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Presented by

Martin SANKOH

TECHNO-ECONOMIC ASSESSMENT OF SOLAR PHOTOVOLTAIC HYBRID POWER SYSTEM IN SIERRA LEONE, WEST AFRICA

"A case study of Masunthu village"

Pan African University Institute of Water and Energy Sciences

(Including Climate Change)

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Techno-economic assessment of hybrid solar photovoltaic power system for rural electrification in Sierra Leone, West Africa

"A case study of Masunthu village"

Presented By

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BEng Mechanical and Maintenance Engineering (Hon)

A Thesis submitted to the Pan African University Institute for Water and Energy Sciences (Including Climate Change) in Partial Fulfilment of the requirements for the degree of

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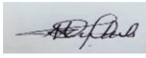
Declaration

I, Martin Sankoh, hereby declare that this thesis represents my work, realized to the best of my knowledge. I also declare that all information, materials and result from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Martin Sankoh		10/10/2021
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Certification

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Abstract

Access to clean and affordable electricity is a fundamental pillar of the United Nations sustainable development goal 7 (United Nations, 2018). In Sierra Leone, less than ten percent of rural communities have access to electricity. This study carried out a techno-economic assessment for hybrid power generation for a remote village in Northern Sierra Leone, Masunthu (latitude 9.1^0W & longitude -12.6^0N). Hybrid Optimization for Multiple Electric Renewables (HOMER) software, a specialized software application for the optimization of hybrid mini and micro-grids was used to carry out simulation, optimization, and sensitivity analyses on selected configurations of electrical systems for the location. With an expected daily electricity demand of 178kWh/day, the result obtained from the simulation showed that a hybrid system comprising of a solar photovoltaic system (45.5kW), diesel generator (31kW), and battery storage (68 batteries /411Ah each), was the most ecomnomical system to provide reliable electricity supply for the village. With the price of diesel fuel at $1/L, and for inflation and nominal discount rates of 10% and 24% respectively, the optimization yielded a Levelized Cost of Energy (LCOE) of $0.336. A further sensitivity analysis showed that a reduction in the discount rate can significantly reduce the LCOE. Furthermore, with a 90% renewable energy fraction, the system was observed to significantly reduce the amount of greenhouse gas emissions compared to a system that uses a diesel generator as the only source of power generation.

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List of abbreviations

AfDB	African Development Bank
BS	Battery Storage
CC	Capital Cost
DG	Diesel Generator
ECOWAS	Economic Commmunity of West African States
ECREE	ECOWAS Centre for Renewable Energy and Energy Efficiency
GDP	Gross Domestic Product
GHG	Greenhouse gas
HES	Hybrid Electricity System
HOMER	Hybrid Optimization for Multiple Electric Renewables
HP	Hydro power
HRES	Hybrid Renewable Energy system
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
NPV	Net Present Value
PV	Photovoltaic
RE	Renewable Energy
SDG	Sustainable Development Goals
SE4ALL	Sustainable Energy for All
SL	Sierra Leone
SPV	Solar photovoltaic
SSA	Sub -Saharan Africa
UN	United Nations
UNDP	United Nations Development Program
WB	World Bank

List of SI units

%	Percent
$	United States of America dollars
A	Ampere
kg	kilogram
km	kilometre
kW	kilo-watts
kWh	kilowatts-hour
m	meters
m/s	meter per second
TW	Tera-watts
MW	Mega-watts
V	volts

Chapter one

1.1 Introduction and background of the study

Sustainable electricity provision is vital to ensure the sustained economic development of any nation. Across the world, economic productivities as well as the level of human development of nations is largely dpendent on their level of energy production and productive use (Sharma, 2010). The provision of sustainable energy is an important agenda in the United Nations' Sustainable Development Goals (UNSDG), with goal 7 emphasizing the need to create universal access to clean and affordable energy for all, emphasizing sustainability and environmental preservation (UN, 2015). By promoting clean energy, the world commits to reducing the impact of Greenhouse Gases GHG emitted by fossil fuel energy sources by transiting to renewable power generation.

Sub-Saharan Africa (SSA) ranks amongst the most economically challenged sub-regions globally, with an estimated GDP of $1.7 trillion (World Bank, 2021). The region marks low economic growth with high poverty rate leading to low living standards for many of its inhabitants. The sub-region has the least developed electricity infrastructure amongst other sub-regions globally, where over two-thirds of the total population lacks access to sustainable electricity supply. In the Northern Africa region, the objective of universal access to electricity was attained in 2016, while South Africa is the most electrified country in sub-Saharan Africa, with a national electrification rate of 86%. Amongst other countries in SSA, the average electrification rate is estimated to be 45%, with seventeen (17) countries reported to account for access rates of less than 30% of their population (International Energy Agency (IEA), 2020.)

SSA has an electricity infrastructure dominated by centralized power generation systems. Extending grid-electricity supply to remote and isolated areas located at considerable distances from existing grids is a challenge in many cases due to the examined technical and economic challenges associated with implementing such projects (Hafner & Tagliapietra, 2018). With the current rate of electrification, around 18 million people in SSA will gain access to electricity each year, indicating that many African communities will remain unelectrified for many decades to come, according to the IEA (IEA, 2019). Such a scenario will undermine the core value of the sustainable energy development goal that aims to universal access to electricity by 2030. Various scenarios have been developed by international agencies working on advancing energy development in Africa. According to IEA, off-grid solutions through mini-grids and stand-alone systems could provide electricity for nearly one half of the estimated population gaining access to electricity by 2040. In the process, off-grid power generation will account for 10% of the total electricity generation capacity (IEA, 2018). International Renewable Energy Agency (IRENA) highlighted mini-grids present a viable alternative for electrifying off-grid communities and can be cost-competitive as an option when compared to national grid extension to remote locations (IRENA, 2014).

Africa possesses a vast potential for renewable energy generation in biomass, geothermal, hydro, solar, and wind energy resources. Solar energy is a predominant resource across all ends of the continent, with areas in the Sahelian region receiving the highest annual global irradiance. Solar power potential on the African continent is estimated to be 10TW (Blimpo & Cosgrove-Davies, 2017). The declining costs of these technologies over the years have seen a considerable increase in their rate of adoption across the world (IRENA, 2014). Solar Photovoltaic (SPV) technologies are widely used for electricity generation, especially off-grid power generation, across the African continent. In 2020, Africa had an installed capacity of 99MW of Solar power, according to IRENA (IRENA, 2020). The regular intermittency and fluctuations in power production from SPV are incapable of providing a reliable power supply. This phenomenon provides an opportunity to combine PV with at least one more generation sources or a storage device that can be renewable or non-renewable, in a hybrid SPV system (Manwell, 2004). Hybrid PV systems have been widely deployed across the world to generate reliable power for on-grid and off-grid locations.

An extensive literature on academic and scientific research works (Dong et al., 2021; Jahangir & Cheraghi, 2020; Yadav et al., 2019, (Adaramola et al., 2014; Azimoh et al., 2016; Mbaka et al., 2010; Moner-Girona et al., 2018) that have been carried out on the topic related to assessing the techno-economics, and environmental feasibility of hybrid SPV across Africa and other parts of the world has indicated the relative effectiveness of the hybrid system in enhancing energy access to rural and isolated communities.

1.2 Statement of the problem

Sierra Leone, according to the United Nations (UN) is ranked amongst the countries with the least developed economies in the world (United Nations, 2018). As a benchmark requirement towards the economic development of any nation, sustainable energy development is a major challenge in Sierra Leone. The electricity infrastructure in Sierra Leone ranks amongst the least developed in the sub-Saharan Africa region and globally. Access to electricity supply stands as an important pillar in the United nation’s sustainable development goal 7, yet in Sierra Leone, with a population of nearly 8 million people, electricity access rates account for less than a third of the national population. According to the World Bank (World Bank, 2019), national access rate in 2019 was estimated to be 23%, with less than 10% rural electricity access. The lack of electricity in the country is significantly affecting human and economic productivity and standards of living; more severely in the rural parts, and as a result, leading to mainstream economic exclusion while increasing poverty rates.

The electricity infrastructure in Sierra Leone is marked with several challenges. National grid extension to remote and isolated parts of the country, including island settlements, is associated with a low profitability ratio, which blockades financial investment in projects in such places. Leading from the global Sustainable Energy for All (SE4ALL) initiative, the country plans to achieve 92 percent electrification rates by 2030, with 27% of the population expected to access electricity through mini and micro-grids (SL Electricity roadmap 2030, 2017). Micro and mini-grids have been identified as the most feasible and cost-effective means of electrifying many remote communities across the country. Hybrid systems using solar photovoltaic technology are expected to play a vital role in providing electricity supply in these locations. However, the slow rate of renewable energy development, especially mini-grids, indicates the most remote villages will still remain unelectrified for several years. This site-specific study seeks to conduct a feasibility study for a hybrid SPV system to provide electricity supply for a village in Sierra Leone. Based on lessons learned from studies on the impacts of previous projects on HRES for rural electrification in SSA and beyond, it is important to carry out scientific and academic research to determine the feasibility of adopting these systems as a model for electrifying remote villages in Sierra Leone.

1.3 Research objectives and methodology

1.3.1 Objectives

1.3.1.1 General

The overall aim of this research project is to carry out a design for a model of electricity generation using a hybrid SPV for a rural and remote village located in the northern part of Sierra Leone, Western Africa. The research seeks to assess the feasibility of a hybrid PV system in the case study location by carrying out techno-economic analysis on selected configurations of hybrid SPV systems.

1.3.1.2 Specific

The specific objectives which are completed in carrying out the research include;

- ✓ To carry out a literature review on techno-economic feasibility studies on hybrid systems in Africa and world wide.
- ✓ To conduct a resource assessment of the case study site to determine the energy resources present, and a load assessment survey to determine the electrical load demands of the village community.
- ✓ Carry out a design and simulation of the hybrid electricity models and conduct a technical and economic assessment of four selected models to determine the most feasible model. Environmental impact assessment is also considered to determine the relative amounts of carbon emissions of the different models. To carry out a detailed analysis of the selected model.
- ✓ To conduct a sensitivity (what if ?) analysis on the preferred model in order to determine the effect of a change in an input economic variable on the specific output variables.

1.3.2 Methodology

1.3.2.1 Resources assessment and data collection

Resources assessment is conducted through a physical site visit. Load assessment and data collection process were carried out using a survey questionnaire to estimate the electrical power demand for the case study area. The data collected is used as input into the simulation software.

1.3.2.2 Electrical load estimation and software simulation

Technical and economic design of the PV hybrid systems was carried out using the Hybrid optimization of Multiple Electric Renewables (HOMER) Software. Four models were considered for simulation in this study;

1. i. A system comprising of Diesel generator as the only power generator
2. ii. A hybrid system comprising of solar photovoltaic array and a diesel generator.
3. iii. A hybrid system comprising of solar photovoltaic array and a Battery Storage (BS).
4. iv. A hybrid system comprising of a SPV system, a diesel generator and a battery storage.

2 Sensitivity analysis

A sensitivity analysis was conducted to determine the effect of various economic variables on the project costing. Input variables used in the sensitivity analysis include: interest rates, discount rates, and inflation rates.

1.4 Significance of research

Rural electricity access in Sierra Leone is considerably low, relative to many other countries in the SSA region. Based on the increase in electrification, many rural communities will remain unelectrified for the next few years. Therefore, an academic study promoting the theme of rural electricity access provides a case study with a methodology that can be replicated across other similar locations of rural Sierra Leone. Furthermore, findings from this study can be referenced in advanced research works, and recommendations highlighted from this study provide possible areas of future academic research related to PV hybrid systems across Sierra Leone and other parts of Africa.

1.5 Scope of research

The research targets specifically the technical design and economic feasibility analysis of different configurations of Hybrid PV-diesel and battery storage systems for electricity generation in Masunthu village in Sierra Leone. The work provides a conceptual model of electricity generation using a simulation software - HOMER. Economic sensitivity analysis is carried out for the preferred system to determine its performance under the influence of selected economic variables.

- Chapter two (2) of this report - the literature review, presents background information on the electricity infrastructure in Sierra Leone, and briefly discusses the technical and economic aspects of hybrid SPV systems.
- Chapter three (3) - the research methodology, highlights the data collection and electrical load demand estimation methods, and explains the simulation, optimization, and sensitivity analysis process.
- Chapter four (4) presents a discussion of the results in detail. The chapter presents key findings from the four simulation scenarios and then gives a comparative analysis on the four models. the best-case system is further analyzed in detail. Finally, results from the sensitivity analysis are analyzed in this section.
- Chapter five (5) gives a summary of the important findings from the study and provides recommendations based on the results.

Chapter two - Literature review

2.1 Profile of Sierra Leone

Figure 2.1: Map of Sierra Leone

Source: United Nations

Sierra Leone is located on the south-western coast of west Africa at the latitude and longitude of 8^0N & 11°W respectively. The country has a land size of approximately 73,529km^2 (acaps, 2014) divided into four political regions – eastern, western, northern, and southern province and share land borders with Guinea, Liberia, and 465km coastline which extends along the Atlantic Ocean. The country's total population as estimated from the national census in 2015 was approximately 7.6 million, with a reported growth rate of 3.7%. Rural settlements represent 57% of the total population. The capital city, Freetown, is the most populated region in the country with a population of 2.1 million inhabitants and a population density of 8,450 people per square kilometer, (United Nations, 2018).

According to the International Monetary Fund (IMF), the economy of Sierra Leone ranks amongst the least developed economies in the world with a Gross Domestic Product (GDP) of \$4.1billion, marking the country as one of the poorest in the world with a poverty index of 64%. The country ranks 183rd out of 187 countries globally in the United Nations human development index, with a human capital index of 0.35. Economic productivity is low with nearly 70% of the active labor force being unemployed, according to a United Nations Development Program (UNDP) [25]. Agriculture is the largest contributor to the local GDP, contributing over two-thirds of the total amount. The sector employs over 70% of the active labor force, where a majority of the farming activities include small-scale and subsistence farming. Mining activities also represent a major source of export revenue and a primary driver of macro-economic growth.

Sierra Leone is found in a wet-tropical monsoon climatic zone with two distinctive seasonal weather patterns experienced annually – dry and wet season, each spanning over six months, with average temperatures varying between 21^0C to 33^0C and an experienced average annual rainfall of 2450mm.

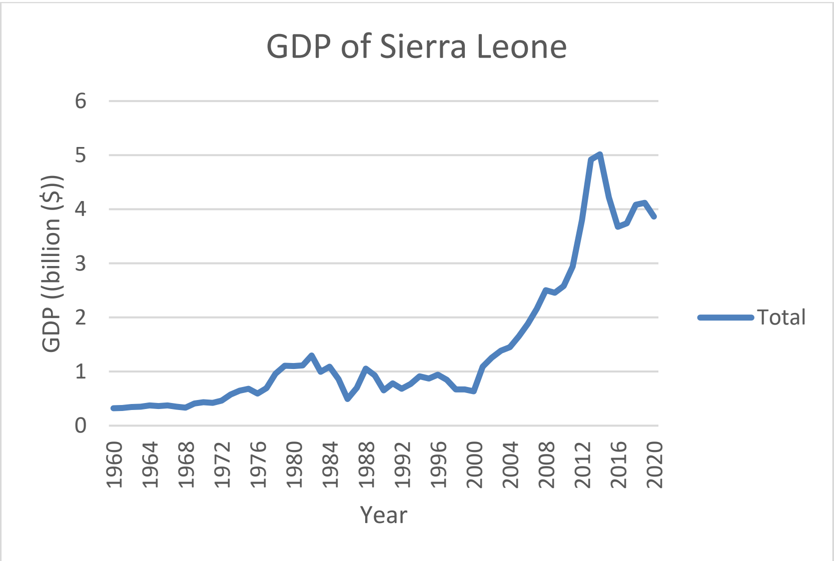


Figure 2. 2: Chart showing GDP of Sierra Leone from 1960 – 2020

Source: world bank data, 2020.

