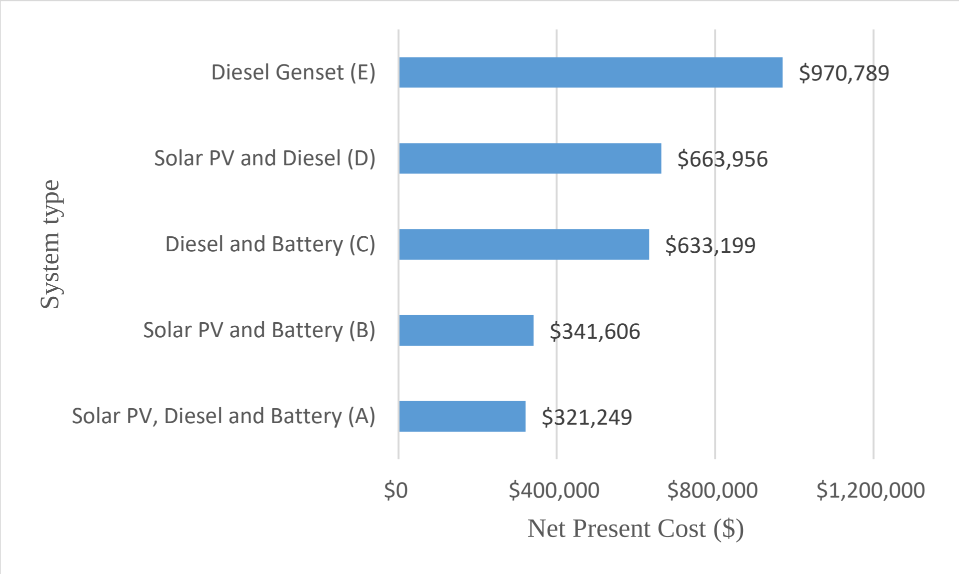

Figure 4.6: Net present cost per system configuration

4.3.1.1.3. Levelised cost of Energy (LCOE)

System A gives the lowest cost of energy at $0.350, followed by system B at 0.381, as shown in Figure (4.7). System B has a larger battery bank as compared to System A which increases its capital costs. C, D, and E have higher LCOE mainly because of the high fuel costs from the running time given to the diesel generator. There is a 71% reduction in the LCOE from $1.06 to $0.350 with the introduction of solar in the system energy mix. The LCOE from the optimal system A is, however, higher than the average low voltage tariff charge from NIGELEC, at 0.158$/kWh

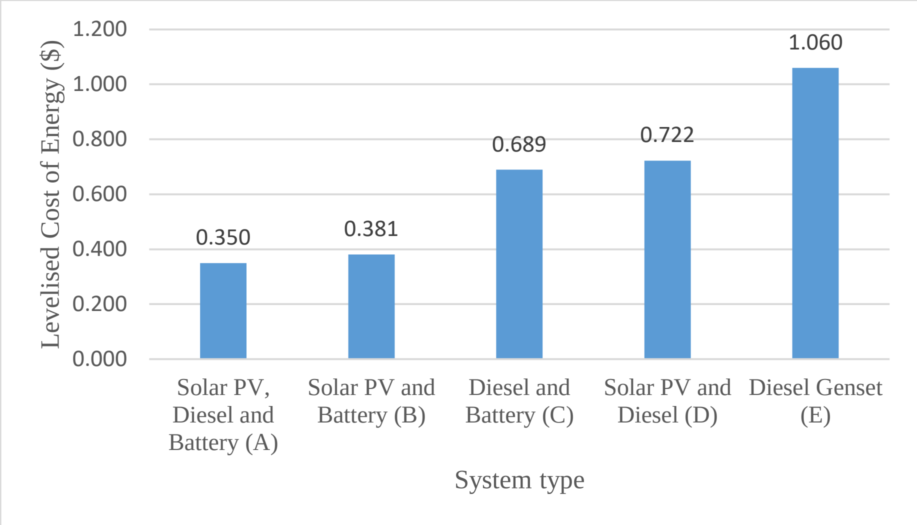

Figure 4.7: Levelised cost of energy per system configuration

4.3.1.2. Technical Analysis

4.3.1.2.1. Electrical Production

The systems configured in Homer Pro have only Solar PV and diesel generator for power sources as found in the energy resource assessment performed on the community. Basing on the locally available resource, the configurations are expected to have production from either two or a single source. The results in Figure (4.8), from the system configurations, considered system D comprising of solar and diesel generator produces more power throughout the year than any of the other system configurations at 112,381kWh/yr. The optimal hybrid diesel system (A), generates 65,188kWh/yr, which is enough to meet the AC consumption of the community at 47,355kWh/yr.

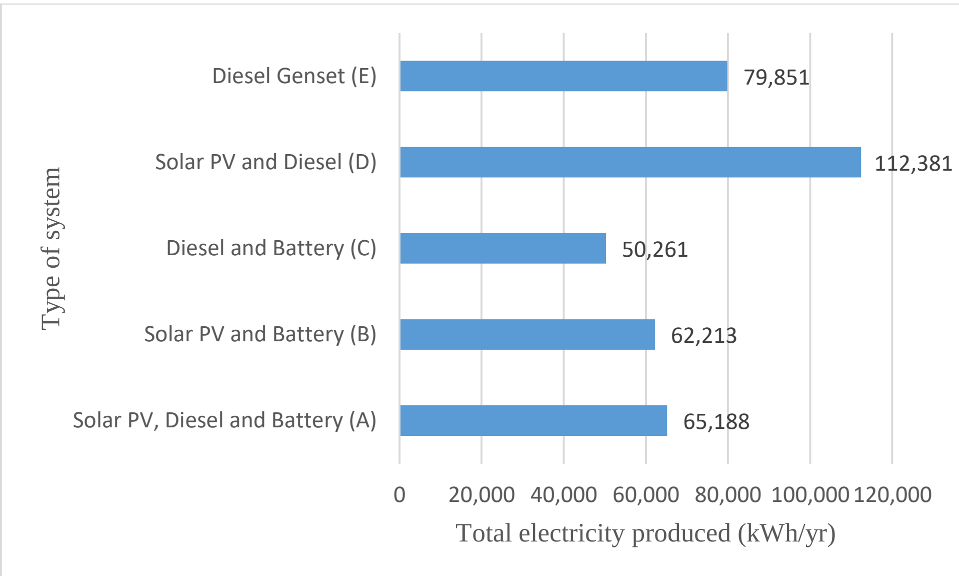

Figure 4.8: Total electrical reproduction per system

The percentage of power that is from a renewable energy source depends on the degree of penetration of the power consumed by the load generated by solar PV. System B has a high renewable fraction at 100% because solar PV is the only power generator in the configuration. System A follows closely though has a small fraction of energy produced by the diesel generator at 4.56% throughout the year, as shown in Table 4.2.

Table 4.2: Electrical energy production per type of source

System configuration	**Solar PV**		**Diesel Generator**		**Renewable fraction (%)**
	(kW/yr)	%	(kW/yr)	%	
A	62213	93.7	2,975	4.56	93.7
B	62,213	100	-	-	100
C	-	-	50,261	100	0
D	60,917	54.2	51,464	45.8	0
E	**-**	0	79,851	100	0

System A has a slightly lower renewable penetration than A because of the diesel generator that generates electricity when the power stored in the battery is not enough to meet the demand. Also, energy from the diesel genset is only 4.56% of the total production, further indicating that it is just a backup when the battery is down. System D has high percentages of both solar PV and diesel power generation because the solar system is used to generate power during the day while the diesel genset is used in the night time and the early morning peak demand before the sun rises. The renewable fraction of this system is zero because even though solar PV generates more than half of the electricity produced by the system, most of the electricity is given off as excess power. The renewable fraction refers to the energy delivered to the load as generated from renewable power sources.

4.3.1.2.2. Excess electricity;

Most of the systems have a large quantity of excess power except system C, which has a meager percentage, as shown in Table (4.4). System A has the lowest capacity shortage at 0 kWh/yr as compared to B with the highest capacity shortage. However, it should be noted that the constraint for capacity shortage during the simulation was set at a maximum value of 3%.

Table 4.3: Excess electricity from the system including the unmet load and the capacity shortage per configuration type

System configuration	Excess electricity (kW/yr)	Unmet load (kW/yr)	Capacity shortage (kW/yr)
A	5678	0	0
B	3569	1215	1467
C	42.2	1.4	20.4
D	64,281	1.4	20.4
E	32,498	1.4	20.4

In the Table (4.3), results show that system D has the highest quantity of excess electricity at 57.2% of the total production per year from the solar PV producing energy during the day when the base load is low. System C expresses the lowest excess electricity at 0.084% due to the small size of the battery bank in the system with the whole system relying on the diesel genset to generate electricity to power the community throughout the day.

4.3.1.2.3. Fuel Consumption

The consumption of fuel highly depends on the number of hours that a diesel genset runs and the load to be supplied. The generator size set at 30kW consumes enough fuel to power the full load, especially when it is the sole power producer. System (E) consumes the most amount of fuel at 33,817 liters per year. System (A) stands out at 1308 liters as it does not depend on diesel generator as the sole producer of electricity to power the load including system (B) which is powered by solar PV as shown in Figure (4.10). Long hours of operation of the generator lead to high consumption of fuel.

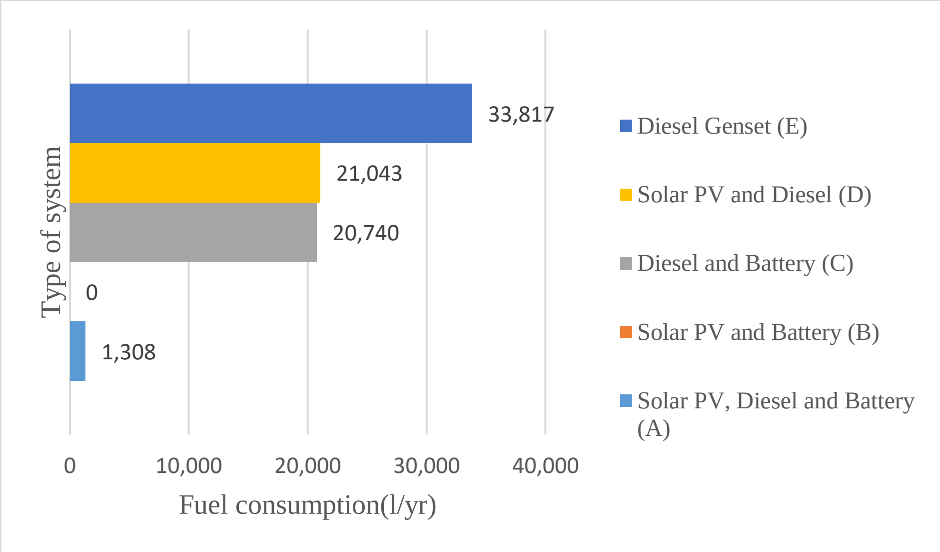

Figure 4.9: Fuel consumption per system type

4.3.1.2.4. CO_2 emissions;

The use of diesel generators for the production of electricity releases CO_2 and other pollutants to the atmosphere. In this analysis, a lot of focus was on the CO_2 emissions per configuration though there are other emissions in the form of particulate matter, unburnt hydrocarbons, oxides of Nitrogen and carbon-monoxide, among others. Even though not prioritized in this analysis, large quantities of CO_2 emissions also indicate an equally high percentage of the other pollutants though not to a similar magnitude.

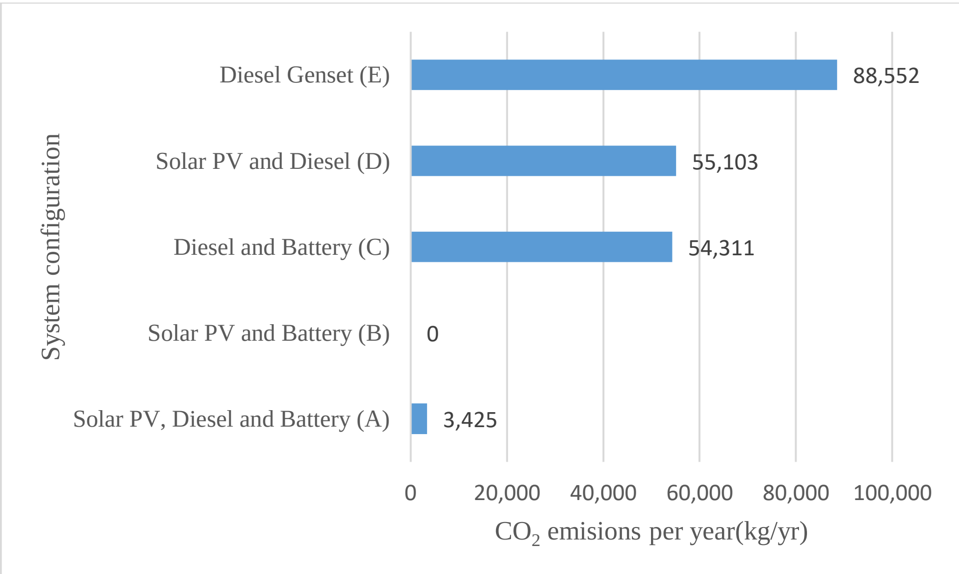

Figure 4.10: CO_2 Emissions per system type

System (E) releases 88,552 kg of CO_2 emissions per year followed by C and D as shown in Figure 4.10. The high levels of CO_2 emissions is as a result of the long run hours of the diesel generator which is a significant component in each of the system configurations above.