2.2 Electricity in Sierra Leone

2.2.1 Institutional infrastructure

Electricity infrastructure in Sierra Leone is still under-developed and the country still faces the challenge to provide a sustainable electricity supply to ensure its economic growth and human development. The country's electricity infrastructure is relatively small and ranks as one of the least developed power sector in the SSA region in terms of the capability of delivering sustainable, reliable, and continuous power supply to its population (Sierra Leone SE4ALL, 2015). Before the civil war in the 1990s which vandalized most of the physical electricity infrastructure in the country, Sierra Leone had a total installed electricity generation capacity of about 15MW. Post-civil-war in 2009, an increasingly inefficient performance of a vertically integrated national power generation sector led to a strategic sector reformation which saw the vertical unbundling of the integrated power generation and supply units into two separate private entities mandated by a government authority through an act of parliament to provide reliable electricity generation and supply services in Sierra Leone. In 2011, a regulatory body was commissioned by an act of parliament by the GoSL to regulate the activities of electricity and water services providers in the country. To facilitate the sector's efficiency, a Ministry of energy, as a separate entity, was commissioned in 2013 by the GoSL as the entity responsible for formulating policies, projects, and programs and provide general oversight of the sector.

The institutional infrastructure working towards the development of the energy sector is made up of a multi-sectoral involvement; an oversight authority, a regulatory commission, and power companies (generation and supply). The ministry of energy of the Government of Sierra Leone (GoSL), provides general oversight on all activities related to the energy sector, including development formulation and implementation of policies, projects, and programs that promote energy development. The regulatory commission, Sierra Leone Electricity and Water Regulatory Commission (SLEWRC) was established in 2011 by an act of parliament to regulate all activities related to energy and water services providers in the execution of their duties; such as operational standards compliance with established practices, and tariff regulation. Electricity generation and transmission are carried out by two separate entities working in parallel, Electricity Generation and Transmission Company (EGTC), a power generation and transmission entity, generates and sells power through a power purchase agreement to a supply and distribution company, Electricity Distribution and Supply Authority (EDSA). EDSA and EGTC were established in 2009 by an act of parliament and these two are mandated to own and operate all government and engage in any electricity development activity through a government authorization. EGTC owns and operates all government energy generation infrastructure and facilities and generates and sells electricity directly to EDSA through a power purchase agreement. EDSA owns, operates, and manages all national generation facilities, purchases electricity generated by EGTC and ensures supply of power to end-use consumers.

2.2.2 Energy demand and supply

The primary energy consumption of Sierra Leone is dominated by biomass, accounting for over 80% of the country's total primary energy consumption in 2012, according to the United Nations Development Program (UNDP) [24]. In 2015, national electricity demand was estimated to be 256MW, of which domestic power demand and demand from the mining sector account for 203MW and 53MW, respectively. In 2016, a comprehensive sector scan by the Sierra Leone Netherlands business group reported the total installed power capacity of 99MW.

The installed capacity for domestic electricity generation is 135MW, dominated by hydro power plants with a cumulative installed capacity of about 75MW. Thermal power plants using fossil fuels and biogas power plants account for the remainder of the installed generation capacity. An external power supply is obtained from 50MW from a floating power-ship owned by Karpower-corporation, a Turkish company, and 27MW power supply from the west-African power pool project with its immediate neighboring countries of Ivory Coast, Liberia, and Guinea. Comprehensive data on the installed capacity of solar power generation is scarce but national generation capacity accounts for an installed solar power plant with 6MW power capacity. The price of electricity in Sierra Leone marks one of the highest in the sub-region with an average price of $0.28/kWh.

2.2.3 Access to electricity

Energy access in Sierra Leone is very low and the country ranks amongst the seventeen (17) countries in SSA with access rates less than 30%. Electricity access rate in 2020, according to the World Bank, accounted for 24% of the total population, with a per capita consumption of electricity of 51.5 kWh/yr, which is less than the sub-regional average of 88kWh/yr (Ministry of Energy, 2016). Urban Access to electricity accounts for 60% of total residents. Access in the rural areas is estimated to be less than 10%, with around 95% of rural settlements accessing electricity through stand alone solar-Pico technologies (SE4ALL, 2019).

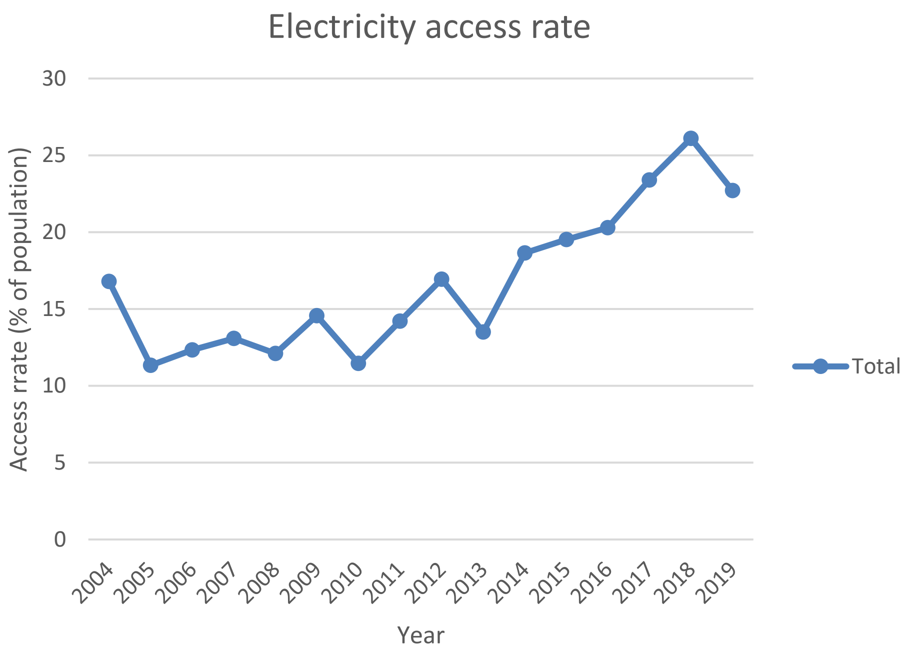


Figure 2. 3: Electricity access in Sierra Leone between 2004 - 2019

Source: World Bank, 2020.

2.3 Renewable energy resources

2.3.1 Solar energy

Sierra Leone is situated in the northern equatorial region, experiencing two major seasonal climatic conditions; dry and wet seasons. The dry season consists of days with longer hours of sunshine with greater levels of solar radiation and daily sunshine hours experienced during the dry season. The Annual global horizontal irradiation experienced in different parts across the country ranges from 1,460kWh/m^2/day to 2,200kWh/m^2/day. The country is reported to record an average of 2187 hours of annual sunshine, with a daily average of 5.6 sunshine hours (Irish Aid, 2016). Direct uses of solar energy can be found extensively in agricultural crop drying practices. Solar energy for electricity is in the form of photovoltaic technologies using flat-faced solar panels to generate electricity. Solar energy use for electricity is dominated by Pico solar products in rural communities, stand-alone PV systems, and community micro-grids provided by utility service providers. IRENA estimated the national installed capacity of solar energy in 2019 to be 4MW (IRENA, 2016), excluding residential stand-alone and pico-solar home systems.

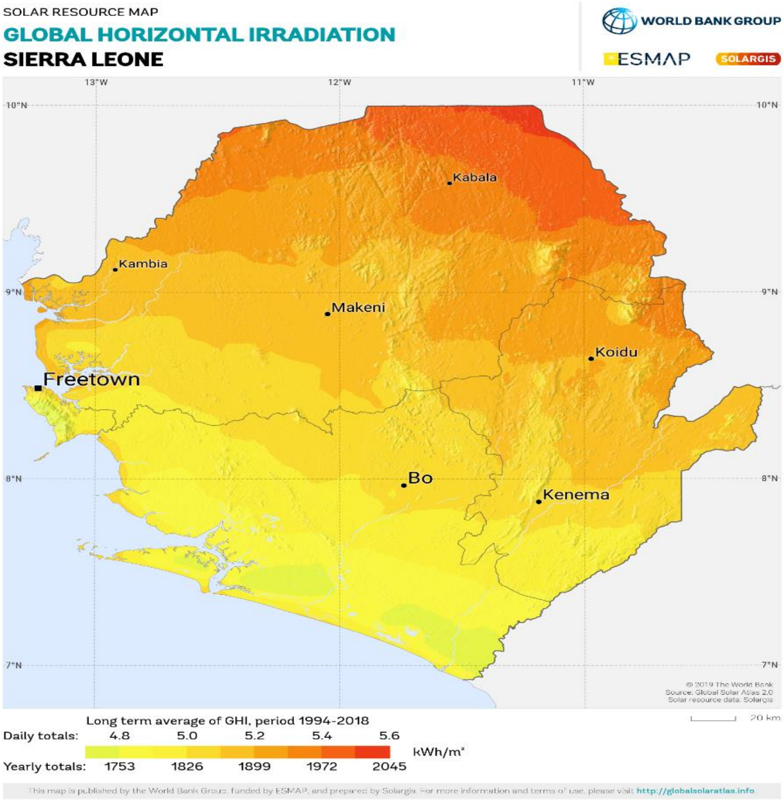


Fig.2-5 – Global horizontal Irradiation of Sierra Leone
Source: World Bank data

2.3.2 Hydro power

There are seven major rivers and several small rivers flowing across Sierra Leone, with most generally flowing from the northeast to southwest, discharging into the Atlantic Ocean. According to the Kellerman foundation, in 1986, hydropower potential in Sierra Leone was estimated to be 1,245MW. However, in 2017, a detailed investigation by the United Nations Industrial Development Organization (UNIDO) reported an estimated theoretical potential of hydro power generation to be 4,381MW. Pico-hydro, with generation potentials less than 1MW, has a theoretical capacity of 140MW, small hydro power capacity 1 -10MW has a theoretical potential of 499MW, while medium and large hydro accounts for the largest potential with 3148 generation potential [22]. Hydro power generation sources contribute the largest share of the installed electricity generation capacity in the country, with a cumulative installed capacity of about 60MW, in 2013, the cumulative power generated from hydropower was 147.9GWh, from a total generation of 325GWh.

The largest installed hydro power generation plant is the Bumbuna hydropower plant, commissioned in 2009, with an installed capacity of 50MW, which provides electricity for over 40 percent of the residence of the capital city. The operations of this and other hydro power plants are characterised by extreme shortges in power production during the periods of the dry season as a result of the reduction in discharge capacities of the supply rivers. The major hydro power plants in Sierra Leone are listed in the table as follows;

Hydro power plants in Sierra Leone		
Name	**Capacity (MW)**	**Type**
Bumbuna hydro power	50	Reservoir
Bankasoka hydro power	3	Run-off river
Charlotte	2.2	storage
Dodo	6	Run-off
Makali	0.12	
Yele mini-hydro dam	0.25	

Table 2. 1: List of hydro power generation plants in Sierra Leone

Source: Ministry of Energy, Sierra Leone.

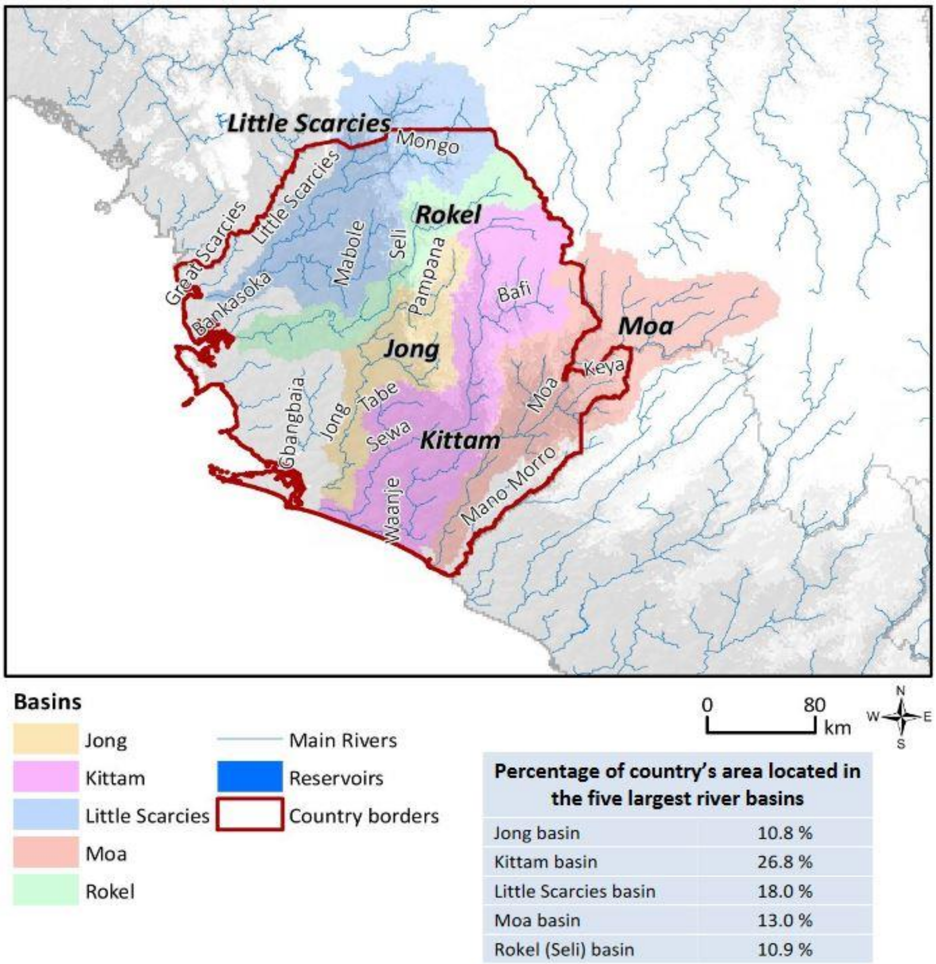


Figure 2.6: Major River basins in Sierra Leone.

Source: (ECREE, 2021)

2.3.3 Wind energy

Wind speed in Sierra Leone according to the meteorological agency in 2012, varied between 3m/s to 5m/s. In some mountainous areas of the country, wind speeds of up to 8m/s have been recorded at 10m above ground level. In the mountainous north-eastern region of the country, there are reported indications of wind speeds of up to 12m/s (Meteorological statistics, 2012). Wind power potential as an alternative for electricity generation has so far not been exploited.