Systems B has no CO_2 emissions during the operation of the system while system A has a negligible amount as compared to the other arrangements. The diesel generator in the hybrid system contributes less towards the energy produced as a whole, leading to low emissions from the system. Carbon-dioxide emissions in this system reduce by 96.13% from the system E to a hybridized diesel generator with battery. The world is transitioning to the carbon-free energy structure; thus, a system with little, or negligible Carbon emissions is essential for diversification of the electricity mix.

4.3.1.3. System E versus a heavily constrained diesel generator.

The constraints of the diesel alone system configuration were changed to study the performance of the system under a shorter operating time. The length time with electricity shortened to five hours a day during the peak hours of the day including 2 hours during the day and 3hours in the night. In this mode, the diesel generator was forced on and off throughout for the running hours in the day to provide electricity when the community most needed it. This mode of operation was introduced to simulate a real situation on how genset alone systems are performing in rural communities. The system configuration is different because the system constraints were changed so that HOMER Pro can find feasible solutions for the scenario. The generator run time was set between 4 pm to 9 pm. The minimum run time changed to 15 minutes, and the capacity shortage increased from 3% to 65% for Homer Pro to run the simulation and find feasible solutions. The capacity shortage of 65% to give viable solutions in HOMER Pro under the given constraints. The lifetime of the generator was set at 20,000 due to the fewer hours it was running per day.

The results of the system show a reduction in the fuel cost from $675,984.84 down to $ 157,716.99 and a total net present cost of 238,872, as shown in Figure (4.11). The total energy produced by the system is $20,889, of which 4.36% is excess energy with an unmet electric load of 57.8%. The generator has a longer life span of thirteen years as compared to the two years of system E mainly as a result of the lower daily run time. Perhaps the crucial factor is the LCOE at 0.616$, which is lower than the 1.3$ for system E for continuous operation of the diesel genset. Annual CO_2 emissions from this system are minimal as compared to system E at 20,660kg/yr.

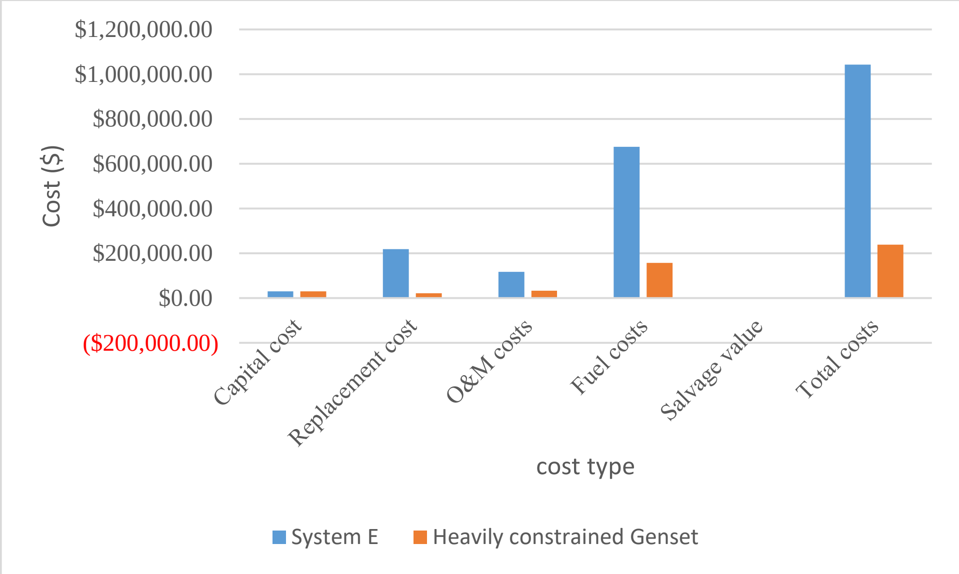

Figure 4.11: Performance of a heavily constrained diesel generator system

In as much this scenario presents a lower LCOE and net present cost, the emphasis is the community is without electricity for three-quarters of the day and only provided when it is most needed. However, this scenario was important in clearly drawing a line in what the tradeoff is when the diesel generator alone is chosen for running a community mini-grid. The system configuration that comprises the genset as the only electricity generator only becomes cheap on a tradeoff between reliability and energy cost.

4.3.1.4. Break-even Grid extension distance;

The advanced grid module was used to carry out a comparison of the costs of grid extension and the consideration of an off-grid system. Ngonga Zarma is located 7km from the village with a connection to the local grid. From the simulation, all the arrangements had a break-even distance higher than the 7km. The break-even grid extension distance refers to that distance at which the net present cost for installation of an off-grid electric system is equal to that invested in connecting the area to the local grid. The break-even distance varies from one system type to another. A change in the net present cost of the system changes the break-even grid distance. The higher the NPC of the system is, the greater the break-even distance as it will require a high value for the grid extension cost per km, including the operating and maintenance costs. Table (4.4), shows the break-even grid extension distances for different system types. To consider an off-grid system for electrification, the distance of the community from the local grid point should be bigger than the break-even grid distance.

Table 4.4: Break-even distance per system type

Type of system	Break-even Distance (km)
A	13.43
B	14.99
C	37.24
D	39.58
E	63

System (A), the hybrid diesel system gave a break-even distance of 13.43km at an NPC of $321,249, as shown in Figure (4.12). According to the Figure (4.12), it is cheaper to extend and upgrade the grid infrastructure to Ngonga Zarma than installing a hybrid off-grid system. The net present cost of installation of an off-grid hybrid system is greater than the required NPC to upgrade the grid infrastructure to provide reliable and adequate electricity to Ngonga Zarma

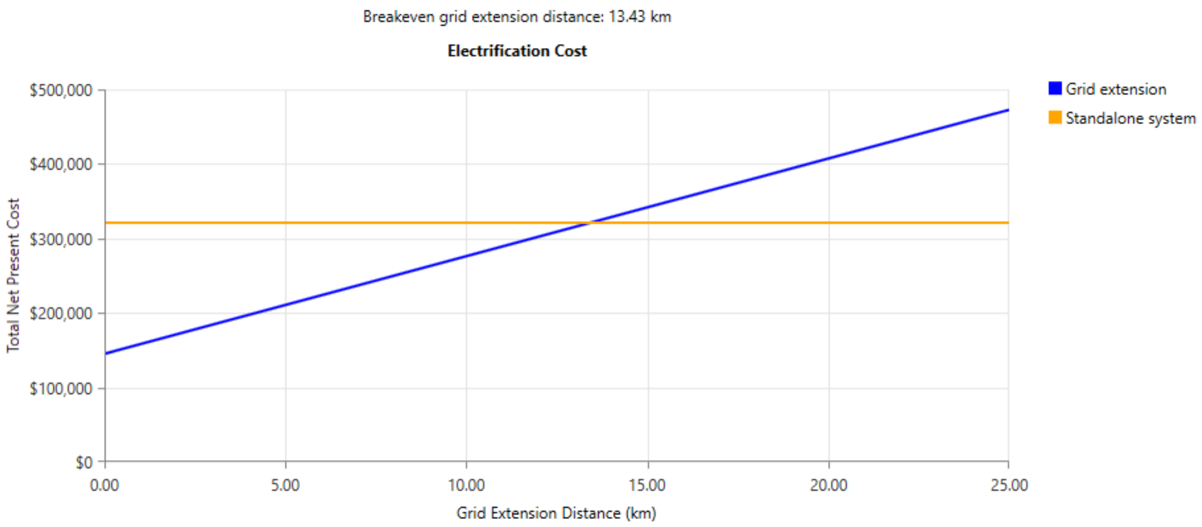

Figure 4.12: Grid extension distance for system A (Optimal system)

4.3.1.5. Sensitivity analyses of the off-grid system;

A sensitivity analysis is essential in studying the effect of unknown variables and uncertainties on the performance of the designed system. Some of the variables are either unknown, and a range of futures is used to estimate or others are constantly changing the economy of the country, such as fuel prices and discount rates. In this study, a sensitivity analysis is used to understand the effect of changes in variables such as the maximum capacity shortage, diesel fuel price, and the discount rate on the economics of the optimal system.

4.3.1.5.1. Maximum capacity shortage

The sensitivity analysis variables for maximum capacity shortage included; 0%,3% and 5% and the diesel fuel price set to 0.88$/L, 1.03$ and 1.5$/L of fuel includes all the expenses spent in securing fuel to a rural community and also a major increase in the fuel price. The battery lifetime was varied 8, 10 to 12 years. According to Figure (4.13), the hybrid diesel system remains feasible for all increments in the renewable energy fraction for maximum capacity shortages below 3.1% at the diesel price of 1.03$/L and the minimum load ratio of 25%. A decrease in the lifetime of the battery increases the maximum capacity shortage to 3.82% for all increments diesel hybrid system (A) maintained as the optimal configuration. However, a reduction in the maximum capacity shortage, the net present cost increases to $320,462 from $295,684 at an increase in battery life to 20 years.

Above 3% at an increase of battery life to 10years, the optimal system is B, with a reduction in the NPC to $309,419. The NPC further reduces$282,091 for longer battery life of 20 years though at higher capacity shortages. From the study, it clearly shows that a longer battery life reduces the replacement costs for the battery bank though to attain a lower maximum capacity shortage, the storage size has to increase. Both A and B are dependent on batteries for storage and any change in the cost of batteries or mismanagement of the battery bank coupled with a change in the reliability of the system can determine which of the systems is optimal for powering the community.

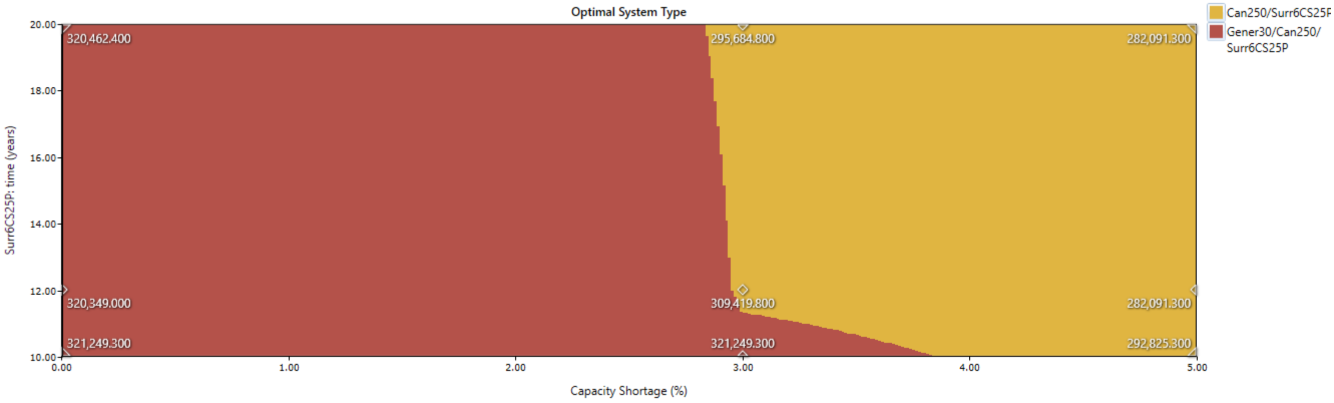

Figure 4.13: Effect of capacity shortage on the optimal system type for off-grid connection

The solar and battery configuration (B) is feasible for capacity shortages greater than 3% for all increments and reductions in the required renewable energy fraction.

4.3.1.5.2. Effect of Diesel fuel price;

Increasing the diesel fuel prices from 1.03$/L to 1.5$/L, the system maximum capacity shortage falls increases to 3.5% for the feasibility of the hybrid diesel system as the optimal solution for electrification of the community as shown in Figure 4.14. An increment in the minimum load ratio to 40% does not change the optimal system but increases the capacity shortage close to 4% for hybrid solar PV- diesel system to remain the optimal system at a Net present cost of $318,788. A higher minimum load ratio results into a healthy performing diesel generator which reduces fuel and operating costs reducing the NPC of the system though increasing the capacity shortage of the system. An increase of the diesel price to 1.2% at a capacity shortage of 4%, gives system B as the optimal system for electrification of the community

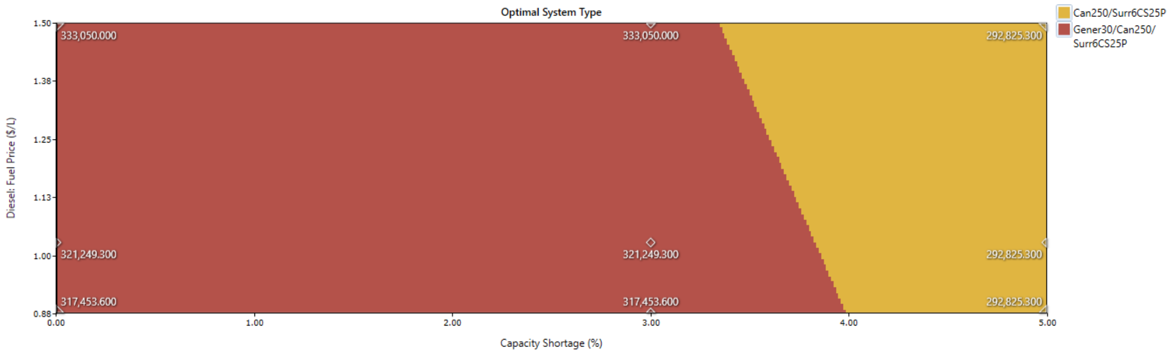

Figure 4.14: Effect of the capacity shortage and diesel price on the optimal configuration for off-grid connection

Growth in the AC consumption by 10% and 20% maintains the hybrid system A feasible at higher fuel costs and higher capacity shortages. System B is only feasible for the load demand of 129.74kWh at a diesel price of 1.5$/L at an LCOE of 0.332. The higher the capacity shortage the lower the cost of energy gets.

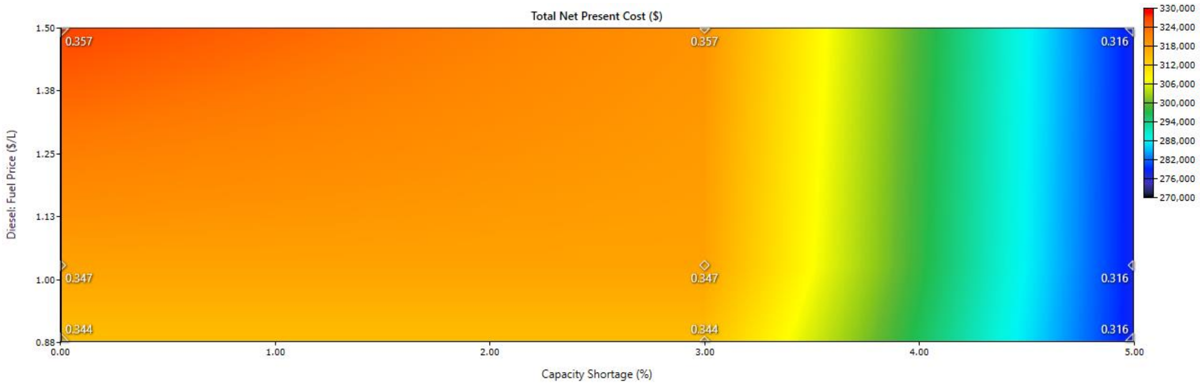

Figure 4.15: A surface plot showing the effect of changes in diesel fuel price and capacity shortage on system A

The maximum capacity shortage increased from 3% to 5% mainly determined by the running hours of the diesel generator. At a very low capacity shortage requires the running of the generator which in the long run consumes a lot of fuel. Thus high fuel costs give an NPC of \$330,000 at capacity shortages lower than 3% and a fuel cost of \$1.50. An increment of the maximum capacity shortage from 3% to 5% gave an NPC in the range of \$276,000 to \$282,000. The LCOE of the system is maintained at 0.316, despite an increase in the fuel price cost. The same happens for capacity shortages in the range of 3% to 4%.

4.3.1.5.3. Growth in the primary load demand of the community

Different % growth in the communities' load demand was introduced as variables in the sensitivity analysis that is 10% and 20% of the present load demand.

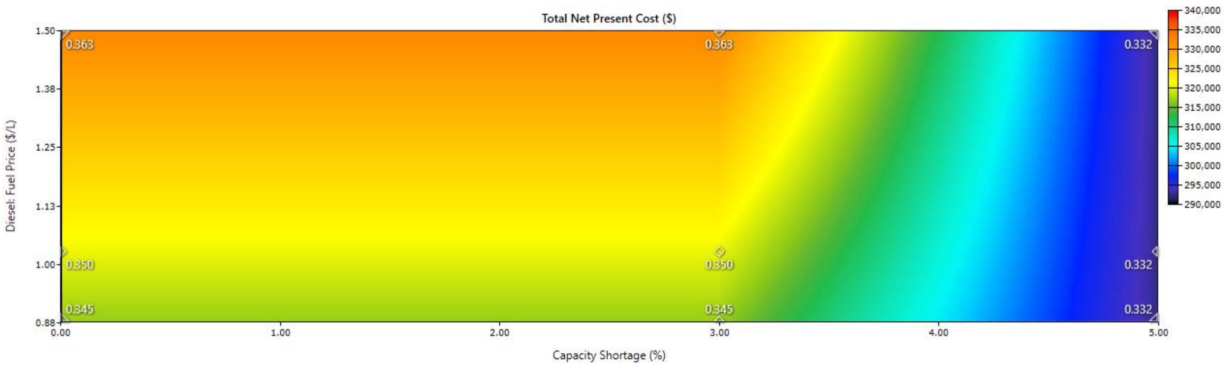

Figure 4.16: Surface plot showing the effect of electric load and capacity shortage on the NPC of system A

The NPC is shown to decrease with an increase in the maximum allowed capacity shortage up to an electrical load of 135kWh per day, giving an LCOE of 0.332. The low cost can is a result of the low fuel costs needed due to less hours the diesel generator is running. However, beyond this, the capacity shortage has no further influence on the NPC, as shown in Figure (4.17). The NPC increases with an increase in the electrical load demand, and this is a result of the need for expansion of the system. The LCOE further changes to a value of \$0.367 from \$0.350 at 3% capacity shortage and 1.03\$/L as fuel price. The net present cost with an increase in the load demand by either 10% or 20% drives the NPC from \$315,000 to \$340,000. The result further shows that a further increase in the set maximum capacity shortage will more also decrease the NPC due to lower fuel costs.

4.3.2. Grid-connected Scenario,

The constraints used in the off-grid system were maintained for the national grid-connected scenario. The scenario is broken down into two options that is one with sales to the national network and another without sales. Configuration of components on the AC and DC bus is as shown in Figure (4.14)

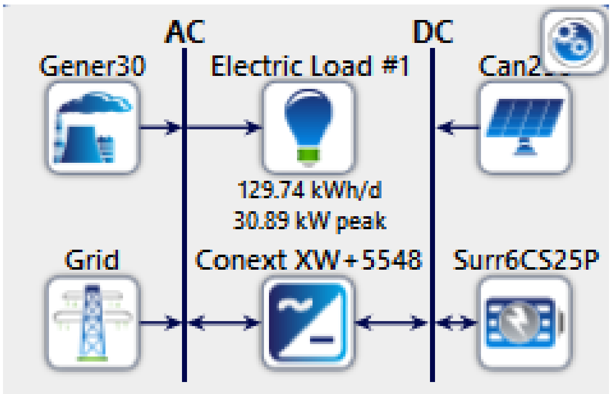

Figure 4.17: System configuration for grid-connected analysis

4.3.2.1. Systems connected to an unreliable network with sale and power purchases.

In this system, the grid component with consideration for scheduled rates is modeled in Homer Pro. The total annual purchase capacity was set at 100kW the maximum amount Homer Pro sets as the highest net amount of energy that can be drawn from the grid. The interconnection charge of the Grid set at \$1500 and the annual standby charge at \$1000 loosely adapted from the assessment done by (Open Capital Advisors, 2017) in the Niger off-grid market. The grid sells back price was set at 0.12\$/kWh (IRENA, 2014), while the purchase price estimated at 0.110 average tariff for medium voltage (Societé Nigerienne d'electricité NIGELEC, 2017)

The demand rates in HOMER Pro were set at 10.5145$/kW/month which is a fixed charge per month for medium voltage (Societé Nigerienne d'electricité NIGELEC, 2018).

The Grid extension costs were not included in the start because of the partly existing structures in Ngonga Zarma. However, IRENA, (2014) enlists grid extension costs for Niger at 20,000$/km. The off-peak hours and on peak hours were not used in this research to keep the assessment simplified however, the average tariff value for medium voltage was used in the design according to NIGELEC. The grid reliability option was used to model the unreliable grid network in Niger and mainly for the case of Ngonga Zarma if connected to the existing lines further including the effect of blackouts, voltage variations, and brownouts. The mean outage frequency was set to 260 times a year (IRENA, 2014) and the mean repair time set to an average value of 4hrs mainly for the rural community. The length of time varies for urban and rural communities. However, IRENA, (2014) places the range of blackouts from 2 to 6hrs. The average was selected in this study as shown in Figure 4.18. The repair time variability was set at 10% a reflection of the assumption taken by taking the mean value of the length of time for a blackout.

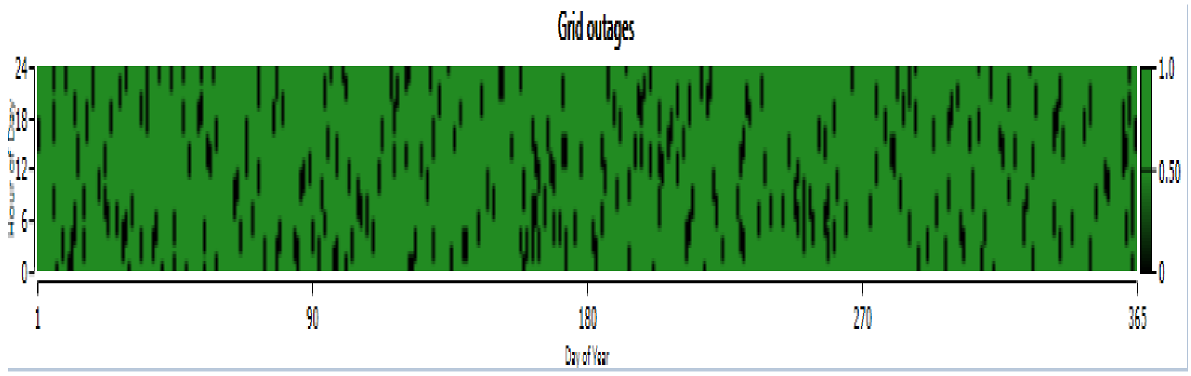

Figure 4.18: Grid outages in Niger

From the simulated model, Homer Pro ran 991 simulations, of which 848 were feasible, 143 were infeasible due to the capacity shortage constraint, and 155 omitted to other reasons regarding the poor configuration of components.

Five categorized possible solutions are presented in Table (4.5) with varying capacities of solar PV and diesel genset as power generation sources with purchases and sales to the grid as backup. The grid alone option is not presented in the analysis because of the maximum capacity shortage constraint, which was maintained the same for smooth comparison with the off-grid scenario.

Table 4.5: System configurations for grid connection

System Configuration	Solar PV	Diesel Genset	Battery	Grid	Converter	Renewable fraction
Solar PV, Grid, battery (F)	35		16	100	21.7	61.8
SolarPV,Grid,Battery,Genset (G)	35	30	8	100	22.1	60.2
Solar PV,Genset,Grid (H)	35	30	0	100	22.5	56.6
Genset,battery,Grid (I)		30	8	100	4.16	0
Genset, Grid (K)		30		100		0

According to table (4.5), the optimized results show a maximum solar PV power of 35kW for all the categorized configuration results from Homer Pro. The diesel generator is maintained at 30kW capacity while that for the battery varied from 16 to 8 batteries with the system (H) having the largest size of the converter at 22.5 kW.

4.3.2.1.1. Economic Analysis

The results from Homer Pro on grid connection of the electrical systems shows that there were higher operation and maintenance costs from all configurations. The O&M costs are higher than fuel costs a change from the off-grid systems whose cost structure is dominated by fuel costs. Figure (4.19) shows that the systems with a diesel generator had lower fuel costs than in the off-grid scenario.

The reduction in the fuel costs is as a result of the grid purchases that are made resulting in the diesel generator giving back up power from the grid hence having less running hours. Despite the high operating costs, System F had the highest penetration of renewables at 61.8%. Systems with solar as a power producer, have higher initial investments than systems that have diesel alone. The operation and maintenance costs take the largest share of the NPC in all configurations.

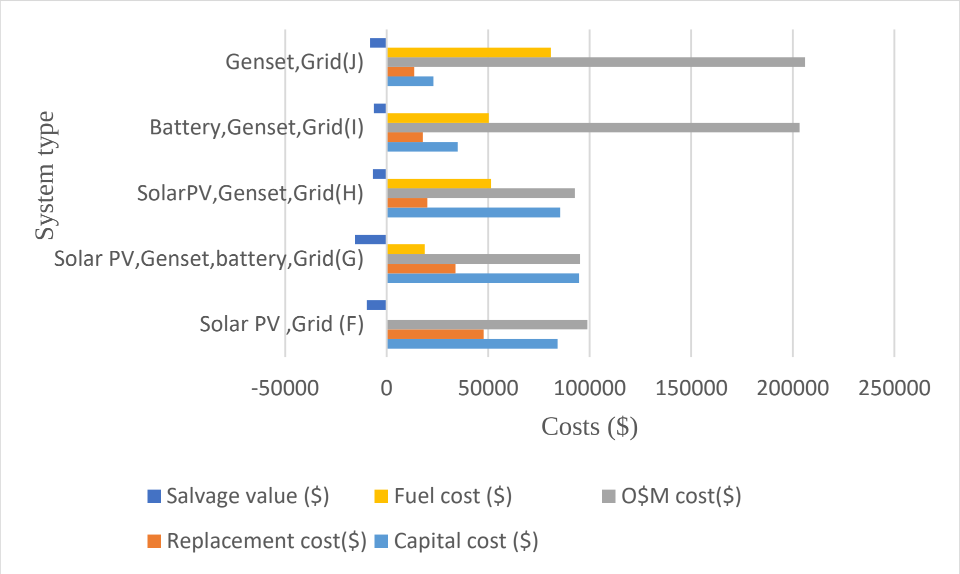

Figure 4.19: Cost type per system configuration

However, G is shown to have a lower operating cost despite the presence of the diesel Genset in the system makeup. The low cost of operation for system F with grid connection as a result of the decrease in the number of batteries from 16 in the system (F) to 8 in (G) as detailed in appendix C

Generally, the modeled systems show a reduction in the net present cost even for systems with intensive fuel costs such as the diesel Genset at $315,436.92 as compared to the off-grid systems. Solar PV, Grid, and Battery (system G) give the lowest net present cost valued at $221,153.36 as compared to the other grid-connected systems Figure (4.20). According to HOMER Pro, which ranks according to the lowest NPC, system F is the optimal system to electrify Ngonga Zarma