2.3.4 Biomass

Sierra Leone has approximately 2.7 million hectares of forest reserves, as reported by UNDP (National energy profile, 2012). Biomass wood sometimes converted into charcoal, is used as the primary source of domestic energy supply for meeting the household's needs and some industrial heating applications and accounts for 80% of the national primary energy use. According to the German company, “Bundesministerium für Wirtschaft und Energie”, the theoretical potential for biomass power generation was 2.706GWh. In 2017, IRENA reported the installed capacity of biomass of 33MW. Biomass electricity is produced through a 15MW installed capacity biogas plant operated by “Addax bio-energy” company and located in Malifabu, the northern part of the country, which supplies electricity to the national grid. Studies have identified a significant potential for an increase in biogas production with an increase in the level of agricultural practice. Waste to energy conversion technologies as an alternative means of generating electricity is an option yet to be exploited in the country.

2.4 Rural electrification and mini-grids in Sierra Leone

The Sierra Leone electricity infrastructure roadmap plans to improve electricity access to about 92% of the population by 2030 with a target to meet the medium and long-term energy demands for industrial and domestic use . Renewable electricity generation is an important component under this initiative to increase the capacity of renewables in the generation mix from 56MW in 2010 to 1,229MW by 2030 (SL Electricity sector reform roadmap, 2017). The capstone project under this initiative, phase 2 of the Bumbuna hydro power project, which targets to add about 350MW of installed power capacity to meet domestic electricity demand was proposed to commence construction in 2020. Under this roadmap, the National Renewable Energy Action Plan (NREAP) document, plans to increase the capacity of off-grid renewables to 178MW, using a combination of mini-grids and SPV standalone home systems, in the process of providing electricity to 37% of the national population. So far, there have been two major donor-funded solar mini-grids projects; the ongoing “Rural renewable energy program”, implemented by the GOSL and partners, will provide 5MW of solar mini-girds across 97 rural communities, with around 500,000 people estimated to be direct and indirect beneficiaries from the project. A summary of national off-grid renewable targets is given in the table. 1-1 below.

Installed capacity (MW)	**2012**	**2017**	**2020**	**2030**
Mini-grids (Solar PV)	31	78	130	174
PV, pico-hydro and small-scale wind systems	4	8	16	44
Off-grid RE	35	56	86	178

Table 2. 2: Renewable energy targets for Sierra Leone

Source: NREAP,2015.

2.5 A literature review on hybrid electrical power systems – techno-economic case studies

2.5.1 Hybrid PV systems – The concept of Hybrid PV systems

SPV generates electricity that is relatively clean and cheap compared to their fossil fuel counterparts. However, the power output of a PV system is dependent on the prevailing weather conditions, which makes SPV an unreliable source to provide continuous power supply. In such a situation, an extra source of power generation is required to ensure a more reliable supply of power. A hybrid SPV system combines an SPV system with at least another generation source and or a storage device, to achieve a continuous supply of power to meet electrical loads (Front Matter, 2021). The generation sources usually employed in conjunction with a PV system can be one or more micro-turbines, wind generators, diesel generators, etc. A hybrid SPV system can generate power for electricity supply in both off-grid and on-grid (grid-connected) applications (Manwell, 2004). In off-grid applications, a hybrid SPV system provides reliable electricity by combining SPV with other renewable or non-renewable energy generation sources. In the case of a grid-connected application, an SPV system is used in conjunction with grid-connected electricity. Where necessary, plus a generation source a net metering system that used a feed-in-tariff allows for selling and buying of power to and from the grid (Del Carpio-Huayllas et al., 2012). In both applications mentioned, where needed, a storage device, can be used to store excess energy produced by the generator(s) and supply. A storage device in a hybrid SPV system can be electrochemical battery storage, pumped hydro storage technologies, etc. Generally, hybrid energy systems can be broadly classified based on the generation sources employed. A hybrid renewable energy systems employs only renewable generation sources, and hybrid non-renewable energy systems employs at least a fossil fuel generator.

2.5.2 Techno-economic feasibility studies on hybrid PV systems

Solar energy presents an abundant potential for electricity generation in almost every part of the globe. The African continent alone has a recorded solar potential of 1.1 billion TWh per year (Wall, 2019). Solar radiation poentials makes generating electricity from solar energy a viable potential across every part continent. Access to electricity in most remote and rural parts of Africa is hindered by the associated high cost of grid extension and minimum expected return on investment associated with such projects, as reported by AfDB (Bank, 2010). Various scenarios on the future of electrification of the African continent (IEA, 2019.; IRENA, 2011.), have proposed the critical role of hybrid SPV systems in the drive towards achieving universal electrification for the African continent.

A body of academic research works exist on the assessment of the techno-economic feasibility study on hybrid SPV systems for both off-grid and on-grid applications, globally. Many of the researches that have been carried out for off-grid feasbility studies are based on conducting a comparative assessment of technical and economic variables to determine the most optimal hybrid system type for a particular location. In many of these studies, the most optimal system is usually the one which provides a reliable supply of electricity and carries the least associated economic cost over the lifetime of the project.

In techno-economic assessments of hybrid systems, specific simulation software is used; HOMER, HYBRID1, PVsyst, RET screen, are few of the most commonly used. Homer is the most widely used tool as it offers the capability to simulate several configurations of systems, optimize the performance of a system, and carry out sensitivity tests to determine the effect of variation of performance of certain variables.

Some important published academic literature based on scientific studies on the techno-economic feasibility of PV- hybrid generation systems for off-grid electrification using homer software are mentioned in the following paragraphs;

A study by (Odou et al., 2020), carried out a comparative techno-economic assessment to determine the most feasible model of HRES that can provide reliable electricity supply for an off-grid community, Fouay village, in Benin, comprising of over 300 households and 3000 inhabitants. The study result showed that a HES comprising of SPV (150kW), DG (62.5kVA), and BS (637kWh), was the most economically viable system, which presented the least cost of generation as well as ensuring an emissions savings of about 97% as compared to a generation system that uses DG as the only source of generation. In conclusion, the authors emphasized how the most economical HRES for a particular location is determined by the energy resources potential and the remoteness of the location.

A similar study by authors (Adaramola et al., 2014), Investigated the techno-economic feasibility of hybrid SPV for electricity generation in selwcted rural and semi-urban areas of Jos community, northern Nigeria, a location with a mean annual global solar radiation of 6.0kWh/m^2/day. Findings from the study showed that a HES made up of SPV/DG/BS was the most economical system with LCOE obtained varying from \$0.348 to \$0.378/kWh, which is relatively lower considering the use of a diesel generator (with LCOE between \$0.417 and \$0.423 per kWh) as the only source of power generation for the locations studied. The analysis further indicated a significant reduction in the amount of annual CO_2 by the former relative to the latter. Form the result, the indicated cost of energy of the HES system is higher when compared to the national tariff for low-power customers. However, the authors suggested the high associated cost of utility grid extension to many rural areas is what makes HES a feasible option for adoption. The study highlighted that further reduction in interest rates for communities and organizations willing to adopt these technologies will lead to a decreasing cost of electricity and an increasing rate of adoption to enable access to electricity in rural and semi-urban areas across the country.

A study by authors (Esan et al., 2019), assessed the reliability of PV-diesel-battery HPS in Lade, a typical rural community in Nigeria. Homer was used to conducting an optimal design of the system and sensitivity analysis was performed using criteria of variation in diesel fuel prices, average solar insolation, and capital/replacement cost of SPV. Further validation of the results was done using a novel approach of capacity outage probability table (COPT). The system obtained comprises a total generation capacity comprising of; 1.5MW of SPV array, 350kW DG, and 1200 battery storage units, and have a total NPV of \$4,909,206 and an LCOE tariff of \$0.396 per kWh. Observations from the simulation showed a reduction of all emissions from pollutants by 97%. The author(s) concluded that the HMS is reliable, highly economical, and feasibly adopted in the case study area.

A study by authors (Mbaka et al., 2010) assessed the techno-economic feasibility of power generation amongst three options of HES; hybrid SPV, stand-alone SPV, and stand-alone DG, for off-grid communities located in northern Cameroon. The result obtained an LCOE to be 0.812 Euros/kWh with the price of diesel at 1.12 Euros/L for a stand-alone system. Sensitivity analysis further obtained a minimum break-even distance of between 5.1km to 5.9km for an LCOE of between 0.692 - 0.785 Euros/kWh, with a renewable energy fraction of 94%, indicating the comparative effectiveness of the proposed models in terms of reducing harmful emissions while promoting small-scale electricity generation capacity for rural communities.

A techno-economic feasibility study by (Murugaperumal & Ajay D Vimal Raj, 2019) developed an optimal design of an improved performance HES model for rural electrification of Korkadu, a remote village in India. The study compared the techno-economic effectiveness of different configurations of HES relative to the utility grid extension. The design which obtained a relatively cost-effective solution concluded HES to be a viable option for rural electrification in similar regions of the case study country.

Authors (Li & Yu, 2016), carried out a comparative assessment for off-grid PV/diesel/battery HES for household electrification in Urumqi, China, a location with annual average solar radiation and household power demand of 4.2kWh/m^2/day and 10.275kWh/day respectively. The technical design of the SPV system used a fixed tracking systems to maximize energy production and prolong availability. The performance based on criteria that include; technical, economic and environmental performance. The results indicated a PV/diesel/battery system as the most economically feasible, where a system coupled to a two-axis tracking can produce an annual average power of 3.83MWh per year. The proposed system has the capability of reducing greenhouse gas emissions by 5.5tCO_2/year when using fixed-tilt arrays relative to using diesel generators alone.

Authors (Lozano et al., 2019), developed and compared the techno-economic feasibility of SPV/diesel, and SPV system for Gilutongan island, in the Philippines. Their study which aimed at proposing a cost-effective and reliable power solution for the island obtained the most optimal system to comprise of a (314kW) SPV array, and battery storage made up of 200 batteries, integrated with a 194 - kVA DG. The cost of energy obtained at US$0.3556 per kWh is relatively lower when compared to the existing solution, which requires US$1.24 per kWh to be paid for power supply available for 4.5h daily, thereby indicating the technical and economic viability of the system in the location considered.

2.6 Hybrid technology and economics

2.6.1 Technical Components of a hybrid SPV/DG/BS system

A typical SPV hybrid system comprises of:

- Power generation component,
- Power conversion unit used for electrical power conversion (AC↔DC)
- Energy storage component used for storage of electrical energy produced by the power generators.
- Charge controller for controlling power input and output from the sources.

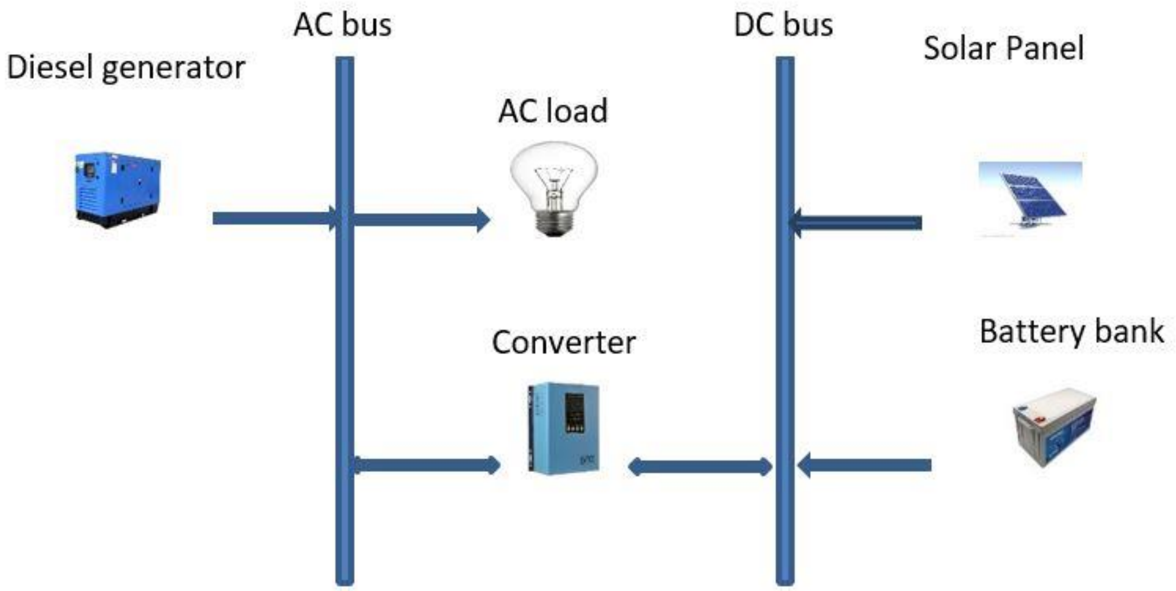


Figure 2. 4: Schematic of a hybrid PV/DG/BS system

Source: Converter & SPV (www.easunpower.com), DG (www.amsa.gen.tr), AC load (www.sunco.com), BS (US.sunpower.com)

2.6.1.1 Solar panel

The Solar panel (module) receives solar irradiation from the sunlight through its flat surface. The panel is made up of a rectangular array of a series of interconnected semi-conductor cells joined together by electrical wires. The cells convert sunlight into electricity due to the photovoltaic effect, with typical conversion efficiency within the range of 10% to 25%, depending on the type of technology used. The electricity produced by the panel is a Direct Current (DC) electricity, which is converted into a certain level of DC or Alternating Current (AC) based on the needs of the electrical load(s) to be served. Thin film and wafer-based technologies are two of the most commonly available solar cell technologies in the market.

2.6.1.2 Power converters

A Power converter controls power in the system by regulating the voltage level. The converter can be in the form of a chopper or an inverter, based on the design and purpose of the application. A DC-DC converter converts the mostly unregulated output voltage produced by the panel to a regulated output voltage level (higher or lower) to enable a safe power supply when a DC load is to be served. The types of DC-DC converters can be either; Buck type converter- steps down input voltage, Boost type - steps up input voltage, and Buck-boost - steps down and steps up DC-

DC voltage. DC to AC converters (inverters) converts DC power into AC power to supply an AC load. Inverters can be single-phase, three-phase, or pulse width modulation. Voltage conversion in an inverter is achieved with the help of devices like inductors and capacitors for storage, and electronic switches; transistors, and diodes(Baharudin et al., 2017).

2.6.1.3 Power controller

A power controller is used to prevent overcharging and deep discharging of battery storage devices when used in PV applications to ensure good performance and preserve the lifetime of the batteries. A Controller uses set points to connect or disconnect the battery based on the battery's state of charge or voltage. The four main types of charge controllers are: shunt, series, maximum power point tracker, and DC-DC type converter. (Khera et al., 2016).

2.6.1.4 Diesel generator

A diesel generator converts mechanical energy into AC-driven electrical power. The output power produced can directly serve a connected AC load or can be converted into a DC through a converter to serve a direct current load. A diesel generator is the main source of fossil fuel used to generate power in a PV HES due to its specific technical and economic advantages over other types of engines and also based on the availability of diesel oil compared to other fossil fuels.

2.6.1.5 Battery bank

Due to the fluctuation nature of power produced and the unreliability of electricity generated from solar panels, battery storage is needed to ensure continuous supply of power to meet the electrical load demand. Electrochemical batteries are used for the purpose of energy storage in a PV system and the battery types used in PV applications include; lead-acid, nickel-metal hydride, lithium-ion technologies (Solanki, 2018). The preferred choice of battery characteristics for use in a PV application include; low cost, high energy-efficiency and self- discharge capacities, long lifetime, low maintenance and a simple operation (Bhayo et al., 2020). Lead-acid is the most widely used battery type in PV applications due to its low cost and availability in the local markets, as well as its simple operation. A typical lead acid battery has a specific energy ranging between 25Wh/kg to 35Wh/kg, specific power between 70W/kg to 100 W/kg, a lifetime of 250 to 750 cycles, and a specific cost of 50 Euro/kWh (Duryea et al., 2016). Available batteries for use in a SPV system have rated voltages of 6V, 12V, 24V and higher (Manimekalai et al., 2020).