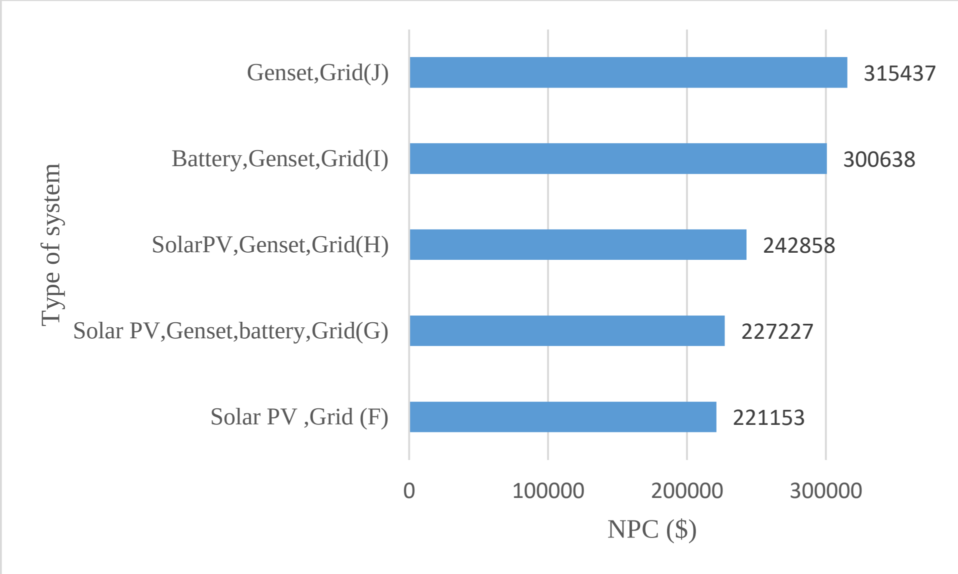

Figure 4.20: NPC per grid-connected system type

Systems G, F, and H when connected to the local network give a cost of energy that is within a close range which is somewhat different compared to systems I and J which have very high values as compared to the average tariff price of a kWh from NIGELEC at 0.163$/kWh (Societé Nigerienne d'electricité NIGELEC, 2017) at a rate 1$ equal to 585fcfa. The lowest recorded LCOE is 0.137 $/kWh, which shows that renewable energy systems are highly feasible in Ngonga Zarma. The hybrid solar PV ,diesel system with storage (G) is very competitive mainly supported by its low operating cost at $6,821 in addition to its LCOE that is 0.1370$/kWh that is the same with system F Table(4.7)

Table 4.6: Levelised cost of energy per system type.

System Configuration	LCOE
Solar PV, Grid, battery (F)	0.137
SolarPV,Grid,Battery,Genset (G)	0.137
Solar PV,Genset,Grid (H)	0.143
Genset,battery,Grid (I)	0.327
Genset, Grid (J)	0.343

4.3.2.1.2. Technical Analysis;

Electrical production

In this scenario, the optimal system solar PV, Grid and battery give a total output of 93,901kWh/yr as shown in Table (4.7). The grid purchases from this system total to 33.7% of the total production, while solar has a share of 66.3%. Of the total electricity generated from the system, 43.9% is sold back to the grid and 55.3% consumed by Ngonga Zarma load. Overall, grid purchases from systems with the diesel genset as the primary energy producer apart from the network had higher purchases at 41,795kWh/yr but lowered excess electricity. However, systems I and J despite having a connection to the grid, had no electricity sales to the local grid network.

The lack of grid sales in the year attributed to the low amount of electricity generated by the systems, which are half of the total amount generated by the hybrid system with storage. All the system configurations except F had no capacity shortage in their supply run throughout the year and were able to supply the whole AC load. System F exhibited a capacity shortage in their supply to the community, which is as a result of overcast days that are notably backed up by the grid due to blackouts.

Table 4.7: Electrical production from Grid-connected systems

System Configuration	Total electrical production kWh	Grid purchases (kWh)	Grid sales (kWh)	Excess electricity (kWh)	Unmet load kWh	capacity shortage kWh
Solar PV ,Grid, battery (F)	93,901	31,687	36,446	6181	849	1057
SolarPV,Grid,Battery,Genset (G)	96,218	31687	38,088	6366	0	0
Solar PV,Genset,Grid (H)	100,152	31,687	40,132	8798	0	0
Genset,battery,Grid (I)	47,844	41,795	0	185	0	0
Genset, Grid(J)	51,331	41,795	0	3976	0	0

CO_2 emissions analysis

Solar PV introduced in electricity production increases the renewable energy mix in the sector. Overall the carbon-dioxide emissions reduced per system connected to the national grid with system F presenting the lowest emissions at 20,026kg/yr and E the highest at 37,016kg/yr in Figure (4.21)

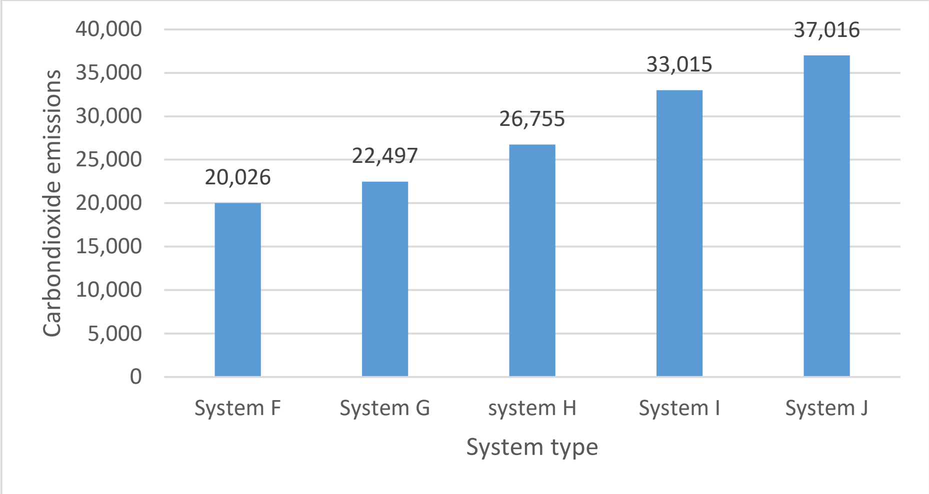

Figure 4.21: Carbon-dioxide emissions (kg/yr) of grid-connected systems

Grid purchases and sales of system F;

Configurations with the diesel Genset as the power producer have the highest grid purchases because it is more costly to run the generator over the grid and thus the generator is a backup to the cheaper power from the network. Most of the energy sold to the network is sold between 12 pm and 4 pm from the solar system with the maximum power produced peaking at a value higher than 24kW as indicated in Figure (4.22).

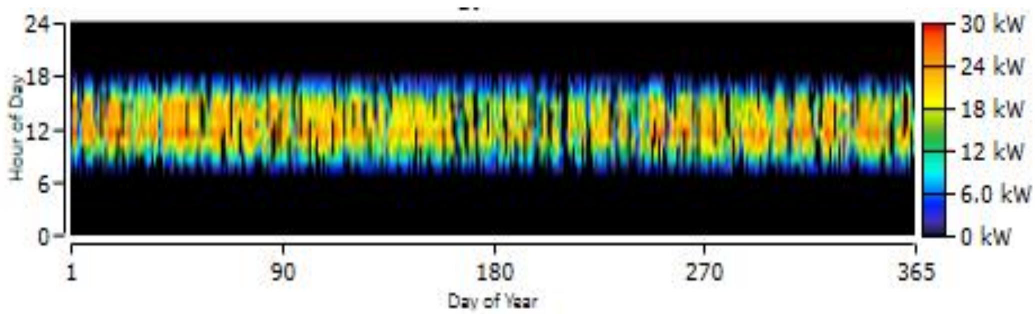

Figure 4.22: Energy sold to the grid from system F

Figure (4.23) indicates that power purchases are made during the night time with the evening peak purchasing electricity as high as 21kW and the early morning hours at a capacity of 7kW and above. However, there are signs of no purchase even during peak time, thus being powered by the battery.

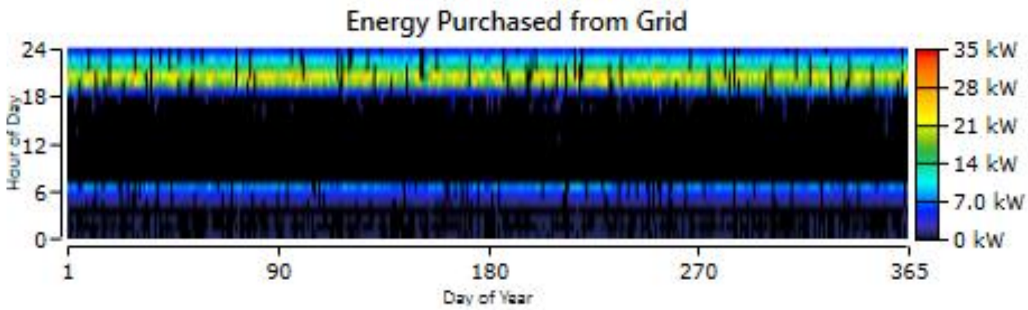

Figure 4.23: Energy purchased from the Grid for system F

Fuel consumption of the system;

Systems with a diesel generator had a decrease in the amount of fuel consumed per year with grid connection. The hybrid system comprising of a diesel generator, Solar PV, and battery, has the lowest fuel consumption at 943 liters. As the hours of operation of the genset increase, so does the amount of fuel converted into electricity, as shown in Figure (4.24). System G had the lowest consumption of fuel at 943 liters with the maximum at 4049 liters experienced in system E when connected to the grid.

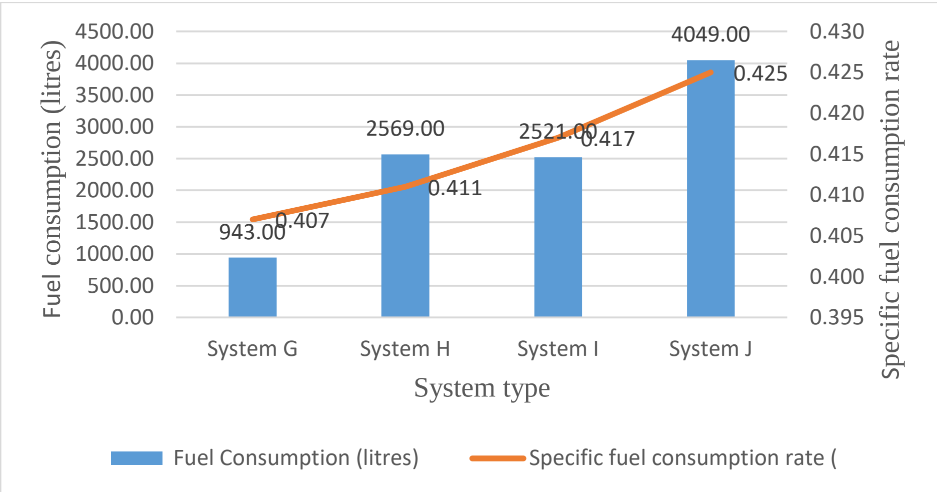

Figure 4.24: Fuel consumption of diesel grid-connected systems

4.3.2.2. The grid-connected Scenario without sales to the national network;

The same constraints and assumptions made during the scenario with both sales and purchases are maintained except the sell-back price to the grid is set at 0$/kWh. The NPC and LCOE from the study are shown in Figure (4.25).

Table 4.8: System component sizes and excess energy produced

Solar PV	Grid	Diesel Genset	Battery	Converter	Excess electricity	Capacity shortage
12	100		16	12	7644	1466
7.36	100	30	8	8.47	2546	0
10.5	100	30		5.85	12,028	0
	100	30	8	4.16	185	0
	100	30			3976	0

From Table 4.8, capacity shortages exist despite not selling power to the grid. The capacity for different generation sources are reduced showing that HOMER Pro sized a smaller capacities but also considered the cheapest costs of energy thus purchasing more from the grid.

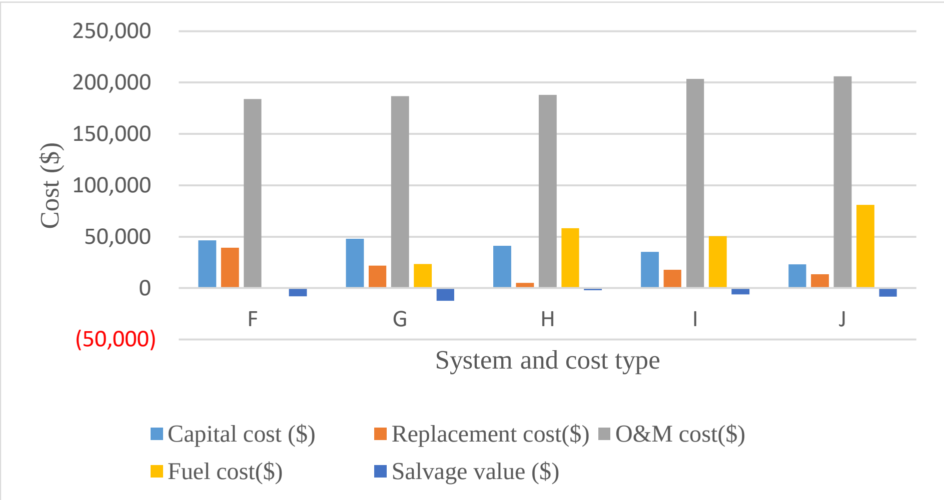

Figure 4.25: Costs per system type in a grid-connected scenario without sales

Operation and maintenance contributed the largest share to the net present costs of the different systems. System J has the highest O&M costs as compared with other sources. There is no distinct variation in O&M costs with all the systems having high operation costs at 206,094 though lower than the off-grid scenario. The systems have lower fuel expenses as compared to the other scenarios with the diesel hybrid system having costs of up to $23342.22, as shown in Figure (4.25).

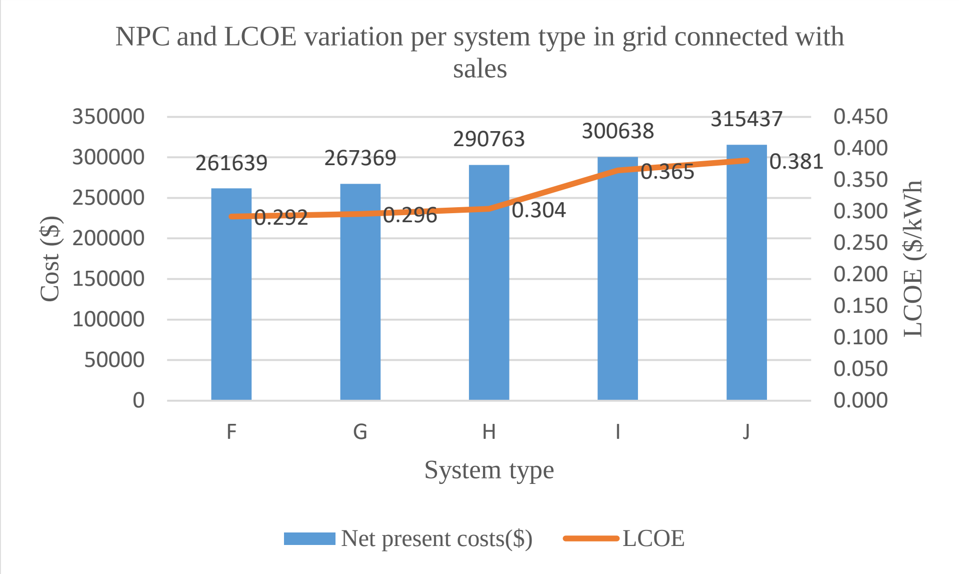

Figure 4.26: Variation of the LCOE and NPC with system type in grid connected scenario with sales

The most important metrics in comparison of energy systems is the net present cost and the Levelised cost of energy as they determine whether an installed mini-grid can offer affordable power. In this scenario, it is observed that buying electricity at a slightly lower price reduces the net present cost and LCOE slightly from 0.350 in the off-grid scenario to 0.292 for the grid-connected with sales Figure (4.26). However, the LCOE is still higher than the local tariff, showing that introducing sales to the system makes electricity affordable. The high costs are due to the high price at which the grid electricity is purchased from the grid. A price incentive is needed to make it possible to have a lower price per kWh of electricity.

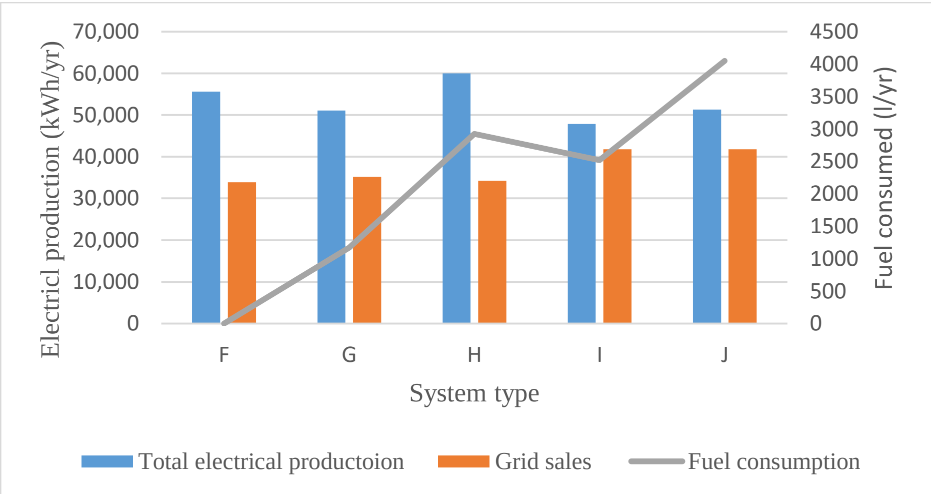

Figure 4.27: Total electrical production by system type

Figure (4.27) shows that grid purchases provide most of the power in all the systems, more than 50% of the total electrical output. In systems that rely on the diesel generator as the energy source, have higher grid purchases than the solar systems. The cost of energy of running a generator is higher than that of the power purchased from the grid.

4.3.2.3. Sensitivity Analysis of the Grid-connected systems with electricity sales;

An optimization type system plot Figure (4.28) is used to check for the optimal system in case of an increase in the mean outage frequency and the establishment of grid-connected costs from 10,000$/km to 20,000$/km. Across increments in the frequency of outages and the extension costs system F remains the optimal system. However, at an extension cost of 20,000$/km for a distance of 5km with grid failures of 330 a year qualifies the off grid solar PV, diesel and battery hybrid system (A) as the optimal system.

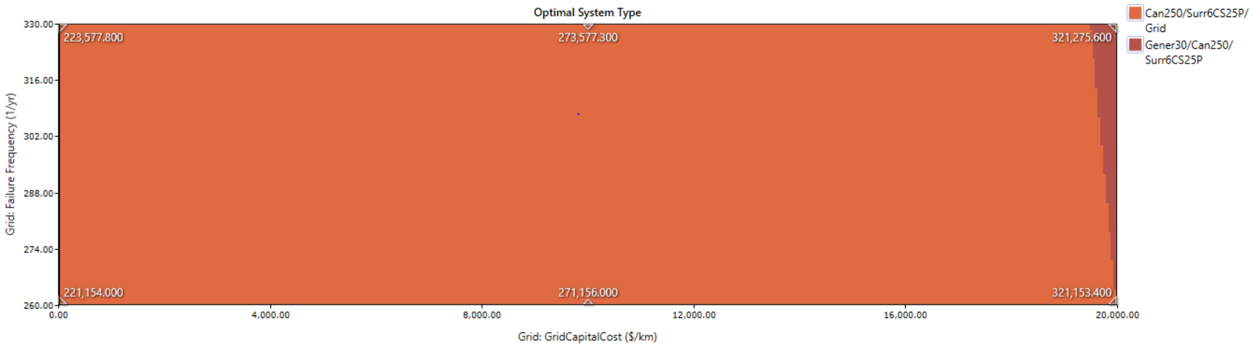

Figure 4.28: Optimal system type plot for the effect of failure frequency and capital cost

The net present costs increase with an increase in the grid extension costs to $321,153 at 20,000$/km and $276,156 for 10,000$/km.

4.3.2.3.1. Effect of the capacity shortage on the optimal system type;

The maximum capacity shortage is increased from 3% to 5%, and later a reduction is made to 0% as shown in Figure (4.29). The results indicate a change in the optimal system with the grid-connected diesel hybrid system with storage (G) becoming the optimal system for electrification of the community. Changes in the grid connection costs and distance do not affect the feasibility of system G. System G is optimal for all higher mean frequency of outages up to a capacity shortage of 2.7%.

Beyond this, the system F becomes the optimal solution for electrification at no grid extension costs. Any improvements that need to be made to the grid infrastructure only affect the net present costs and the cost of energy but still maintain the diesel hybrid system being the optimal system for the connection of the community to a reliable electricity network with 0% capacity shortages. The NPC at 0% capacity shortage increases to $227,226.9 from $221,154.

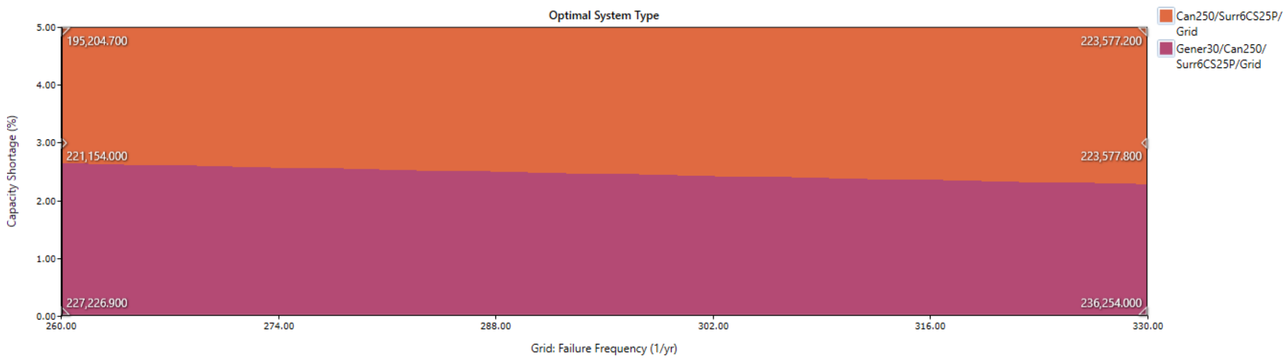

Figure 4.29: Optimal type system plot for changes in capacity shortage and grid failure frequency

4.3.2.3.2. Effect of growth in the load demand

The load demand was increased by 10% and 20% to assess the effect on the optimal system for the community. At a low frequency of outages at 260 per year, the hybrid solar PV diesel system with storage remained feasible for all percentages of load growth. However, an increment of the rate of outages to 330 per year affected the system as shown in Figure 4.30. For a load beyond 137.0 kWh, the optimal system gradually became feasible for capacity shortages above 3.04% to a higher value of 3.6% at a load growth of 20%. At a 10% load growth the value, the capacity shortage over which system G remains feasible peaked at 3.69%. The study further shows that in order to have a more reliable system without capacity shortages then G is the feasible system. The grid extensions costs and distance did not affect the optimal system but significantly changed the projects net present cost and Levelised cost of energy.

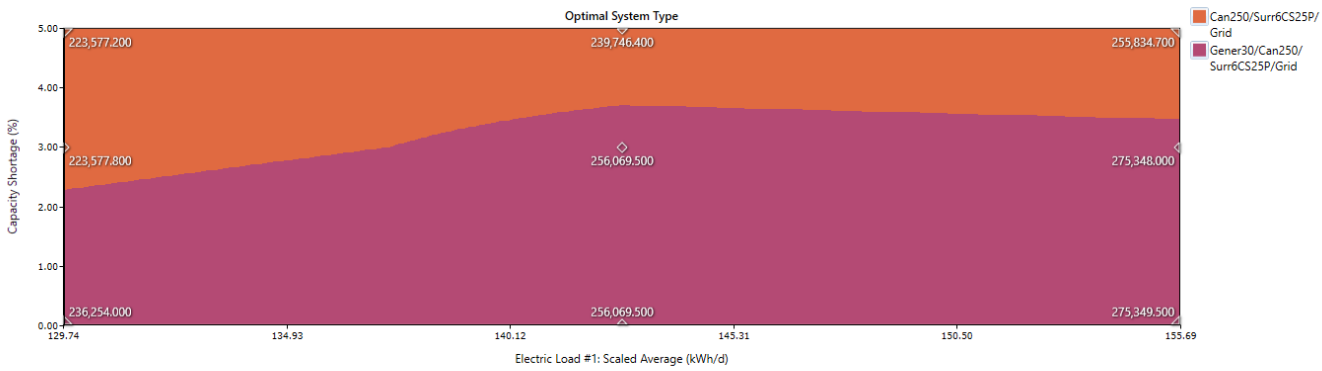

Figure 4.30: Optimal system plot type for the effect of load growth and capacity shortage

4.3.2.4. Impact of extension costs and distance on the net present cost of system F

Introduction of grid extension costs to the cost structure of the systems increases the Levelised cost of energy to 0.168 at a grid extension cost of 10,000 for 5km and 0.181 for 7km as shown in Figure (4.31). For a cost of, 20,000$/km, the Levelised Cost of energy rises to 0.350 at a net present cost of $320,000.