2.7 Economics of hybrid power system

2.7.1 Levelized cost of electricity (LCOE)

The LCOE indicates the unit cost of electricity generated over the lifetime of a generation technology (Shen et al., 2020). The LCOE compares the lifetime costs of power generation amongst different source. The lifetime cost of a power generation technology can be categorized into capital, operation, maintenance, and salvage (disposition) costs. Capital cost represents the cost of the construction of the power plant. Operations and maintenance costs are the costs incurred when running a power plant during its useful lifetime - this cost can be divided into variable and fixed costs. Disposition (salvage) cost represents the cost incurred at the end of the useful lifetime of a plant. LCOE in terms of economics represents the average price of electricity, a specific generation technology must earn to break even. LCOE methodology is a metric widely used by policymakers in long term electricity planning and incentive formulation, by developers to compare the attractiveness of various generation technologies, and investors to understand long term economic trends of renewable power generation (Branker et al., 2011)

$$\mathbf{LCOE} = \frac{\mathbf{C_{ann,t}}}{\mathbf{total\ energy\ served}} \qquad \text{equation 1}$$

Where:

$C_{ann.\,t}$ = annualized cost ($/yr) and, Re_{served} = total electrical load served in (kWh/yr.)

2.7.2 Annualized Cost

The annualized cost is the annual cost of components which includes the annualized capital cost (C_{cap}), the annualized cost of replacement (C_{rep}), and the operation and maintenance cost, throughout the lifetime of the project. The annualized cost compares relative costs of individual components and measures their contribution to the Net Present Value of the project (Anthreas, 2021).

$$\mathbf{C\_ann = CRF(i, N) \times C\_NPC} \qquad \text{equation 2}$$

Where:

$\mathbf{C\_ann}$ - Annualized cost

$\mathbf{CRF(i, N)}$ - Capital recovery factor

$\mathbf{C\_NPC}$ - Net Present Cost

The total annualized cost can be calculated as given in the following equation:

$$\mathbf{C\_ann = \ 〚CRF〛\_tot\ (i, N) \times C\_(tot\ NPC)} \qquad \text{equation 3}$$

Where:

C_{ann} - Annualized cost ($)

i - Real inflation rate (%)

N - Project lifetime (years)

C_{NPC} - Net Present Cost of components ($)

(HOMER,2016).

2.7.3 Net Present Cost

The Net Present Cost (NPC), also called Net Present Value (NPV) of a project is the sum of all income and outlay costs associated with a project during its entire lifetime, including the future cash flows discounted to the present. The NPC takes into account; the initial capital cost of installing the components, replacement cost of components, and the salvage value of components - the net worth remaining of the system component after the system lifetime) during the lifetime of the project.

NPC can be calculated by the equation:

$$\textbf{Net Present Cost} = \frac{\textbf{Total Annualised Cost}}{\textbf{Capital Recovery Factor}} \quad \text{equation 4}$$

$$\textbf{Capital Recovery Factor} = \frac{([\mathbf{i}(\mathbf{1+i})]\text{^}\mathbf{N})}{((\mathbf{1+i})\text{^}\mathbf{N-1})} \quad \text{equation 5}$$

where:

i - the interest rate.

n - the number of years.

(HOMER, 2016)

2.7.4 Salvage value

The salvage (S) value of property represents the net amount of money obtainable from the sale of that property at the end of the project's lifetime (Kimia, 2015). Where a component is replaced during the project's lifetime, the replacement cost is used in the calculation of the salvage value.

The following equation gives the salvage value of a component:

$$\mathbf{S} = \frac{\mathbf{C\_rep\ R_{rem}}}{\mathbf{R\_comp}} \quad \text{equation 6}$$

(R_{rem}) - the remaining life of the component at the end of the projected lifetime is given by:

$$\mathbf{R\_rem} = \mathbf{R\_comp} - (\mathbf{R\_project} - \mathbf{R\_rep}) \quad \text{equation 7}$$

The replacement cost **(R_{rep})** duration is given by:

$$\mathbf{R\_rep = R\_comp\ \ INT}\left[\frac{\mathbf{R\_proj}}{\mathbf{R\_comp}}\right] \quad \text{equation 8}$$

Where:

C_{rep} - component replacement cost,

R_{rem} - remaining life of component (t),

R_{comp} - is the lifetime of the component (t),

INT () - a function that returns the integer amount of a real number.

(HOMER, 2016)

2.7.5 Real discount rate

The discount rate is the opportunity cost of a project and it gives the break-even rate of the capital of the capital below which an investment made is infeasible. The real discount rate is used to convert between one-time costs and annualized costs. The nominal discount rate is a function of the following three factors; inflation, risk-free real return, and extent of risk of the project (Khatib, 2015). The discount rate is calculated as:

$$\boldsymbol{R} = \frac{(\boldsymbol{r}-\boldsymbol{f})}{(\mathbf{1}+\boldsymbol{f})} \quad \text{equation 9}$$

Where:

R = real discounted rate,

r = nominal discounted rate,

f = the expected inflation rate.

(HOMER, 2016)

Chapter three - Study materials and methodology

3.1 Background

The aim of this work was to carry out a techno-economic feasibility study for a standalone hybrid SPV system for a remote power supply for a village called Masunthu, located in northern Sierra Leone. The study aimed at assessing the technical performance and economic cost associated with power generation using an SPV HES to provide a continuous power supply to a remote village in Sierra Leone. The primary requirements for completion of this study include;

3.1.1 Needs and energy resources assessment

This was carried out to determine the existing resources for electricity generation for the village. An assessment of the renewable energy resources potential was carried out using available climate data for the location obtained from the climate database of the National Aeronautics and Space Association (NASA)

3.1.2 Data collection and electrical load estimation

Load data collection – load data for the village were collected to determine the approximate load requirement of the village. The data collection was carried out using a survey questionnaire and results from the survey were used in estimating the electrical loads' requirements.

Economic price data – including the costs of the technical components of the power generation systems (DG, solar panel, inverter, controller, battery bank) available in the local market were also collected.

3.1.2.1 Survey questionnaire format

Data for the report was obtained through a two-day physical site visit to the village. The purpose of the visits was to conduct a resource assessment and a survey to establish an understanding of the electricity situation and the energy generation resources of the site. A total of 50 in-person interviews were conducted with household occupants and service providers using a survey questionnaire. The survey questionnaire was divided into 2 sections:

- **Section A** asked general questions about the villagers' primary means of meeting their energy needs for cooking, lighting, heating, and phone charging, and any other purpose for which electricity is used.
- **Section B** collects data based on the household electricity requirement. Data were collected to determine the electrical load demand for every household.

3.1.3 Simulation

The four different configurations of power generation systems (scenarios) were simulated for comparison as possible options for energy generation in the village. These four scenarios include:

- Scenario A (SA) - A power generation system that uses DG only
- Scenario B (SB) - A system that uses SPV system and a DG as generation sources
- Scenario C (SC) – A system that uses SPV system as a generation source and a Battery bank as an energy storage device.
- Scenario D (SD) - A system that uses SPV system and DG as sources of generation, and a battery bank as an energy storage device.

All four configurations of power generation systems were simulated using Hybrid Optimization for Multiple Electric Renewables (HOMER) professionals' software, version 3.14.5. A side-by-side comparative analysis on the technical, economic and environmental output parameters was presented for the four different models to determine the most feasible option of electrification for the village. The most feasible system in this study is the system that offers the least NPC over the lifetime of the project as well as maximizes the use of renewable energy generation and produces the least amount of GHG emissions during its operational lifetime, as simulated by the HOMER software.

Sensitivity analysis is carried out on the most feasible system to determine the effect of a change in the project's economic input on its cost. The economic input variable considered were; (1) inflation, (2) discount rate interest rate, and (2) The price of diesel fuel. The project costing variables considered were (1) NPC, (2) CC and, (3) LCOE.

A breakdown of the study methodology is given in the figure below:

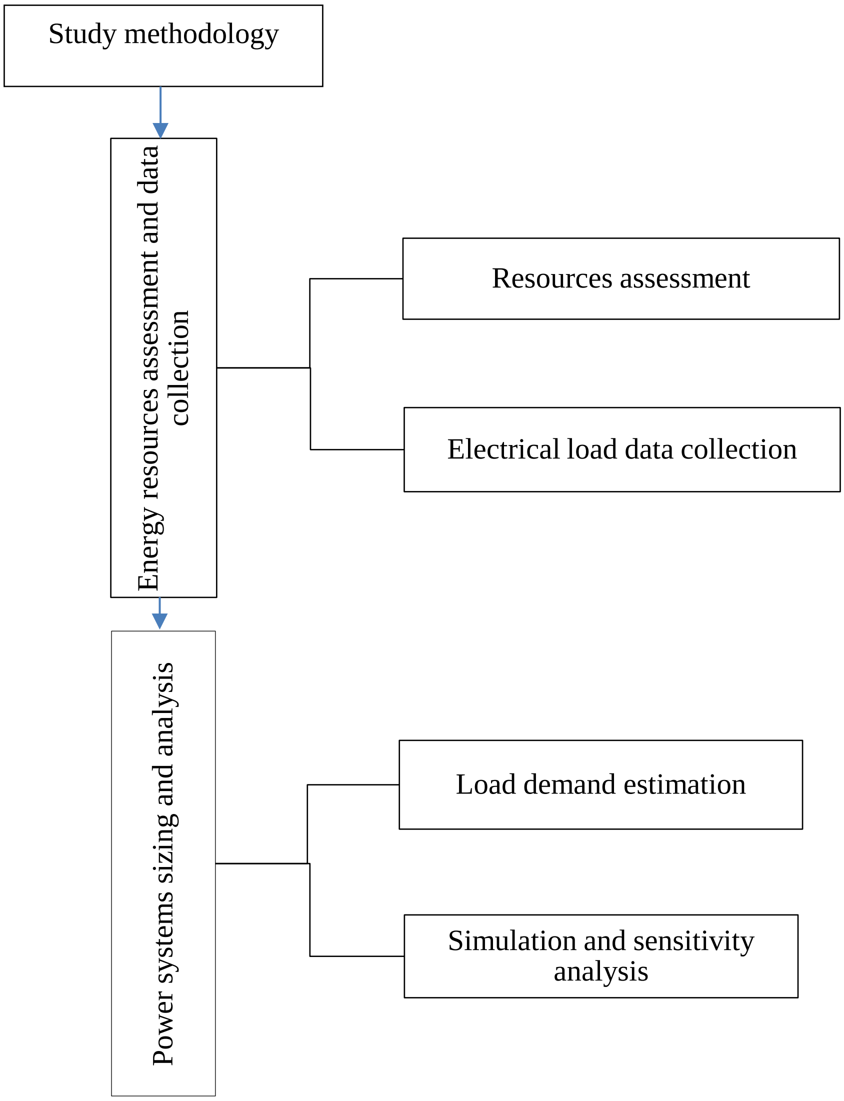


Figure 3. 1: A breakdown of the research methodology

3.2 Description of HOMER software

Homer software is an optimization tool developed in 1993 by the National Renewable Energy aboratory (NREL). It is one of the most widely used tools to develop small-scale renewable and conventional energy systems. Homer is used in both off-grid and grid-connected applications and to date, the software has reported a global use in 193 countries (Kassam, 2010). In its application, the homer software carries out three key functions; simulation, optimization, and sensitivity analysis (Okinawa Entech Co., 2016). Firstly, homer software works with specific input parameters needed to simulate a given number of solutions for a selected input. Inputs in homer include;

- Energy resources (climate resources which can be obtained from NASA or NREL online database),

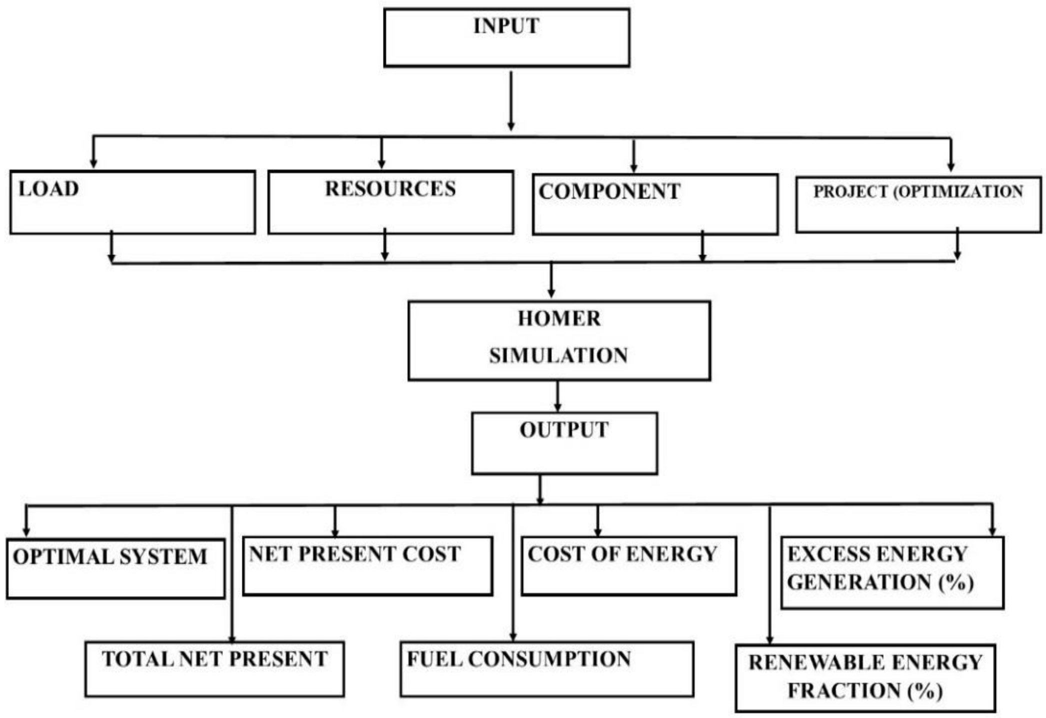
- Electrical load data (arranged in a time series over 24 hours),
- Cost and performance characteristics of the components of the hybrid system (power generators, storage, converter, and controller)
- Specific project economic characteristics (project economics, constraints, and sensitivity)

Climate and energy resources used in homer can be downloaded directly from NASA or NREL online data, these data include data on solar radiation, air temperature, relative humidity, wind speed, , hydropower, biomass, and any other resources as required for a particular project. Electrical load data input in homer can include electrical or thermal load and in cases where a load has no specific time of consumption, it can be input as a deferrable load. The daily electrical load consumption data over a 24hour period in timesteps of 1 hour is used as a load input in homer. A component in homer can be one of; a generator (solar panel, wind turbine, diesel generator, etc.), an energy storage device (electrochemical batteries, pumped-hydro, flywheel, etc.), a power converter (converter, inverters), or a power controller (load following, cycle charging, an alternation or a combination of both). For each component, adoption is provided to describe specific technical and cost characteristics (capital, replacement, operation, and maintenance) of the particular component used. Homer provides a catalog of various components from manufacturers across the globe.

The specific project economic inputs in homer include the nominal discount rate, inflation rate, and the price of diesel fuel (provided a DG is used in the system that is being simulated). Homer calculates the real discount rate and uses this value to calculate the economic performance of a project over a specified lifetime.

Homer runs several simulations from the given inputs and calculates the technical and economic performance of the system over a year (8760h hours) in a user-defined timesteps (typically between 15 to 60 minutes), discounting the economic cost over the project's lifetime to the present value - this process is called optimization. Optimization in homer involves selecting the most technically and economically balanced system from several simulated results and ranking the result based on the NPC as the criteria for the best-case option. The most optimal system is usually the option that meets the electrical loads' requirements providing the least NPC over the project's lifetime. Finally, homer performs sensitivity analyses for a simulated system to determine the effect of an input variable on the calculated output results, for example, assessing the effect of variation in inflation rate on the NPC of a project. Over the years, a wide range of academic studies has been conducted using HOMER software. Some of the available works of literature on techno-economic analysis, specific optimization, management strategies for hybrid power systems are cited as follows (Adaramola et al., 2014; Ali et al., 2021; Bekele & Tadesse, 2012; Chambon et al., 2020; Fadaeenejad et al., 2014; Islam et al., 2021; Jahangir & Cheraghi, 2020; Jumare et al., 2020; Kristiansen et al., 2021; Li et al., 2020; Lozano et al., 2019; Muh, 2017; Nyeche & Diemuodeke, 2020; Suman et al., 2021; Syahputra & Soesanti, 2021; Tomar & Tiwari, 2017; Tsiaras et al., 2020).

Figure 3. 2: Outline of how HOMER works



3.3 Profile of case study area

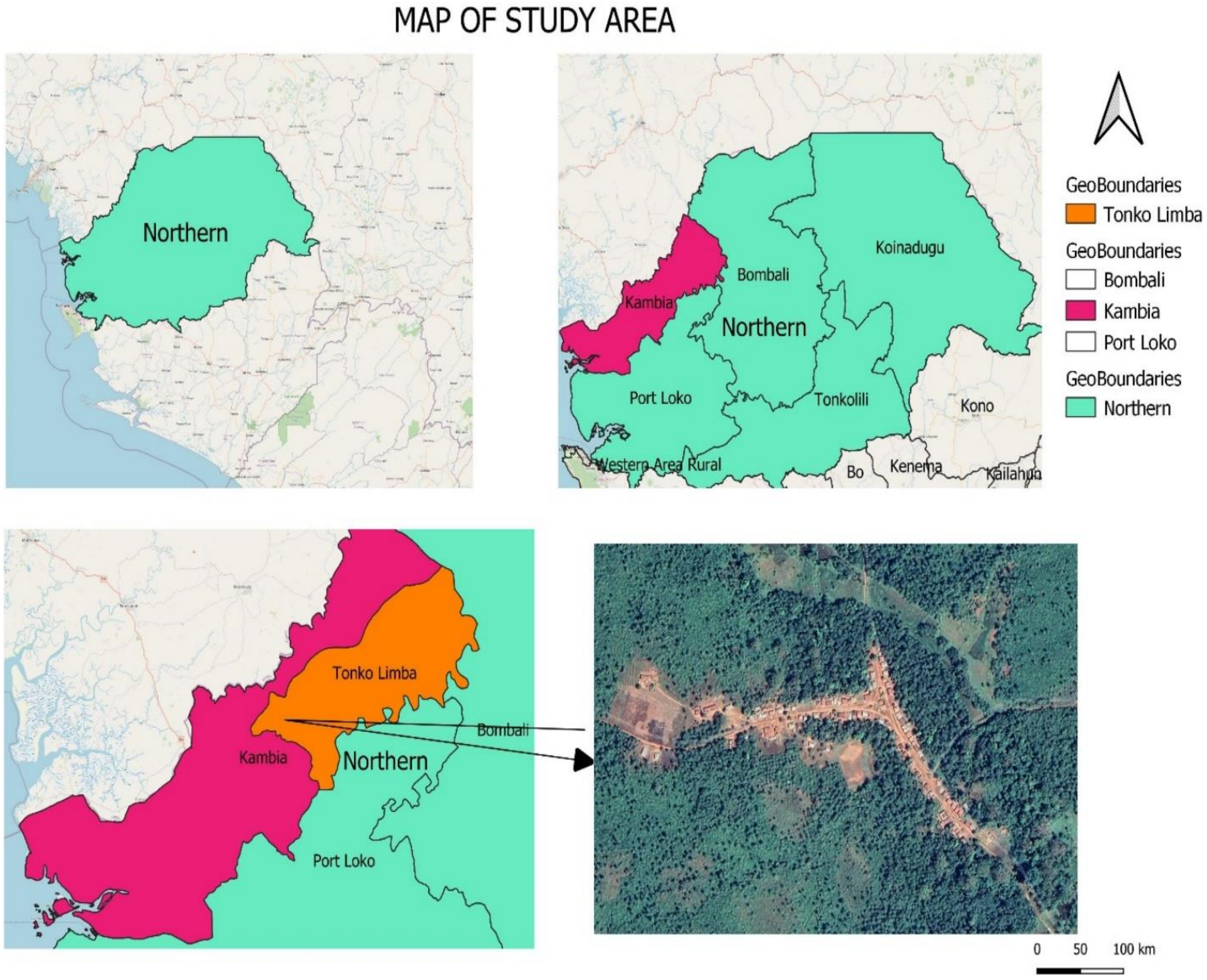


Figure 3. 3: Ariel view of the case study area

Source: Google maps

The case study area, Masunthu village, is situated in the Kambia district, located in the North-western part of Sierra Leone along lines of latitude and longitude of 9.1^0W & -12.6^0N respectively. The village occupies a land area of approximately 110,000m^2 (google earth, 2021) and has a total population of 1004, with a 54% female population. The village's location is approximately 27km away from the district headquarter (administrative) town of Kambia district (google maps). The villagers' primary source of economic livelihood is subsistence farming, where crop production and livestock rearing is a common practice. Local gari production and soap making, as well as cassava trading, are common practices. The community's basic social amenities include; a church, a cinema, clinic, playing field, mosques, schools, small shops, and a water supply system.

The area is located in a typical equatorial climatic region dominated by savannah a specific type of savannah vegetation (swamp lands). The location experiences two annual seasonal weather patterns: The rainy and dry seasons, lasting for six (6) months. The dry season spans from December to April and it is dominated with days of longer sunshine hours with average daily sunshine hours exceeding 4.5 hours a day, while the rainy season, spanning from May to November, is characterized by higher levels of rainfall (between 2000mm to 3000mm) and frequency of cloudy days (Meteorological statistics, 2012). The vegetation type is tropical savannah grassland.

3.2 Electricity situation

The community is an off-grid community and its location is approximately 80.4 kilometers (50miles) from the closest national transmission grid (google earth, 2021), the Bumbuna hydro power transmission line. Primary energy use in the village is to meet the needs of cooking, lighting, and powering of electronic devices (radio and phone charging). According to the United Nations multi-tier framework for energy access, electricity access for the village is categorized under the "Tier-1" framework, where pico-solar lanterns and torch-lights with small photovoltaic cells and batteries are used to provide night-time lighting for households. Charging of phones is accessed through a local telecentre for $0.1USD per charge cycle per phone. Electricity generated from a 250Wp solar module supplies power to an existing underground water-pumping system used for community water supply purposes.

3.3 Energy resources Assessment

Energy resource was assessed using meteorological data from National Association for Space Activities (NASA).

3.3.1 Solar radiation (Irradiance)

Solar irradiance represents the intensity of the sun's rays striking a unit area on the earth's surface per unit of time, while the clearness index determines what fraction of extra-terrestrial radiation reaches the earth's surface passing through the atmosphere (NASA, 2021). The average global solar radiation and the number of sunshine hours are the two most important factors considered in determining the solar energy potential of a particular location (Şen, 2018).

Average daily solar radiation data obtained for NASA open-source database varied between 4-6Wh/m^2/day. The higher levels of solar irradiance are experienced during the dry season, and the month of March and July records the highest and lowest levels of annual solar radiations respectively, with an estimated average daily sunshine period expected to be of the national average of 5.5 hours, which makes solar energy a viable source of power generation for the site.

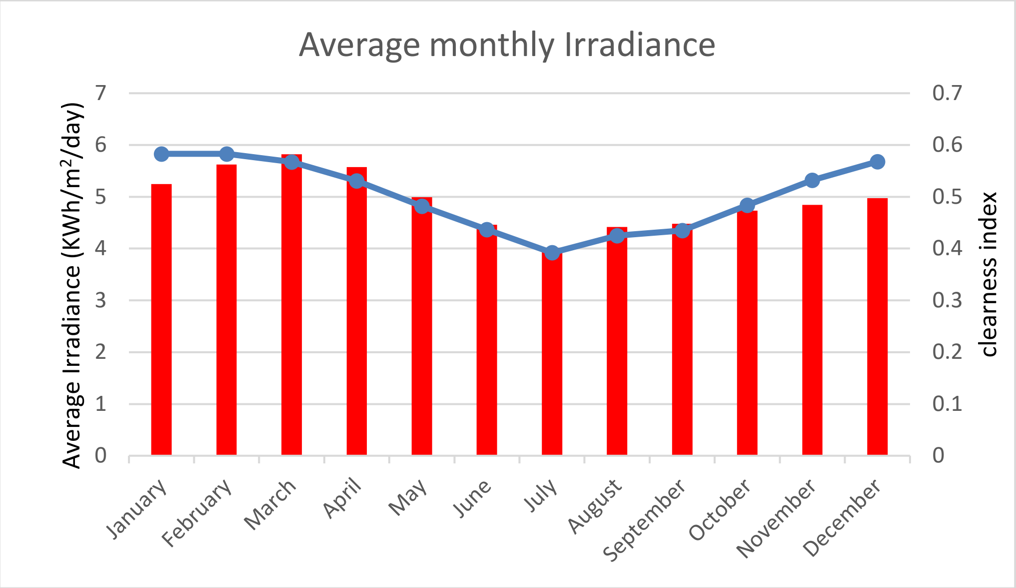


Figure 3. 4: Chart showing average monthly global radiation and clearness index profile of case study area

Source: NASA, 2021.

3.3.2 Temperature

According to NASA, the average annual temperature for the location ranges from 23.43^{0}C to 27.57^{0}C·, with average monthly temperatures higher during periods of the dry season than those in the rainy season. The month of March and August, respectively record the highest and lowest average monthly temperatures (appendix 1).

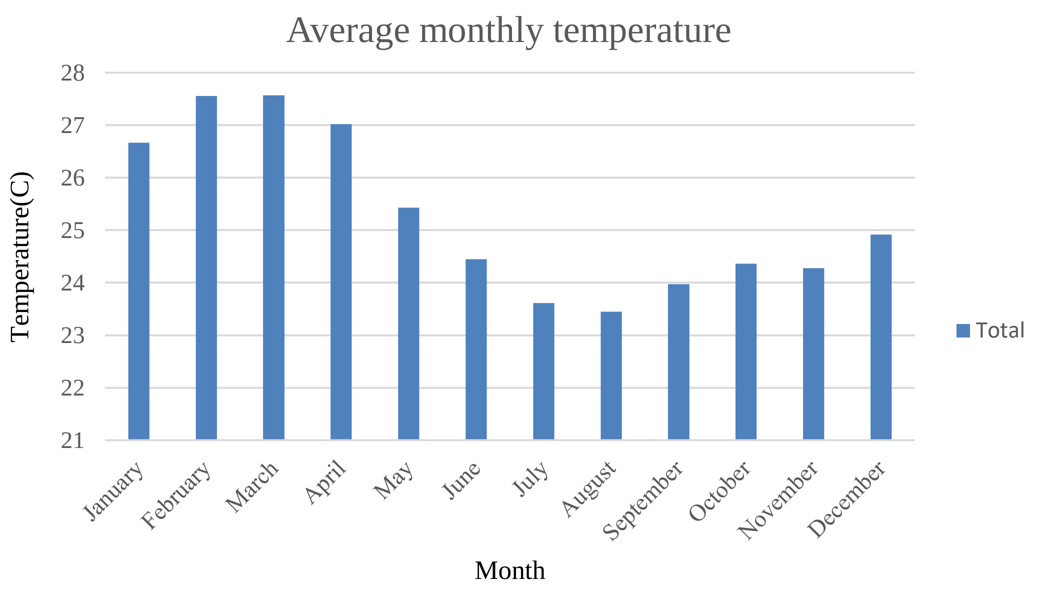


Figure 3. 5: Chart showing the average monthly temperature profile of the study location

3.3.3 Wind speed

The elevation of the site is between approximately 90m above sea level (Google earth,2021), the average wind speed measured at 10m above ground level for the location according to NASA, 2021, ranges between 3m/s to 7m/s on a monthly basis. Such values indicates the low feasibility of wind power generation on the site.

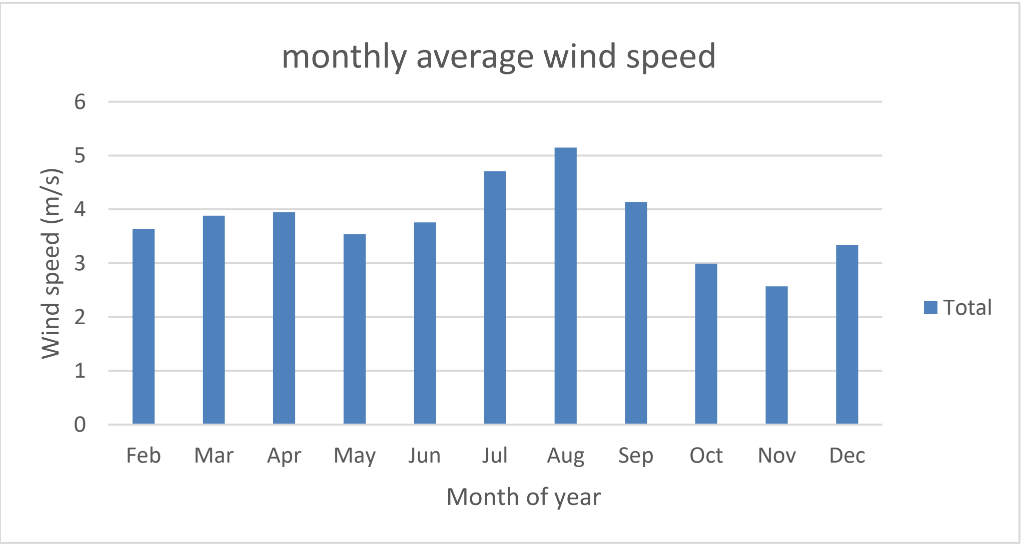


Figure 3. 6: Chart showing the average monthly wind speed of the study location

3.4 Electrical demand Load estimation

3.4.1 Load category

The electrical load demand for the village were divided into three categories, namely; community loads, commercial loads, and household loads. The load statistics for the different categories is summarized in table 3 – 1 given below.

Category	Load Type	Number
1. Community loads	Church	1
	Health center	1
	Mosque	1
	School	2
	Street Lighting	15
2. Commercial loads	Cinema	1
	Shop	1
	Training center	1
3. Household loads	Household	91

Table 3. 1: A table showing statistics of the different categories of consumers

3.4.2 Electrical loads requirement

The expected energy consumption for the location was estimated using standard assumptions related to the type of load consumed, the load's electrical power requirements, and the load's period of use based on assessment from a survey. The following assumptions were made in this regard.