The costs increase further when the frequency of outages is increased to one per day per month driving the Levelised cost of energy to $0.355 from 0.151 for no extensions made to the existing system for a 10% growth in the load demand. Increasing the load demand by 20% further increases the LCOE to 0.367 from 0.156 at no grid extension distance at a cost of 20,000$/km as shown in appendix C.1

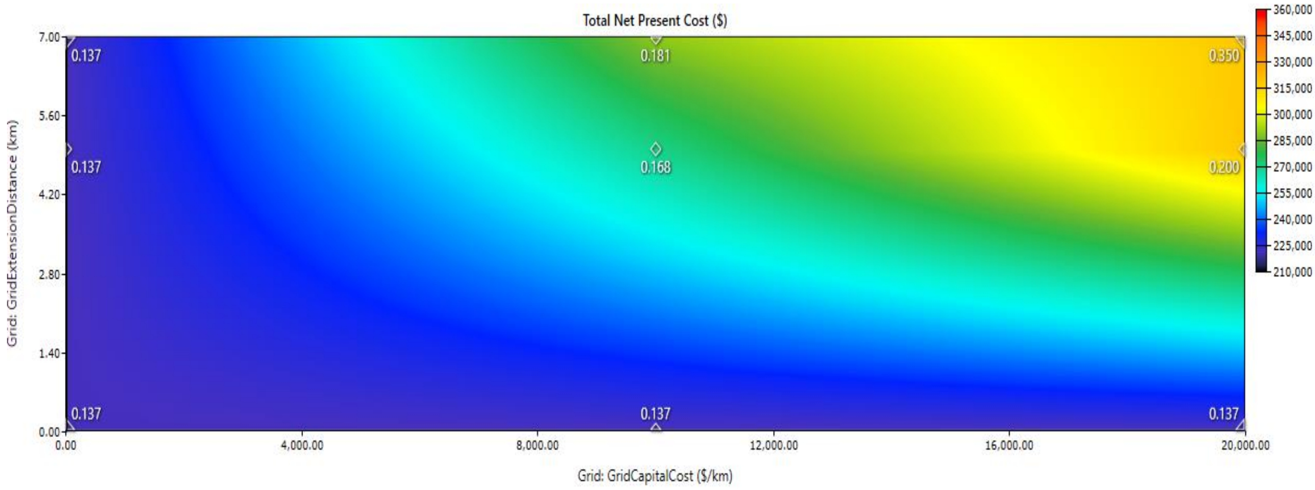

Figure 4.31: Surface plot for the effect of grid extension distance and capital cost on the net present cost and LCOE of system F

4.3.2.5. Performance of the System F against system A set as the base case;

According to Table 4.9, the lowest cost system (F) reduces the initial capital investment of the optimal system under off grid scenario by 45.4% and the operating costs by 18.04%. A 60% reduction in the cost of energy makes it worthwhile to invest in the grid connected system for Ngonga Zarma

Table 4.9: Cost Comparison of system A (base case) and system F

	Base Case	Lowest Cost System
Initial Capital	$154,291	$84,284
Operating Cost	$8,604	$7,052
Cost of Energy	$0.350	$0.137

4.3.2.6. Multi-Criteria Decision Making for Choice of system type.

Multi-criteria decision making tool is important in determining the best alternative among different options based on series of criteria. The weight of the criteria is dependent on what the system developer or planner considers the most important depending on technical knowledge, previous research and consultations made with the stakeholders. Amidst the different tools available for use, the weights of the selected criteria were assigned basing on the pairwise comparison performed and thereafter, TOPSIS (Technic of Order Preference by Similarity Ideal Solution) deployed to determine the suitable system for Ngonga Zarma. In order to build resilient communities, the installed energy systems need to be assessed on their performance across the three areas of sustainability (Economic, technical and environment) as shown in Table 4.10. See Appendix C for values of the chosen sub-criteria

Table 4.10: Weights and criteria for Analysis

Sub-Criteria	**Weights**	**Attribute**
Excess Electricity	0.00867	More is better
Renewable Fraction	0.015	More is better
Fuel consumption	0.0215	Less is better
Electricity Production	0.047	More is better
Capacity Shortage	0.0052	Less is better
CO2 emissions	0.2388	Less is better
Compatibility with Energy Policy	0.0293	More is better
Social Acceptance	0.06495	More is better
Net Present Cost	0.1927	Less is better
Levelised Cost of Energy	0.2749	Less is better
Capital Cost	0.027	Less is better
O&M cost	0.016	Less is better

According to the results shown in Table 10.11, the suitable system with a relative closeness of 0.650544 is System F (grid connected solar PV with storage). System F and G as compared with the rest of the systems have better econometrics due to the low costs on NPC and LCOE. System A (Off-grid solar PV, diesel with storage) performed better than other grid connected systems because of the low CO2 emissions greatly favoured by high weight of the criteria.

Table 4.11: Summary of results from TOPSIS

System Type	**Relative closeness to the ideal value**
System F	0.650544
System G	0.610362
System H	0.534802
System I	0.157046
System J	0.098467
System A	0.565001

4.3.3. Discussion;

The main objective of the study was to carry out a techno-economic analysis of the hybrid electric system for rural electrification giving a projection that the grid-connected Solar-battery system as the optimal system for electrification of Ngonga Zarma village. The energy demand for Ngonga Zarma in this study is 129.74kWh per day with a peak load demand of 30.89Kw after a random variability factor of 10%. The community had two sharp peaks in energy demand typical for villages and a low baseload throughout the day typical of village load curves (GIZ, 2016). However, during the prediction of load demand of Ngonga community understanding the willingness to pay and connect to electricity was based on assumptions made from a similar community the rural electrification Agency (ANPER) to avoid an oversized system. Oversizing prepares the installed system for an increase in power demand; however, this affects the resulting high net present costs, which increases the Levelised cost of energy. The optimal system size was calculated for the community to avoid oversizing costs, and the effect of load demand carried out in the sensitivity analysis.

In the design of hybrid rural electrification systems, local renewable energy sources generate power for household and community institution use. Domestic energy sources are essential as they reduce costs that would be incurred in distribution costs and power losses while providing energy at a reasonable price to villages. In Ngonga Zarma, the only existing renewable source that was feasible for power production was solar PV eliminating other renewable sources like biomass and Wind, which are not sustainable in that community. Due to the availability of the solar resource in the area, solar PV qualified as the primary energy source with the backup of other systems such as the diesel generator and battery for a reliable system. Solar resource with an average of 5-7kWh was considered a reasonable basis to establish an electrical system.

The main objective of this research was to assess the feasibility of a hybrid electric system to provide electricity for rural communities in the Dosso region, taking Ngonga Zarma as the case study. Different system configurations under particular scenarios were simulated using Homer Pro. The two scenarios, mainly considered in the study, were off-grid and grid connection scenario. Under the off-grid connection, the diesel hybrid system with storage (A) emerged as the optimal system with a net present cost of $321,276 and an LCOE of 0.350. In most off-grid systems, the solar PV-diesel with storage hybrid system is usually the cheapest option because of the high battery costs that often have a shorter life span, which becomes expensive later on in replacement of the battery bank (IRENA, 2016). The diesel hybrid system has a lower battery capacity level as compared to the solar battery system increasing the system costs.

Hybrid systems are known for increasing reliability due to the presence of two energy generation sources. The energy sources complement each other revealing that the system could achieve 0% capacity shortage. Despite the suitability of the hybrid solar PV diesel with storage system (A) as a low cost and reliable means for electrification, the study delved further to check if the off-grid system was the suitable configuration for the community. The breakeven grid extension distance was calculated and found to be 13.43, whereby the community's distance to the nearest local grid is 7km. In light of this, an off-grid system, despite the characteristics, is not the optimal system for the community. The optimal method for electrification of the village was found to be a solar grid-connected system. The connected grid system had a low net present cost at $221,154 and a cost of energy of 0.137$/kWh.

However, grid connection scenario had two options for analysis in the design the sale of electricity back to the national grid or a grid-connected the system with grid purchases only. In the network connected with sales, the optimal system was found to be the solar hybrid system with a net present cost of $221,154 and the LCOE of 0.137$/kWh which was lower than that of the national grid of $0.163(average tariff at 95.15fcfa) (Societé Nigerienne d'electricité NIGELEC, 2017). The diesel hybrid system with storage (G) showed though to have a lower LCOE at 0.137, but a slightly higher net present cost at $227,227.

In this scenario, to have a system without a capacity shortage, system G was found to be optimal for capacity values less than 2.6%. The system was further found optimal during the sensitivity analysis for load growths of 10% and 20% with the system staying optimal for capacity shortages below 3%. During the study, the results of the sensitivity analysis showed that battery life is significant in determining the net present costs of the system and can dictate the optimal system configuration. High quality and expensive battery were used in the study, and due to its long battery life reducing the replacements costs throughout the lifetime of the project. The battery lifetime considerably made the system (F) perform better than the hybrid solar PV-diesel system with storage, further reducing the LCOE when the nameplate lifetime reduced the replacement costs.

For the system to provide electricity at the current grid price, electricity sales to the grid were introduced. Installation entails making sure that the built systems are at the same frequency and voltage as the national grid electricity. System configurations that only have grid purchases are cheaper than the off-grid system, but the LCOE of $0.292 given is higher than that national tariff. To benefit significantly from the grid-connected system configuration, power purchases, and sales should be enabled across the meter. The fare used in this study for purchasing grid power is the amount NIGELEC uses to sell electricity to medium voltage subscribers. The price in the study however was not used as per period of electricity use. The sellback price set at 0.12 was the $/kWh that coal plants sell electricity to NIGELEC. From this, an assessment can be made that there currently are no set tariffs for mini-grids selling and buying power from the network, including known tariffs. Any changes in the prices as set by NIGELEC can affect the economics of the system though the cost of energy is guaranteed to be lower than that of off-grid systems and even further for systems that accept purchases and sales across the meter. However, it should be noted that the system becomes cheaper or expensive, depending on the final power purchase agreement made if the operator is private, government utility or the community.

From the situation of Ngonga Zarma, the connected grid system can be used to provide electricity in the short term. The community in this manner is used to produce part of the electricity for its consumption with the excess being sold to the grid using the community for the generation of power to improve local production. Most of the component prices were to a more significant effort based on the Niger market pricing though some components such as the batteries were adapted from the market in Nigeria. Even though the government of Niger lifted the tax on solar equipment(Open Capital Advisors, 2017), the prices of the material can change which can affect the Present Net Cost and LCOE the power produced making it unaffordable for the local communities.

According to the situation of Ngonga Zarma, the solar hybrid system configuration (F) is the best option for electrification of the community basing on the cost of energy as optimized in the model. The result of the study agrees with the hypothesis set; however, disagrees with the 100% renewable energy fraction. The 100% renewable grid-connected electric system cannot be achieved because all the electricity generated in Niger until recently was fossil-based. However, the electrical system comprises of only renewable resources, which increases the renewable fraction in the mix.

Ngonga Zarma has two neighboring communities lacking access to electricity that is Noumey Kagourou Zarma within a distance of 2km. The village has a household number of 150. Thus a system at Ngonga Zarma with an increment in the size of the Solar PV capacity from 35kW to 40kW can ably supply the community with electricity. Increasing the ability of the Ngonga Zarma power can be a subject for further research on how the hybrid system can be used to electricity to both Boulakorgui Zarma and Nourmey Kargou Zarma.

Hybrid renewable energy systems and rural electrification for Niger;

The hybrid renewable electric systems proposed in this study can contribute significantly to the development of the energy sector in Niger for all rural communities whose locality qualifies for the different scenarios. Hybrid systems can contribute significantly to the energy dependence of Niger as elaborated before depends on electricity imports and high-cost electricity from diesel generators. According to Ministère de l'Energie et du Pétrole, 2015, Niger's plan for 2030 involves increasing the renewable energy output to 30%. However, the country has a current renewable energy output of 0.6% thus the construction of hybrid solar systems as a means to increase installed capacity while providing electricity to rural communities that are lacking access due to a lack of enough power to distribute. The existing diesel generators have high CO_2 emissions, as shown in the study.

Long-running hours contribute to the number of emissions released by the systems. For example, the results show; emissions for a generator that runs for 5 hours a day were 20,660kg/yr a reduction from 88,552kg/yr of a generator that runs throughout the day. When these generators compared with the emissions from a diesel hybrid system, then a decrease of 96.86% in carbon emissions from the diesel-only system. Aside from the carbon emissions, hybrid systems will reduce the load shedding hours in the country. Communities such as Ngonga Zarma not connected to the network mainly because of the poor quality of infrastructure and a lack of enough generation capacity to continuously provide electricity without breaking down the entire system.

Solar-diesel hybrid systems with storage are essential for powering off-grid communities located far from the local grid network. In the study, observation showed that diesel hybrid system could provide reliable electricity for more hours at a competitive price and when the national grid reaches the location can drive the cost of electricity down as observed from 0.350$/kWh to 0.137$/kWh without grid extension costs. Through the hybrid-electric systems, the country can be able to increase the renewable energy proportion in the existing diesel mini-grids drawing closer to the 2030 commitment as a country.

Allowing grid connection of renewable electric systems such as solar and batteries through the right electronics can enable high electricity consumers who are deeply affected by the unreliable electricity by being able to generate their electricity and trade the electricity over the meter. Through this NIGELEC without investing in infrastructure for installation of plants, can have such producers increase local capacity by buying power from them. However, to enable the growth of such systems needs regulations and policies in place such as net metering and feed-in tariffs which are currently not in place.

5. CONCLUSION

5.1. Summary

This study aimed at analyzing the techno-economic feasibility of a hybrid power system for rural electrification in Niger, taking Ngonga Zarma village as a case study. Firstly, a survey was carried out to determine the energy demand of the community. The survey results using Microsoft Excel concluded that the peak demand of the Ngonga Zarma was 22.4kW. After including a random variability of 10%, the peak demand increased to 30.89kW with an energy demand of 129.74kW. Secondly, HOMER Pro 3.13 was used to model, optimize, simulate, and carry out the sensitivity analysis. Finally, the optimal system for electrification of the village was determined to base on the results from the simulation.

Different system components were chosen from the database of Homer Pro to model an electric system. During the modeling phase, two scenarios were chosen, that is the off-grid and the on-grid connected systems. The grid connection scenario was further divided into two options that is one with and without grid sales. The components chosen to carry out the study included the Genset 30kW, 250Watt solar panels from Canadian Solar, 820AH Surette battery, and finally a converter from Schneider Connect XW series. The load following dispatch strategy was chosen to control the performance of the system. Under this, the optimal system was found to be solar PV –diesel hybrid system (A) at NPC of $321,249 and an LCOE of 0.350. The break-even grid extension NPC was higher than that for grid connection, and at a distance of 13.43 kilometers, the scenario was considered not feasible.

The grid-connected scenario gave lower NPC and LCOE values as compared to the off-grid configuration. The solar PV system with battery and grid (F) had an NPC value of $221,153 and LCOE of 0.1374. However, the hybrid system of diesel and solar PV had a slightly higher NPC of $227,227 at an LCOE of 0.137$/kWh. According to the results from the on-grid case, the system without grid sales had a similar optimal system. However, solar PV, battery, and the grid presented 0.292 as the LCOE and an NPC of $261639. The optimal system with consideration of the NPC alone, system F had a total electrical production of 93,901kWh/yr enough to power the community load of 47,355kWh/yr. The optimal system plot was used to determine the more feasible solution of system F and G with the sensitivity analysis run on uncertain variables such as maximum capacity shortage, frequency of grid failure and growth in the load demand.