3.4.2.1 Assumptions for load estimation

- Power ratings of equipment are assumed to be of standard average sizes, to cater for the probability using non-energy saving appliances.
- All electrical loads considered are Alternating Current (AC) loads
- Load types are divided into two seasonal loads: (1) Summer loads and (2) Winter loads (representing load consumption in the dry and rainy seasons respectively)
- For identical units more than one in number; household, school, and shop, a standard electrical load demand assumptions are made.
  - ➢ A typical household consist of between 2 to 4 bedroom and family sizes ranges from 5 to 10 members. A standard household is assumed to consist of the following electrical loads: four (4) light bulbs, a fan, a Television (TV), a DVD player, a radio, and 3 phones.
  - ➢ The shop consists of the following loads: two (2) light bulbs, a Fridge, TV, radio, and a phone.

- Two schools exist in the community, each consisting of 3 classrooms, and two management offices.

- Periods of daily load consumption are estimated taking into account the living patterns of the inhabitants.

3.4.2.2 Electrical load requirements

The standard daily load requirements are summarized in the table given below. The daily energy consumption was formulated using an excel spreadsheet.

Electrical energy is calculated as follows: Electrical energy = electrical power × time.

Electrical loads characteristics					
	Load type	**Amount**	**Power**	**Hours per day**	**Daily energy consumption(kWh/day)**
1. Church	Light	3	10	10	1.21
	Fan	65	65	9	
2. Health Centre	Light	12	10	10	20.50
	Fan	5	65	8	
	Computer	1	120	9	
	Television	1	120	8	
	Phone	5	5	9	
	Fridge	2	2	23	
3. Mosque	Light	3	10	10	1.18
	Fan	2	65	7	
4. School (2)	Light	8	10	10	6.60
	Fan	8	65	7	
	Fridge	1	100	6	
	TV	1	120	5	
	DVD	1	30	5	
	Phone	3	5	15	
	PC	1	120	8	
5. Street Lighting	Light	15	40	10	6.6
6. Shop (3)	light	2	10	10	5.31
	Fridge	1	120	7	
	Fan	1	65	6	
	Radio	1	30	15	
	Phone	1	5	8	
7. Cinema	Light	5	10	10	4.18
	Fan	3	65	8	
	Television	3	120	5	
	DVD	3	30	5	
8. Tailoring center	Light	4	10	19	2.83
	Fan	2	45	7	
	Phone	4	5	7	
	Television	1	120	8	
9. household	Light	4	10	10	
	Fan	1	45	8	
	Television	1	120	5	

	DVD player	1	30	5	
	Phone	2	5	18	
	Radio	1	30	15	
	Fridge	1	100	12	123.21
Total expected daily energy demand					**178.355**

Table 3. 2: breakdown of electrical load requirements

3.5 Simulation input parameters

3.5.1 Electrical load profile

Shown in the chart above is the daily load profile for Masunthu village obtained from the load estimation. The expected consumption pattern of the village varies at different times of the day. During the early hours of the morning between 00:00 – 04:00 hours, the electricity demand is expected to be low as most villagers register their sleeping time during those hours. There is an expected rise in electrical power demand between 05:00 am to 06:00 am, mainly due to the Muslim villagers rising to attend their daily religious prayers. In the, household demand is expected to decrease as villagers attend their daily occupations. Demand from the community and commercial loads is expected to increase during this period. The peak demand is estimated to occur in the evening hours between 7 pm to 10 pm due to an increase in household electrical load demand. The expected peak power demand for the village was estimated to be 18kWh. Based on the load estimation, household loads account for 69% of the total load, commercial and community, 7% and 24% respectively. Electricity consumption is estimated to vary on a seasonal basis, with electricity demand in summer estimated to be greater than in the winter due to the use of certain electrical appliances.

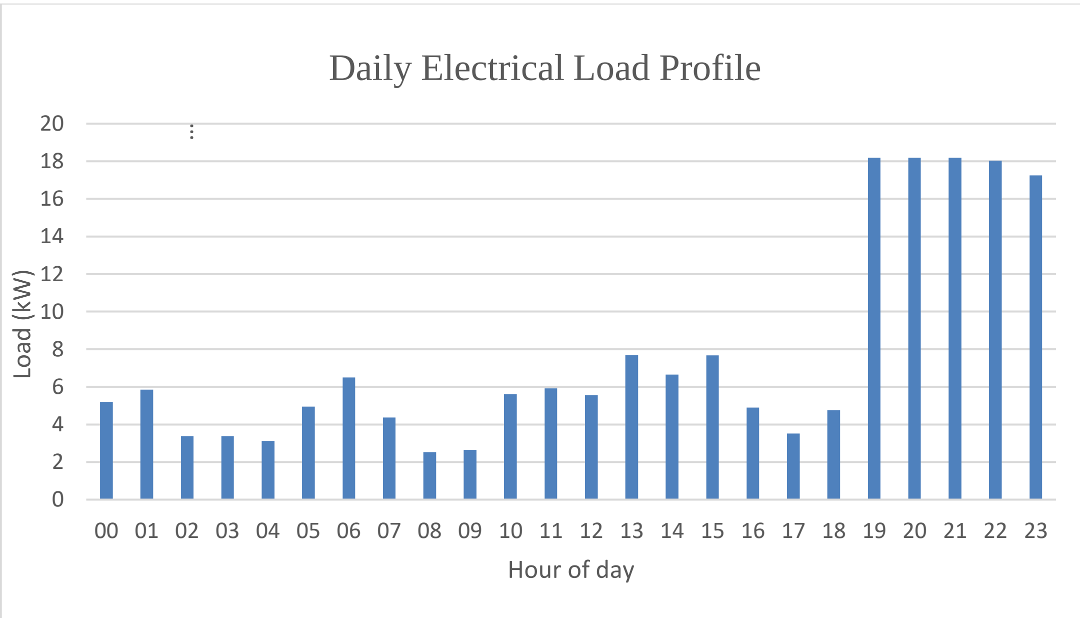


Figure 3. 7: Figure showing the daily electrical load profile of the village

3.5.2 Technical input

3.5.2.1 Solar photovoltaic panel

A SPV module generates electrical power to supply daytime electrical loads and charges a battery bank where required. Normally, PV panels are sized to match the total daily load requirement, considering compensation factors for technical and non technical losses . In this study, HOMER will simulate the capacity of the PV panel required to provide a reliable electricity supply to the village. For such, some specific technical and economic inputs are required by HOMER for the selected panel.

For this study, the selected panel was a 250W monocrystalline silicon solar module with characteristics summarized in Table 3-3. Typical lifetime for a PV module is between 20 to 25 years, beyond which expected power output is significantly lower (NREL, 2019), in this case, a lifetime of 25-years was assumed for a solar module, thereby requiring no replacement cost during a 25-year project lifetime. The solar panel has a unit price of $200. The operation and maintenance cost per kilowatts is assumed to be $10/kW. A summary of the characteristic of the PV panel used in the simulation is given below.

PV panel specifications	
Manufacturer	Jinko Solar, China.
Nameplate	Solar250JKM250P-60B
Type (kW)	Monocrystalline silicon
Rated Power	250
Rated Voltage (V)	37.7
Rated current (A)	8.9
Temperature of the solar cell (^{0}C)	46.1
Temperature coefficient(^{0}C)	-0.43200
Derating factor (%)	85
Efficiency (%)	13
Lifetime (years)	25
Capital cost ($) per kW	800
O & M cost ($/year) per kW	10

Table 3. 3: Table of technical characteristics and economic cost of the solar PV panel.

3.5.2.2 Converter

A system converter device is used in a hybrid system to convert between two voltage forms. A specific kind of converter can be used depending on the voltage transformation type required in the system. Voltage conversion can be from one level of DC to a higher or lower level of DC, or from DC to AC (or the reverse), the converter can be designed to operate in a one-directional or bi-directional interface. Converters are usually sized to meet the peak demand load requirements, normally taking into account a factor of safety of 30%, to cater for a future increase in the size of a system (Leonics, 2013). For this study, HOMER will simulate the exact size of the inverter required to efficiently handle the voltage conversion process in the system during the assumed project lifetime of 25 years, as well as estimates economic cost associated with its operation. The estimated lifetime of the converter was 15 years, and the cost of replacement of the converter is assumed to be the same as its capital cost. The inverter output is calculated in HOMER using the following equation in appendix 4. A summary of the conveter's specifications is given in Table 3.4 below.

Converter specifications	
Item	**description**
Name	System converter
Type	Bi-directional
Rated Voltage	480
Efficiency	97.5
Life-time	15
Capital Cost ($/kW)	350

Table 3. 4: Table showing the technical characteristics and economic cost of the power converter.

3.5.2.3 Charge controller

A controller in HOMER serves the purpose of charging the batteries and determining power generation sequence and strategies. In homer, a controller can use different types of dispatch strategies to regulate/ rotate power production among the selected power sources. This study used two different dispatch strategies: Homer Cycle Charging (HCC) and Load Following (LF) strategy, based on the generation sources selected (Lambert et al., 2006). In CC strategy is used in a case where there is a little renewable fraction of renewable power production, the generator operates at full power when needed. It charges a bank battery with an excess power produced. LF strategy is used in a case where a large amount of RE is generated and this strategy, operates a generator to produce power that meets just the load demand. The configuration with diesel only does not require a controller. A configuration with SPV/DG uses the LF strategy. The configuration with SPV/DG/BS employs the HCC strategy. Controller inputs are summarized in the table below. The input specifications for the controller have summarized in the table below.

Controller specifications	
Item	**description**
Type	Homer cycle charging /Load following
Lifetime (yr.)	25
Capital cost ($)	3000
Setpoint state of charge (%)	80

Table 3. 5: Table showing the technical characteristics and economic cost of the controller

3.5.2.4 Battery storage

Battery storage stores electrical energy and can serve as a secondary or a backup power supply, where needed. For this study, the selected battery was a generic lead-acid battery type with a charge capacity of 411Ah, a nominal voltage of 12V. Battery lifetime normally depends on the charge and discharge capacity(Shah, 2015). A minimum state of charge must be kept for batteries in a PV system to ensure better battery performance and prolong the lifetime of use of the battery. The battery depth of discharge was 70% with an expected lifetime of six (6) years. Battery replacement is required thrice during the project's lifetime, with the cost of replacement the same as the capital cost.

Homer simulates and determines the number of units of this particular kind of battery that matches the system requirement and calculates the related technical and economic output variables over the battery's lifetime. The specifications of the battery used in the simulation are summarized in the table below.

Battery characteristics	
Item	**description**
Manufacturer	EnerSys PowerSafe SBS XC 190F
Type	Lead - Acid
Battery capacity (Ah)	2.51
Rated Voltage (V)	12
Throughput (kWh)	2589
State of charge (initial)	100
State of charge (Minimum)	30
Efficiency (%)	97
String	4
Lifetime (years)	6
Unit cost ($)	250

Table 3. 6: Table showing the technical characteristics and economic cost of the BS.

3.5.2.5 Diesel generator

Diesel generators provide a backup power supply when used in a PV system. In this study, the homer automatically sizes a generator with a capacity that matches the load requirements of the village. the initial cost of the generator is assumed to be $850, and the operational and maintenance cost is associated with the diesel generator. The generator's fuel consumption is diesel fuel has a carbon content of 88% and produces a GHG emission of 16g/L of fuel consumed. There is operational and maintenance cost associated with this specific generator model.

Diesel Generator specifications	
Name	Diesel generator
Fuel type	Diesel
Minimum load ratio (%)	25
Initial capital ($/kW)	850
Replacement cost ($)	850
Operation & maintenance	$0.02/hr
cost of diesel fuel ($)	1
Lifetime (hrs)	20,000

Table 3. 7: Table showing the technical characteristics and economic cost of the DG

3.5.3 Specific economic Inputs

The specific economic inputs into homer include (i) discount rate and (ii) inflation rate. In July 2021, the national inflation rate in Sierra Leone was reported to be 10.2% and the nominal discount rate on financial lending provided by the Central **Bank of Sierra Leone**, 24.37% (Statistics Sierra Leone, 2021)

3.5.4 Sensitivity input variables

For this study, inflation rate, discount rate, and diesel fuel prices were chosen as the sensitivity variables for which sensitivity analysis is to be performed. Sensitivity analysis is commonly called “what if?” analysis. It is a test made to determine the effect of an input variable on an output variable. For this study, the output variables to be observed include the NPV, capital cost, LCOE, O&M, IRR, ROI, and payback period.

Table of Sensitivity input variables		
Variable	**Value**	**Sensitivity input values**
Interest rate/ discount rate (%)	24	30,15,4
Inflation rate (%)	10.2	13,6,3
Diesel fuel price ($)	1	0.95, 1.25

Table 3. 8: Table showing inputs variables for sensitivity analysis

Chapter four - Results analysis

4.1 Background

This chapter discusses the important findings from the study. It describes the case study area's load profile and discusses the key simulation results from the different configurations of systems used. The chapter further discusses the proposed (most feasible) system, including results discussion from the sensitivity analysis.

4.2 Simulation scenarios

The four different scenarios for which simulations were done are the following

Scenario	Configuration
Scenario A (SA)	Diesel generator only
Scenario B (SB)	PV + DG
Scenario C (SC)	PV + BS
Scenario D (SD)	PV + DG + Battery

Table 4. 1: Table showing configuration of the four scenarios

4.2.1 Scenario A (SA) – DG only

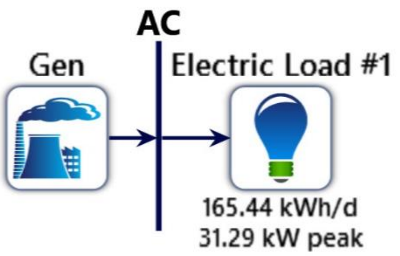


Figure 4. 1: Schematic of SA

In this configuration, a diesel generator was selected to be the only source of power generation. The key economic, technical, and emission outputs are discussed in the following paragraphs.

From the simulation, the size of the diesel generator proposed by homer to meet the expected electricty demand for the village was 35kW. The total NPC obtained for the system was \$436,336. The initial cost of the diesel generator, based on a price of \$850 per kW was calculated as \$29,750. With an estimated operational lifetime of 20,000 hours, with the generator expected to provide a continuous power supply, the total cost of replacement of generators over the project's lifetime will amount to a sum of $89,726. The combined operation and maintenance cost required during the operational lifetime of the generator was calculated to be $23,201. The generator is estimated to operate for 24 hours, and the cost of fuel over the project lifetime is $293,736. A salvage value of -$77 was obtained at the end of the 25-years project lifetime. An LCOE of $0.9549 was obtained for this system.