The maximum capacity shortage was found to significantly influence the choice of the optimal system with percentages less than 2% giving the solar PV-diesel hybrid system as the optimal system. At a change in the load growth while maintaining the same level of unmet load at a capacity shortage below 2.5% keeps system G as the optimal system; however, above that configuration F (solar, battery and Grid) takes over as the optimal system. A conclusion drawn from the sensitivity analysis is that to have a reliable system at 0% capacity shortage, then solar PV, diesel generator, the battery, and grid was the optimal system.

Beyond the capacity shortage constraint, the optimal system remained F, and this includes changes in the renewable energy fraction, carbon emissions and higher percentage of load growth. The effect of an upgrade introduced to the existing grid infrastructure showed that solar PV, the battery and grid connection found that the NPC increases with increase in the grid extension distance increasing the grid capital cost resulting into a high LCOE of 0.181 at 10,000$/km and 0.350 at 20,000$/km making system A the optimal system for electrification. System F, comprising of 35kW of solar PV, 16 batteries and a converter size of 21.8KW with grid connection qualified as the most feasible system for the electrification of Ngonga Zarma. The study concluded that in connecting the system with sales and purchases across the meter enabled making the system achieve grid parity with electricity being cheaper than NIGELEC electricity with the price being $0.163 basing on the existing structures

5.2. Conclusion;

Hybrid power systems are of great value in the electrification of rural communities which are very far from the grid and are not expected to have access shortly. From the study, it was concluded that a solar PV diesel with storage hybrid solution is a low-cost solution in providing reliable electricity especially to communities that are far from the grid where the net present cost is lower than that for grid extension. Thus for communities which have high solar radiation between 4-7kWh per day, solar PV diesel with storage hybrid mini-grids can provide lower-cost, reliable electricity with fewer emissions.

Through this initiative, most of the communities powered by diesel systems shall have an integration of renewable energies in their mix not only reducing the cost of the system but also enabling Niger to fulfill its climate goals of a 30% renewables by 2030. The use of a solar PV-diesel hybrid system reduces the amount of fuel used per year, and this gives the communities a certain level of security of supply due to the diversification that is attained from the multiple energy sources.

Due to the reliance of Niger on energy imports makes the distribution network of great importance to the quality of electricity in the country. Current challenges such as instability of power on the grid lines that affects the distribution network, causing constant blackouts can be reduced if specific communities that are completely blocked off by allowing them to produce their electricity to back up the unreliable grid. Niger is currently investing in mini-grids in different parts of the country for connection of rural outside the Niamey region. Basing on the findings from this research, mini-grids will be more beneficial if connected to the national distribution network so that the country can benefit from the existing infrastructure.

Community mini-grids are an opportunity for increasing the generation capacity of the country through NIGELEC. However, the regulations and the renewable energy policy in place can contribute to their success, such as giving of incentives, exemptions, and also enabling the sold electricity over the meter to the national grid network. Large business owners in Niamey through this opportunity can reduce their monthly losses due to the frequent blackouts by funding in hybrid solar systems and through this increased reliability while contributing to the countries generation capacity.

For installation of a mini-grid, the community members should have the ability to purchase electricity monthly when connected. Rural communities and Ngonga Zarma, in particular, have existing businesses such as grain mills and shops for selling ice that can ably buy power if provided. Other key customers include the existing commune administration building which receives funding from the departmental funds, not forgetting other community loads such as health centers. The ability to pay is essential in the sustainability of mini-grids because the components used have high capital costs.

The study also revealed that the choice of components is vital in setting the NPC of a project for example investing in a higher capital cost for a good battery with a longer life span can go further into reducing the LCOE of the project. The chosen batteries have a longer lifetime and if properly managed, can make the electrical systems cheaper. Replacement costs through the lifetime of the project dwindle reducing further the LCOE of the electric system

5.3. Recommendations;

The diesel generator is an essential component in many mini-grids in rural communities a proper optimization of its performance, and best working conditions influence the cost of energy provided. In this study, one large generator was sized to provide the peak power; however, for further studies, the size of the generator reduced to two smaller units. Connection of a mini-grid lowers the COE, making grid-connected systems more competitive than standalone systems. The study showed a distinct difference in the cost of energy when the system purchases and sells electricity to the grid. However, the price per kWh of electricity used is the average consumer tariff for medium voltage Niger. Notice is made that in mini-grids connected to the network, the price is different due to the power purchase agreements negotiated between the project developer and the government utility company. The before, it is recommended that a good sell back price is used when determining the profitability of with or without grid sales on the cost of energy.

The fixed charge by large energy-producing stations per month was used as the demand rate to further study the effect of increments in demand on the LCOE. The tariff rate used for purchasing power from the grid was not disaggregated according to the off peak and on peak tariff rate instead an average tariff rate from the website of NIGELEC was used. Therefore, for further studies of the same type, I recommend the utility set demand rates to visualize the impact on the cost of energy accurately and also applying tariff rates at different pea. The demand rates are essential in proper energy management of the users. Ngonga Zarma has a solar-powered solar water pumping system which was not included in the system designed in this work. However, for future studies, the deferrable water pumping load should be included in the design to increase capacity for irrigation in the area further.

During the period of stay in the community, the temperatures experienced felt much higher than those adapted through the NASA database in HOMER Pro. There is a need to carry out a ground study of the temperature variation throughout the day at different regions in Niger, especially Dosso. Temperature affects the performance of the solar panels. Thus estimation using the measured values would go a long way in increasing planning for all solar projects, especially mini-grids. To ascertain the actual performance of the solar PV system over the years, mainly on the amount of energy produced, time-series temperature data uploaded into HOMER Pro would give a more realistic solar PV output per year as the Niger peak temperature per day would reduce the efficiency of solar panels. Ngonga Zarma community is surrounded by Boulakorgui Zarma and Nioumey Kargorou Zarma which face power instabilities on their network. A study is recommended to analyze a feasible electrification system and capacity to provide reliable electricity to the communities surrounding Ngonga Zarma.

Changes occur every day on the costs of equipment which are affected by the discount rate and inflation rate in the country. Favorable rates enable developers to secure financing for the establishment of mini-grids impacting the cost of energy in the long run. However, the effect of the inflation rate and cost of different equipment was not discussed during the sensitivity analysis. An in-depth study is recommended for the impact of changes in the inflation rate and equipment costs on the economics of the feasible system (F).

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APPENDICES

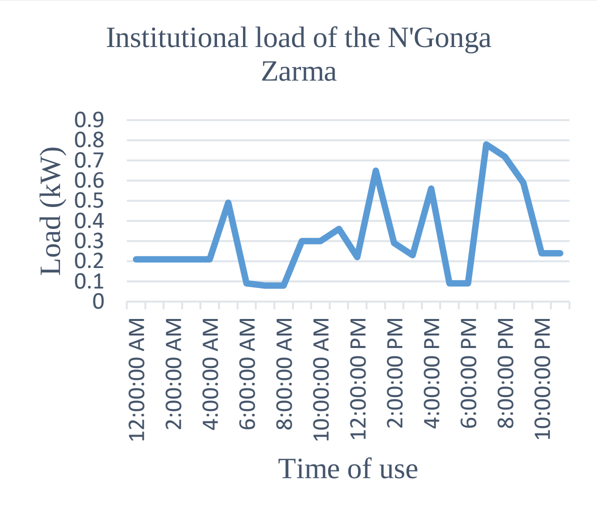
APPENDIX A: NGONGA ZARMA LOAD PROFILE

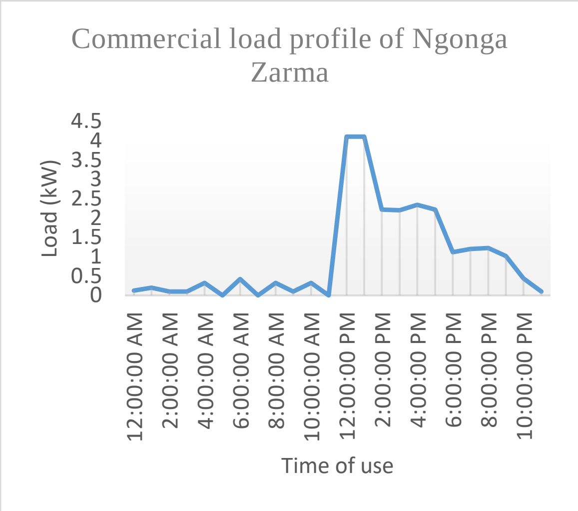
Load Category	Appliance	Quantity	Number	Time of Use	Duration(h)	Power required(W)	AC load (Wh)
Household _1							
Radio	10	1	255	4:00-8:00	4	2550	10200
Lamp	10	1	255	7:00-11:00,4:00-6:00	6	7650	45900
Electric outlet	10	3	255	6:00-9:00	3	2550	7650
Total						**12750**	**63750**
Household _2							
Radio	10	1	45	16:00-20:00	4	450	1800
Television	60	1	45	19:00-21:00	3	2700	8100
Lamp	10	3	45	19:00-23:00,5-6	6	1350	8100
fan	50	1	45	17:00-21:00	4	2250	9000
DVD video	30	1	45	20:00	1	1350	1350
Electricity Outlet	15	1	45	19:00-21:00	3	675	2025
Refrigerator	80	1	2	On and off during the day	10	160	1600
Total						**8775**	**31975**
Commercial load							
Grain mill	1000	1	4	12:00-14:00pm	4	4000	16000
freezer	100	1	1	On and off during the day	9	100	900
Television	60	1	3	18:00-21:00	3	180	540
Telephone	5	10	10	18:00-22:00	4	500	2000
Radio	15	1	8	16:00-22:00	7	120	840
Lamp	10	2	10	19:00-22:00	4	200	800
Refrigerator	80	1	4	On and off during the day	10	320	3200
Total						**5320**	**24280**
Institutional load							
Mosque							
Lights	10	4	4	Prayer time	4	160	640
Radio	30	1	4	Prayer time	5	120	600
Fan	30	2	4	Prayer time	3	240	720
Lights(External)	15	1	4	20:00-5:00	10	60	600
Total						**580**	**2560**
Public light	30	1	1	20:00-5:00	10	30	300

Total						**30**	**300**
Primary School							
Classroom lights	10	1	6	20:00-22:00	2	60	120
Fan	30	1	1	12:00-16:00	5	30	150
Bulb(Ext)	15	1	1	21:00-6:00	10	15	150
Total						**105**	**420**
Secondary School							
Classroom lights	10	2	6	20:00-22:00	3	120	360
Fan	30	1	1	12:00-15:00	4	30	120
Bulb(Ext)	15	1	1	20:00-5:00	10	15	150
Computer	100	1	1	10:00-13:00	3	100	300
Printer	100	1	1	10:00-13:00	3	100	300
Total						**365**	**1230**
Nursery School							
Telephone charge	5	2	2	9:00-13:00	4	20	80
Office light	10	1	2	19:00-21:00	2	20	40
Fan	30	1	2	10:00-14:00	4	60	240
Total						**100**	**360**
Health center							
Fan	30	3	1	12:00-16:00	4	90	360
Refrigerato r	80	1	1	on and off during the day	24	80	1920
Lights	10	3	1	20:00-00:00	5	30	150
Radio	10	1	1	16:00-21:00	5	10	50
Lights_ext	10	1	1	20:00-5:00	10	10	100
Total						**240**	**2580**
Administr ation Load							
Fan	55	3	1	12,14:00-16:00	4	220	880
Lights	10	5	1	20:00-22:00	2	50	100
Lights(exte rnal)	15	1	1	20:00-5:00	10	15	150
Computer	50	2	1	10:00-14:00	4	100	400
Printer	100	1	1	10:00-11:00	2	100	200
Stokage_1	10	1	3	20:00-21:00	2	30	60
Stokage_2	10	1	2	20:00-5:00	10	20	200
Total						**535**	**1990**
Grand total							**12975 0**

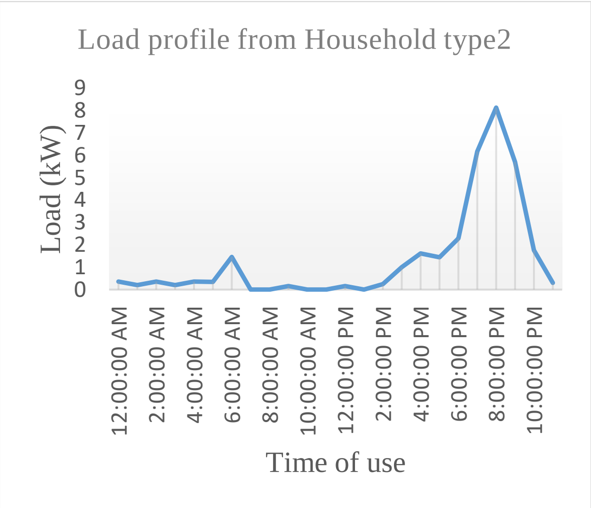
APPENDIX B: Load profiles for different electric consumers in Ngonga Zarma

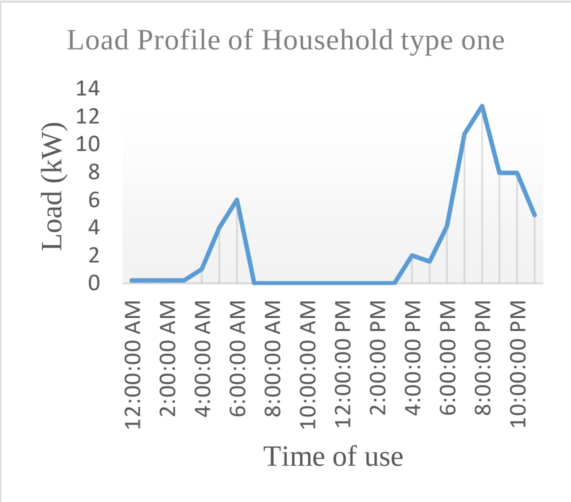
B.1: Institutional and Commercial Load Ngonga Zarma.