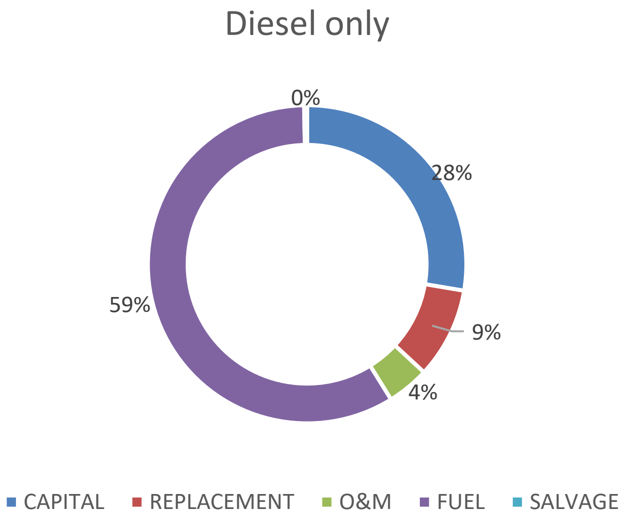


Figure 4. 2: chart showing economic cost (NPV) breakdown of SB

Using diesel generator only, 91,869kWh electrical power is estimated to be generated each year, in the process of supplying an AC load of $60,386kWh. Therefore, 31,483kWh of energy is produced as excess electricity.

For this system, the DG is expected to consume 38,816L of diesel fuel per year, producing 101,606kg of GHG emissions in the process.

4.2.2 Scenario B (SB) – SPV + diesel generator

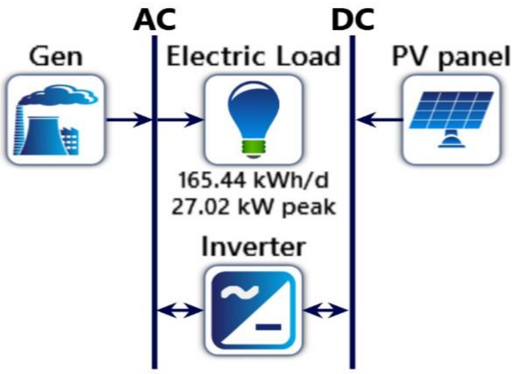


Figure 4. 3: Schematic of SB

In SB, a hybrid system consisting of two power generators; SPV and diesel generator, a power converter and a charge controller was simulated and a summary and key details of the results obtained are as discussed in the following pragraphs.

Form the simulation, the hybrid PV/DG system obtained, required to provide a reliable supply of electricity for the village is specified as follows; a 56.2kW of PV array, 30kW of diesel generator, 17.7kW inverter capacity. The controller type used for this is homer load following.

From the simulation, the NPC obtained for this system $297,470. From this, the capital cost, which includes the initial cost of acquiring the various components of the hybrid system was obtained to be $77,776, representing 23% of the total project cost. In SB, a 20,000 hours generator lifetime was assumed and due to the projected frequency of utilization, the simulation result showed that the generator has to be replaced after every six (6) years during the project's lifetime. The converter has a lifetime of 15 years, requiring replacement once during the project's lifetime. The total cost of replacement of components in SB was calculated as $60,814, representing 18% of the project's total cost. Operation and maintenance cost relates to the cost of running the diesel generator (cost of fuel plus the cost of continuous maintenance) and in this scenario, O&M cost is $12,079, accounting for 4% NPC. Fuel cost includes the cost of buying diesel fuel that is used by the DG. The generator runtime obtained for this system is 5,317 hrs/yr., with a total cost of $164,437, which represents 59% of the NPC over the project lifetime. A summary of the cost breakdown is given in the chart below.

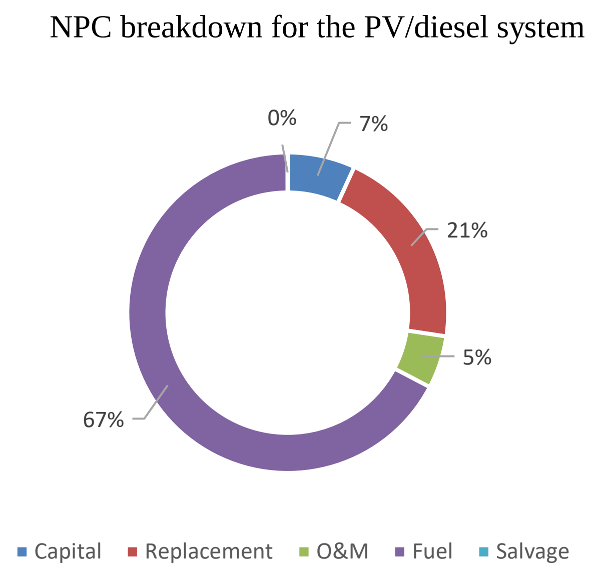


Figure 4. 4: Chart showing economic cost (NPV) breakdown of SB

The annual total energy production from this scenario is 137,089kWh/yr, whereas the total load consumption is 60,386kWh/yr, thereby indicating an excess electricity production of 75,877kWh/yr, i.e., 55.3% of the total electricity generated. The PV array produces about 82,787kWh/yr, representing 60.4% of the total production, while the DG produces the remaining 39.6% of the annual energy generated.

The annual fuel consumption is 21,730L, with 56,880kg of GHG emissions produced per year.

Scenario C – SPV + BS

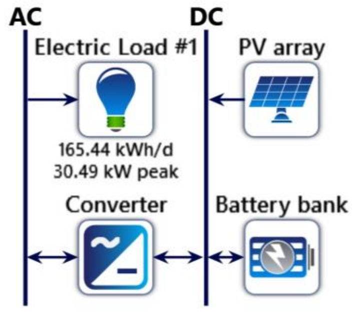


Figure 4. 5 : Schematic of SC

In SC, a hybrid model consisting of a SPV system as the only source of power generator, and a BS system as an energy storage device was simulated and the results are discussed as follows. From the simulation the architecture of the system comprise of a 77.3kW SPV array, 108 battery storage cells, and inverter of 30.2 kW, and a cycle charging controller type.

From the simulation, NPC obtained for the model was \$153,141, with a capital cost of \$112,131, operation and maintenance cost of \$6,937, and an LCOE of \$0.337/kWh, over the projected lifetime of 25 years. In this scenario, a cost of \$6,937.24 is associated with the operation and maintenance cost is associated with the cost of maineneance of the SPV and BS. The BS and the coverter have a cumulative replacement cost of \$36,088.25 over the lifetime of the project.

A breakdown of the percentage contributions of the individual economic costs to the total NPC of the model is as given in the chart below.

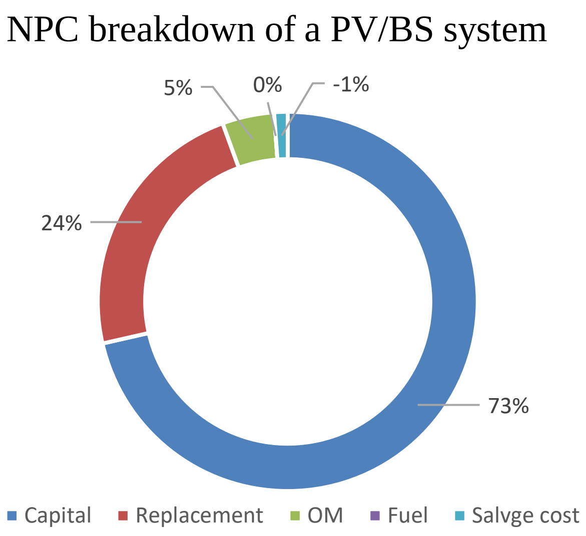


Figure 4. 6 : Chart showing breakdown of NPC for SC.

The expected annual energy production from this model was obtained to be 112,728kWh. With a 60,326kWh of annnual electrical load to be served on an annual basis, an excess of 47,952kWh of electricity is expected to be produced each year over the projected lifetime.

The cumulative storage capacity of the battery bank was estimated to be 533kWh. The expected annual enery input and output from the battery storage were obtained to be 45,888kWh and $44,614kWh respectively. The expected annual throughput of the battery storage was 45,299, and the battery bank has a cumulative power losses of 1,378kWh.

The 100% renewable system does not consume fuel in electricity production and has a zero accciated carbon emission over its operational lifetime.

4.1.3 Scenario D (SD) – SPV + DG + BS

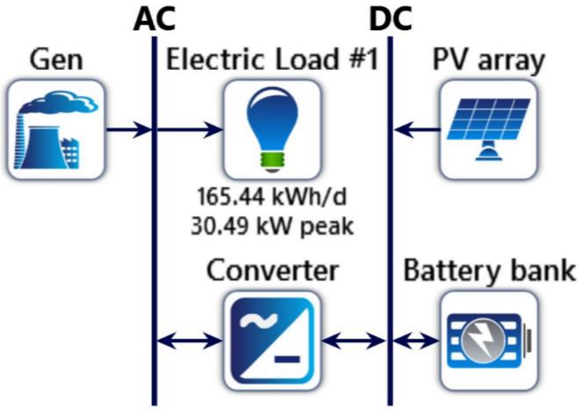


Figure 4. 7: Schematic of SD

In this scenario, a hybrid system consisting of; two (2) generation sources;, a PV array and a diesel generator, a storage device (battery bank), an inverter, and a controller.

The technical specifications of the hybrid system that meets the electrical load demands for the village under this configuration was obtained from the simulation and consists of: 45kW SPV array, 30kW DG, 68 BS cells, 31kW inverter, and a cycle-charge controller type.

Based on the result, the PV array is expected to generate power to meet day-time electrical loads, while the battery bank operates as a secondary power source. The diesel generator in this case provides a source of back-up power supply to meet the peak-load demand. The NPC obtained for this hybrid system was \$153,488, with an initial capital cost of \$97, 482. The associated replacement cost of \$85,229.91 over the entire project lifetime includes the cost of replacing the DG, power converter, and charge controller.

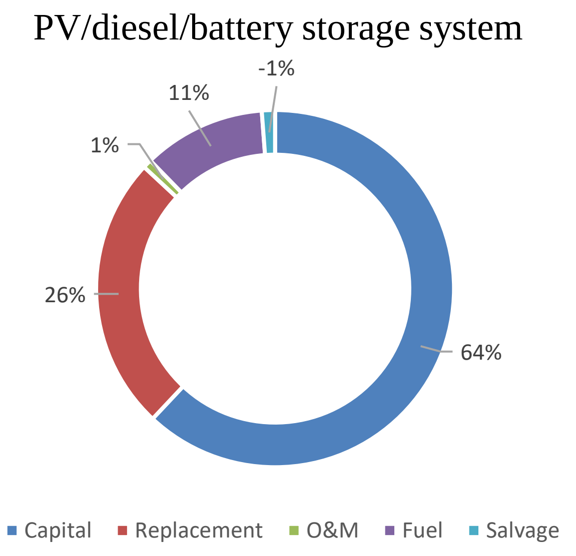


Figure 4. 8: Chart showing breakdown of NPC of SD

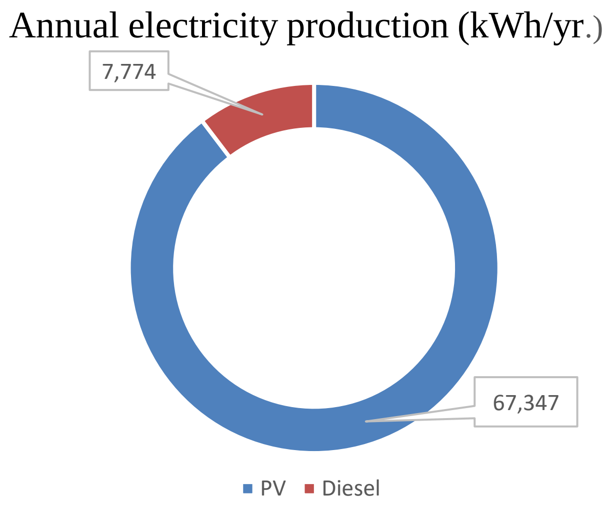


Figure 4. 9: Chart showing annual electricity production of SB

4.2 Comparative analysis of the four scenarios

The table gives a summary of some of the important outputs based on optimization results for the various scenarios.

	SCENARIO TYPE			
	Scenario A (SA)	Scenario B(SB)	Scenario C (SC)	Scenario D (SD)
Architecture	Diesel only	PV + Diesel	PV + Battery	PV + Diesel + Battery
NPC ($)	496,336.00	309,541.60	153,349.55	152,491.31
CC ($)	29,750.00	78,147.92	110,131.43	97,482.24
LCOE ($)	0.955	0.677	0.337	0.336
O&M ($)	23,201.61	24,141.48	6,937.24	1,266.78
Total electricity production (kWh/yr.)	91,869	137,090	112,728	75,121
Excess electricity produced (kWh/yr.)	31,483	75,877	47,952	10,165
Renewable fraction	0	0.10	1	0.87
Fuel consumption (L)	38,816	21,730	0	2,302
Greenhouse gas emission (kg/yr)	103,103	57,733	0	6,117

Table 4. 2: Table showing specific techno-economic output parameters of the four scenarios

From the optimization, scenario A, which generates power using a 30kW DG only, gives the highest NPC and highest capital cost amongst the four options considered for this study. The NPC and CC of SA are $496,336 and $29,750 respectively. SB possesses the second highest NPC with an amount of $309,541.60, and a CC of $78,147.92. SC possesses the second lowest NPC and the highest CC with amounts of $153,349.55 and $110,131.43 respectively. SD possesses the least NPC and the second highest CC with amounts of $152,491 and $97, 482 respectively. The high initial CC of SD relative to the other scenarios was derived from the inclusion of a battery storage component, which covers about 20% of the initial CC in this scenario.

The running cost which includes; total O&M cost, fuel cost, plus the component replacement cost, is highest when generating power using SA, as depicted in the table above. Similarly, SB also has a higher running cost due to a high frequency of use of the DG. The running cost of SC of $6,937.24, is relative lower when compared to SA and SB due to the non-comsumption of diesel fuel and the minimal maintenance required for the SPV and BS systems. In SD, the DG is used as a backup power supply and requires a relatively lesser runtime of 60hrs/yr when compared to the SA and SB, as a result, the sum of fuel expenditure of $6,105, over a 25 year period is lowest relative to the other two scenarios.

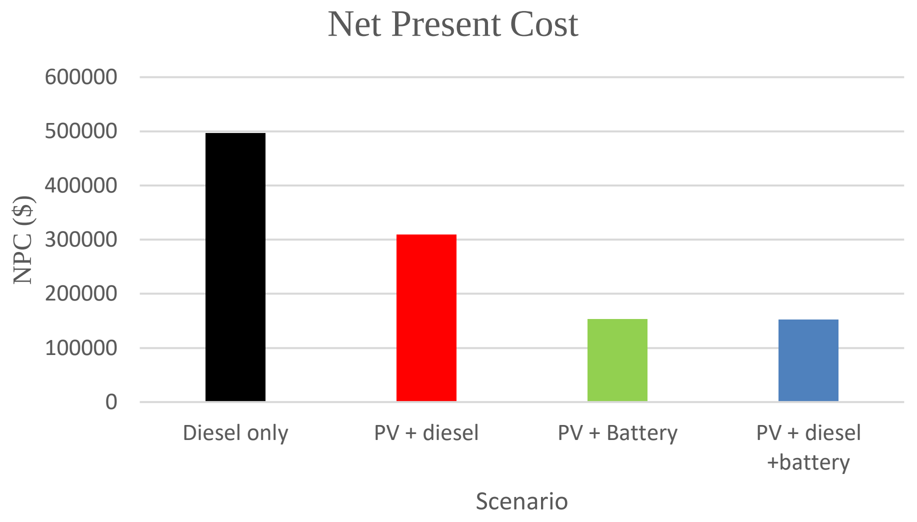


Figure 4. 10: Chart comparing NPC of the four scenarios.