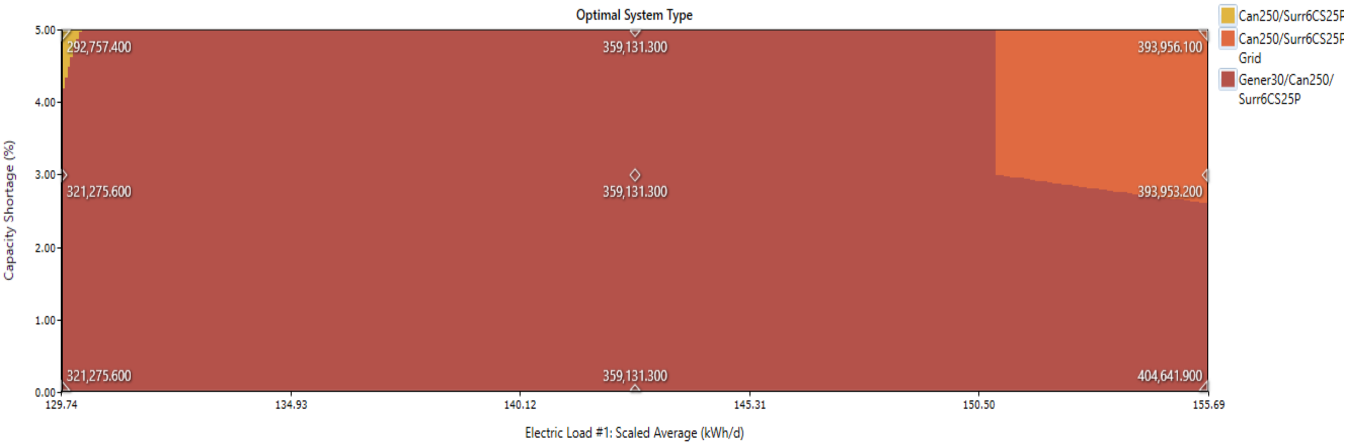
B.2: Household type 1 and type 2 load.



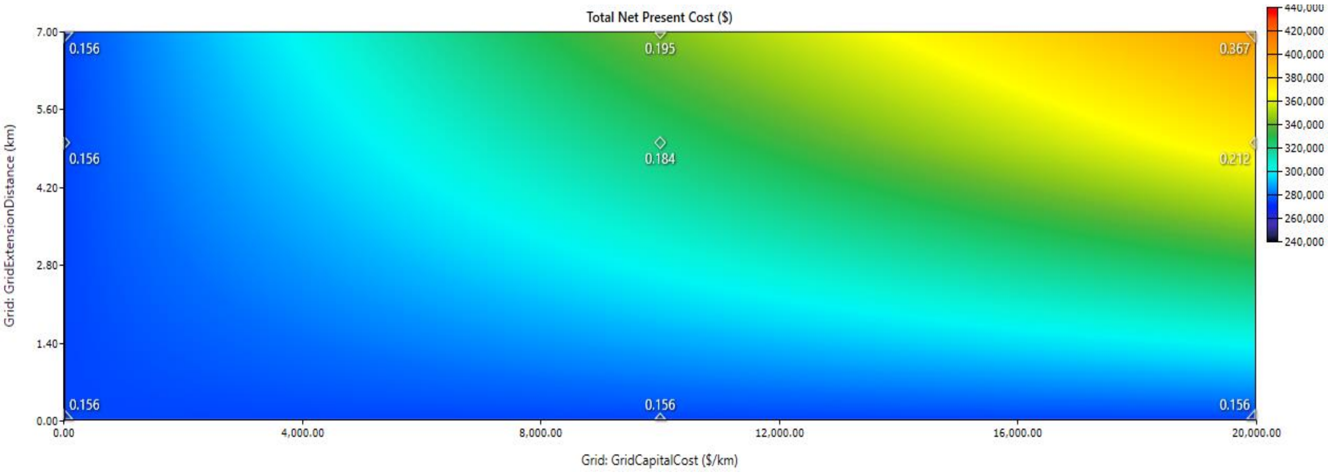


APPENDIX C:

C.1: Effect of increased Load Demand and Capacity shortage on the optimal system



C.2: Effect of investment in grid extension on the system s capital cost under increased grid power failures.



C.3: Criteria chosen for evaluation using TOPSIS

	Sub-criteria	Units	F	G	H	I	J	A
1	Excess Electricity	kW/yr	6181	6366	8798	185	3976	5678
2	Renewable Fraction	%	61.8	60.2	56.6	0	0	93.7
3	Fuel consumption	l/yr	0	943	2569	2521	4049	1308
4	Electricity Production	kW/yr	93901	96,218	100152	47844	51331	65188
5	Capacity Shortage	kWh/yr	1057	0	0	0	0	0
6	CO2 emissions	Kg/yr	20026	22497	26755	33015	37016	3425
7	Compatibility with Energy Policy	0,1	0.65	0.8	0.8	0.7	0.5	0.7
8	Social Acceptance	0,1	0.9	0.8	0.6	0.7	0.5	0.85
9	Net Present Cost	$	221,153	227227	242858	300,638	315,437	321,249
10	Levelised Cost of Energy	$/kWh	0.137	0.137	0.143	0.327	0.343	0.35
11	Capital Cost	$	87247	94,855	85513	35,094	23,000	154,121
12	O&M cost	$	98804	95,224	92,756	203451	206094	42,906

APPENDIX D: BUDGET

o.	Item	Unit	Quantity	Rate	Months	Amount ($)	Link to Research Activity	Comment
	Material and Supplies							
1	- Software License Fees, HOMER PRO	months	6	31$/month	March April May June July August	190$	Techno-economic analysis of the hybrid electric system Important for the full exploration of the software applications and for developing mastery in the use of the software.	
2	Stationary, Printing and Photocopying				May - June August	100 50	Thesis and questionnaires and necessary stationary for defence of thesis and also during data collection. Partly to be done in Niger and Algeria	
3	Internet Recharge	10gigabytes in Niger	5months	50/month	March - August	450	Important for desktop research and also for updates, webinars concerning the updates and also related to my research area. http://www.orange.ne/particuliers/1/29/nos-offres-internet-mobile-69.html	
5	Field Assistance (2)	days	20	20$/person day	May	400	Carrying out the interview of the households in the area under assessment and also coordinating the interviews with other departments related to the energy sector. Important for determining the load requirement. From French into the local language for the identified village and Transport	
	Sub-Total					**1190 $**		

	Equipment							
	Sub-Total							
	Travel and Visa costs							
	Flight Ticket	n/a	1	600	May	700	Flight to Niger; case study in Niamey for data collection an ‘open ticket’ that can be changed whose return flight can be adjusted accordingly	Pauwes to Purchase the Ticket
	Visa costs	n/a	1	40	May	40	Visa cost to Niger for data collection	
	Tlemcen to Algiers	n/a		35	May	100	Travel costs to the Algiers Airport	
	Subtotal;					**840**		
	Special Activities							
	Grand Total:					**$2030**		

APPENDIX E: Ngonga Zarma Questionnaire

Name of Interviewer:	**Start time of interview:**					**Survey Date:**
Name of village:	**End Time of Interview:**					
Region:	**Household:**	**Business:**	**Institution:**	**Other:**		**Questionnaire Number:**
Department :						
GPS Co-ordinates:	**Head of Household/Business Name:**					
	Type of Business:					
1.Characteristics of Household/Business/Administrative Unit						Comments
1.1Head of Household	Husband;	Wife;	Specify;			
1.2 Respondent						
1.3 Respondent's Age						
1.4 Respondent's Educational level	Illiterate ( )	Primary ( )	Secondary ( )	Tertiary ( )		
1.5 Respondent's Occupational status	1. Employed ( )	2. Unemployed ( )				
If yes Respondent's monthly income level (CFA)?	1. 1-18000	2. 18000 – 36000	4.36000 –50000	5. Above 50000		
If no Respondent's Source of Income?						
Does this apply to a specific season? if yes how does the figure change with season?						
1.6 Members of the Household	Age of household member	Sex		Relation to household	Educational level	
		Male	Female			
Charachteristics of the dwelling						
1.7 Type of Roof	1.Straw ( )	2. Others ( )	3.Tile2 ( )	4.Concrete ( )		
1.8 Type of construction	1.Straw ( )	2.Bamboo ( )	3.Brick house ( )	4.Kiosk/container ( )	5.Others ( )	
1.9 Number of rooms						
2.Current Energy Expenses						**Comments**

2.1 Type of Energy source	Oil	Candles	Kerosene	Gas	Batteries	Firewood	Diesel		
2.1.1 Quantity									
2.1.2 Hours of Use per day									
2.1.3 Distance travelled									
2.1.4 Frequency of purchase									
2.1.5 Unit price									
2.1.6 Transport cost									
2.1.7 Activity for which it is used									
2.2 Type of Electricity Source Used									
2.2.1 Generator									
2.2.1.1 Type of Generator									
2.2.1.2 Capacity									
2.2.1.3 Hours used per month									
2.2.1.4 Type of fuel used									
2.2.2 Solar household system									
2.2.2.1 type of solar system									
2.2.2.2 size of system									
2.2.2.3 type of panel used									
2.2.2.4 Is it possible to get maintenance									
2.2.3 Electrical appliances;									
	T.V	Radio	Refrigerator	Processing	Phone charger	Computer	Pump/ irrigation	Lamps	Others
2.2.3.1 Old/new type									
2.2.3.2 Type of appliance									
2.2.3.3 Availability of maintenance									
2.2.3.4 Year of acquisition									
2.2.4 Battery/Inverter									
2.2.4.1 Type and capacity used									
2.3 Do you use any of energy sources for productive purposes such as irrigation etc If yes; Specify?	Yes ( )				No ( )				

Would you consider engagement in the above activity if availed the energy?						
3. Life style						Comments
3.1 What time do you normally wake up?	1.6am ( )	2.7am ( )	3.8am ( )	4.Others specify ( )		
3.2 What time do you leave and return home?	Leave ………………………………………		Return …………………………………………			
3.3 What time do you sleep?	1.7pm ( )	2.7pm ( )	3.8pm ( )	4.10pm and above( )		
Do you think this sleeping pattern would change if connected to electricity?	Yes ( )	No ( )	Cannot tell exactly ( )			
If yes; How do you think it will change?						
3.4 Please describe your schedule during the week that is from when you start your day till it ends?						
3.5 Please describe your routine during the weekend from when you start your day till it ends?						
3.6 Which season does your routine described above apply too?	Dry Season ( )		Wet ( )			
3.7 Can you describe your routine if it changes, during another Season (wet/dry)?						
4. Supply Chain of Purchase						Comments
4.1 Where do you purchase your house hold products from Including Diesel, Batteries and other household items?	1. Shop/market in the village ( )	2. In the City ( )	3. Other ( )			
4.2 Why do you specifically shop from there						
4.3 What mode of transport do you use to get the area of purchase?	1.Walking ( )	2.Bicycle ( )	3.Motocycle ( )	4.Donkey ( )	5.Car ( )	
4.4 Who makes the decisions on what items to purchase in the home?	1.Husband ( )	2.Wife ( )	3.Others ( )			
5. Planned Load s and Demand forecast						

	Planned load in year 1	Planned load in year 2	Planned load in year 3	
5.1 Fridge				
5.2 Television				
5.3 Radio/CD				
5.4 lamps				
5.5 Radio				
5.6 Phones				
5.7 Computer				
5.8 Air conditioner				
5.9 Iron				

6. Willingness to buy					Comments
6.1 If there were plans to extend electricity would you consider paying? List the person/position of the determinant	1.Yes ( )		2.No ( )		
	…………………………………………………………………				
6.2 Do you have a solar system in place?	Yes ( )	No ( )		Considering it ( )	
6.3 Are you able to say that electricity introduced to your village will change the state of your business and your livelihood?	Yes ( )		No ( )		
6.4 Are there currently activities/items that you would want your business to do and is not doing? If yes? What are they?	Yes ( )		No ( )		
6.5 What amount of money are you willing to pay electricity for?	1.20-40 FCFA ( )	2.40-60 FCFA ( )	3.60-80 FCFA ( )	4. 80-100 FCFA ( )	
6.6 What do you consider the most important when it comes to Electricity?	1.Quality of electricity ( )	2.The cost of electricity ( )		3.Duration of supply ( )	
6.7 Does your current electricity supply cover your needs?	1.Yes ( )	2. No ( )		Percentage (if partially): ( )	
6.8 Which mode of payment can you use to pay for the electricity?	1. Cash ( )	2. Mobile money ( )		3.Other mode of Payment ……………………………	

6.9 Do you feel satisfied or not with the system in place?	1.Very satisfied ( )	2.Satisfied ( )	3.Not Satisfied ( )	4.Can live with it ( )	
6.10 Do you think the electricity provided from the system will improve your livelihood/business	1.Yes ( )	2.No ( )		3.Not sure ( )	

(Adapted from the (GIZ, 2016) **Survey template and further improved for use in Ngonga Zarma community.**