The LCOE of the four scenarios as obtained from the optimization results, SA, SB, SC and SD in their respective orders are; $0.955/kWh, $0.677/kWh, $0.337/kWh, and $0.336/kWh, indicating SD as the system with the lowest LCOE.

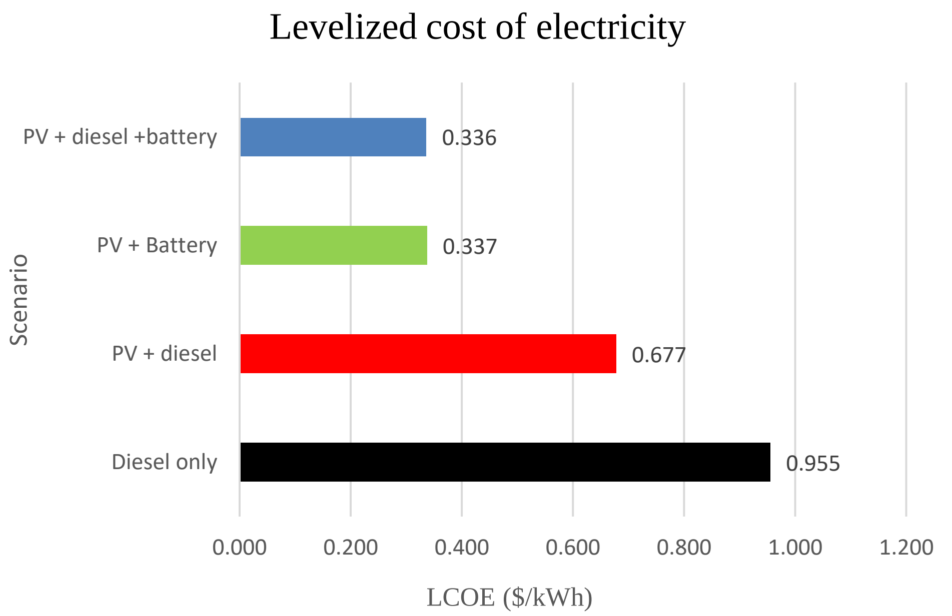


Figure 4. 11: Chart comparing LCOE of the four scenarios.

The total load to be served on an annual basis, based on the estimated village load demand is 65,000kWh/yr. The total electricity production in SA is 91,869kWh/yr, from which 31,483kWh/yr., i.e., 34% is accounted for as excess electricity produced. SB produces cumulative amount of electricity of 137,090kWh/yr, with an excess production of 75,877kWh/yr. SC produces 112,728kWh/yr. of electricity, with an excess production of 47,238kWh/yr. SD produces of 75,121kWh/yr., with an excess electricity of 10,165kWh/yr, depicting SD as the system with that generates the least amount of electricity as well as accounting for the least excess energy produced.

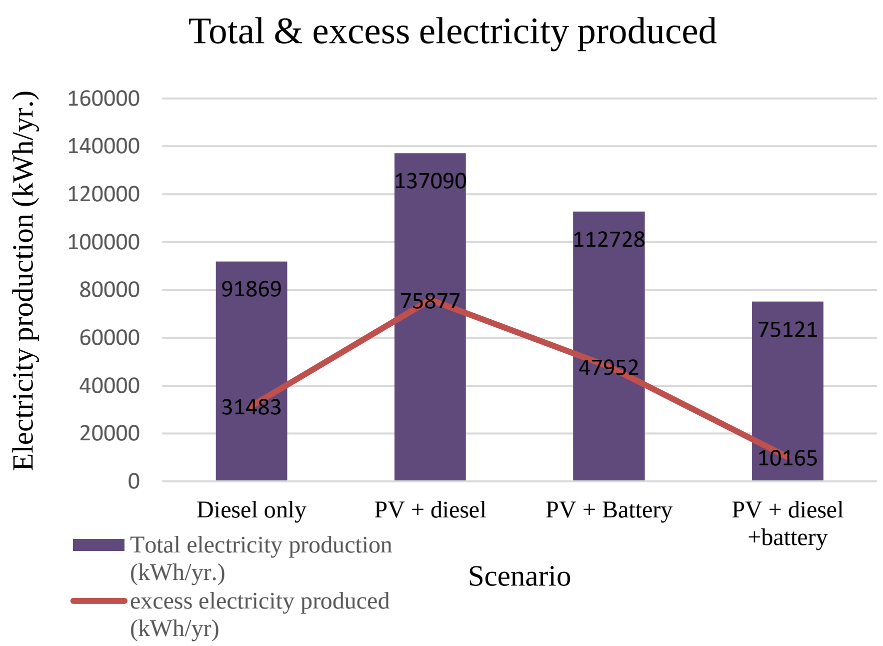


Figure 4. 12: Chart comparing electricity production of the four scenarios.

Amongst the four scenarios, it was observed that the quantity of fuel consumed is proportional to the amount of GHG emissions. SC has no associated fuel consumption and therefore is expected to produce no emission over the projected lifetime. SA consumes 38,816L of diesel fuel each year, producing a cumulative amount of 103,129kg of GHG. Diesel fuel consumption for SB and SD is 21,730L and 2,302L, with GHG emissions of 57,733kg and 6,117kg, respectively. On a relative scale, the annual emissions savings of SD is 97,011kg when compared to SA and 51616kg when compared to SB.

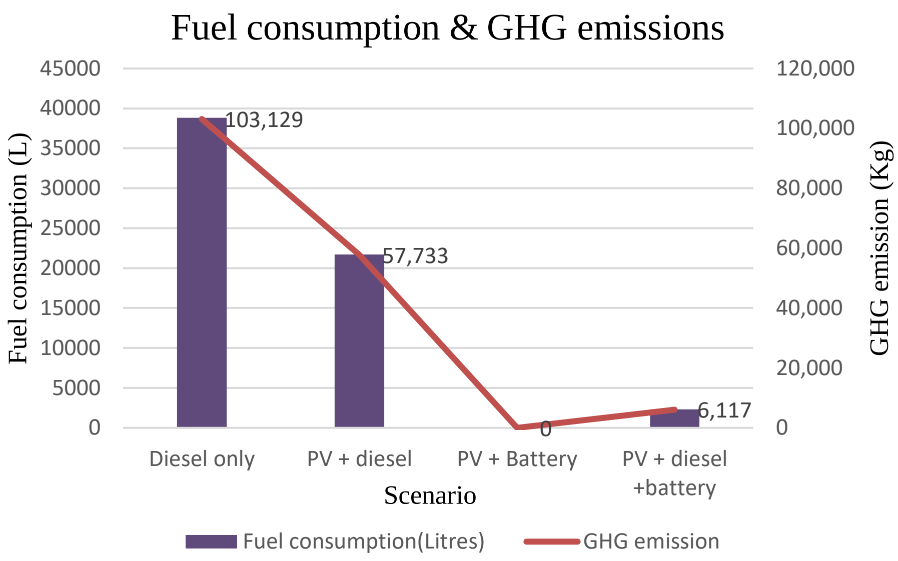


Figure 4. 13: Chart comparing fuel consumption and emissions of the four scenarios.

4.3 The proposed system

Optimization was performed using HOMER software to assess the techno-economic feasibility of hybrid power generation system to provide reliable electricity supply for the village. Based on the methodology of a comparative analysis amongst four different scenarios considered in this study, the best-case scenario for electricity supply for the village was determined, taking into account specific economic and technical output variables. Amongst the four different scenarios considered in this study, the proposed system is scenario D which generates electricity using an SPV array as a primary source of electricity generation, a battery bank as an energy storage device, and a DG as a backup power supply. The proposed system has the following characteristics relative to the others:

- The system with the lowest NPC and LCOE.
- Technically maximizes the use of renewable energy, emits the least amount of GHG, and fully meets the electrical load requirements of the village with minimum wastage of electricity.

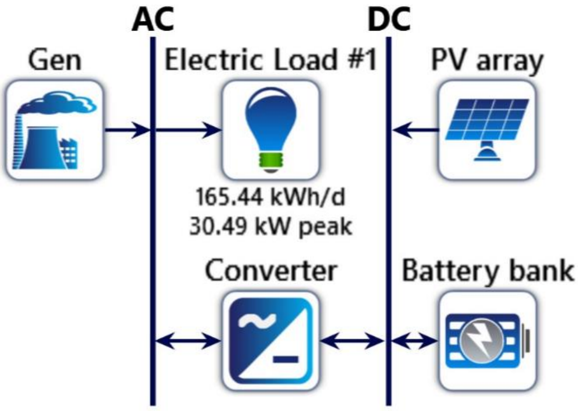


Figure 4. 14: Schematic layout of the proposed system

4.3.1 System overview

The proposed hybrid PV system for the village electricity must supply a daily load of 165kWh, with a peak load of 30 kW. Electrical power from the system is generated using SPV and DG. The system has a renewable energy fraction of 88%, and significantly minimizes GHG emissions relative to a generation system consisting of a large proportion of diesel generators. Table 4 - 3 below summarizes the important components of the architecture of the proposed hybrid system.

Component	Specification
PV array	45.5kW
Battery	68 units
Diesel generator	31kW
Converter	28kW

Table 4. 3: Table showing the architecture of the proposed system

The proposed system is expected to produce 75,295kWh of electricity on a yearly basis. The SPV array in this model produces 68,002kWh/yr whilst the DG produces 7,257kWh/yr. Electricity output from the PV array is highest in March, whilst the lowest monthly output is expected to occur in June. Output from the DG is expected to be low during the dry season due to limited usem and increases during the rainy season due to increasing runtime as the PV array is expected to produce low power output during this period. The figure below gives a graphical representation of the power generated by the hybrid system.

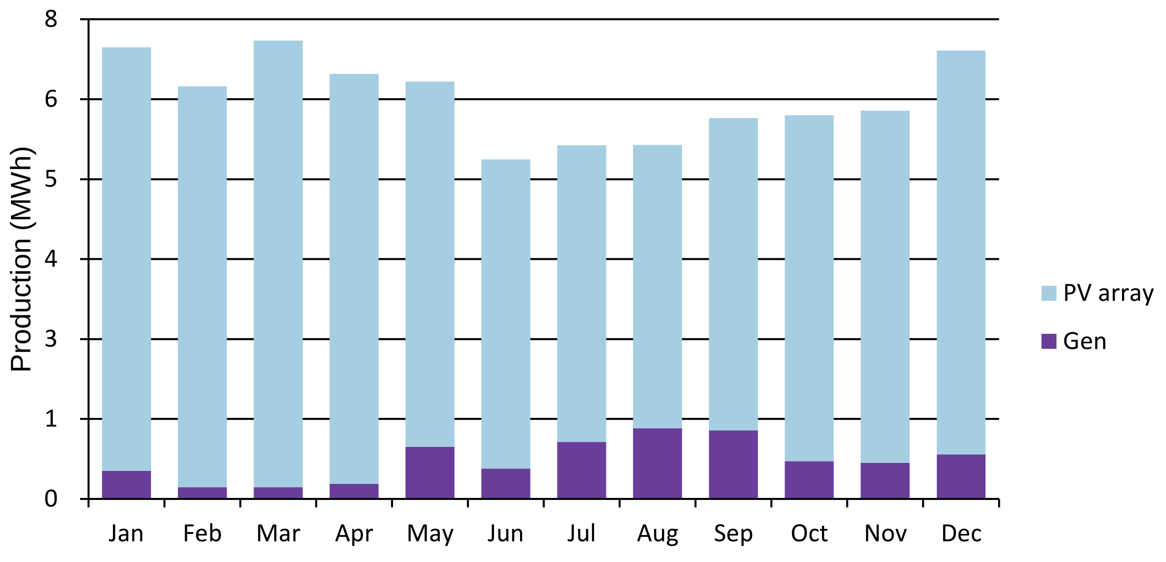


Figure 4. 15: Chart showing monthly electricity production for the proposed system (SC).

The NPC of the proposed system obtained from the simulation was $157,447, with an initial CC of $98,130. The annualized O&M cost of the project over a 25year lifetime is $7,838. The system is a simple payback period of 1.4 years with an LCOE of $0.345/kWh. The IRR and ROI of the system are 70% and 60% respectively.

4.3.1.1 PV panel

From the simulation results, the SPV array has a rated capacity of 45.5kW which is expected to provide a source of reliable power supply to meet the expected electrical demand loads, with a selected PV nodule of 250 watts rating. The PV array has a mean output capacity of 186kWh/day. The SPV penetration is 113% and is expected to operate for 4,319 hours on an annual basis, producing a total amount of energy of 68,002kWh per year, which accounts for 90.4% of the total electricity generated the system. The LCOE of the PV array is $0.0720/kWh.

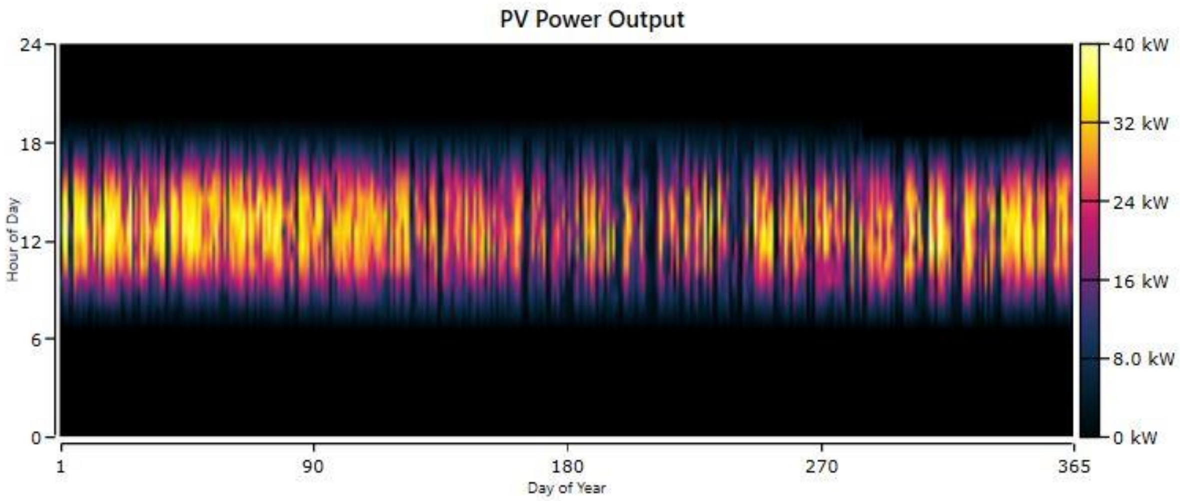


Figure 4. 16: Figure showing power output from PV array for SD.

4.3.1.2 Diesel generator

From the simulation results, a DG of 31kW capacity was obtained to provide electricity supply for the village. The DG is estimated to consume 2,139L of diesel fuel while producing an average output power of 7,257kWh/yr., representing 9.6% of electricity generated on an annual basis. The generator is expected to operate on an annual basis for about 246 hours, incurring both fixed and marginal generation costs of $3.67/hr and $0.236/kWh. For 20,000 operational lifetime hours for the DG as estimated by the HOMER, the DG is expected to last for 81 years exceeding the project's lifetime of 25 years, due to the low frequency of use as simulated by the HOMER. The Fig 4-14 shows the operation of the DG over a year.

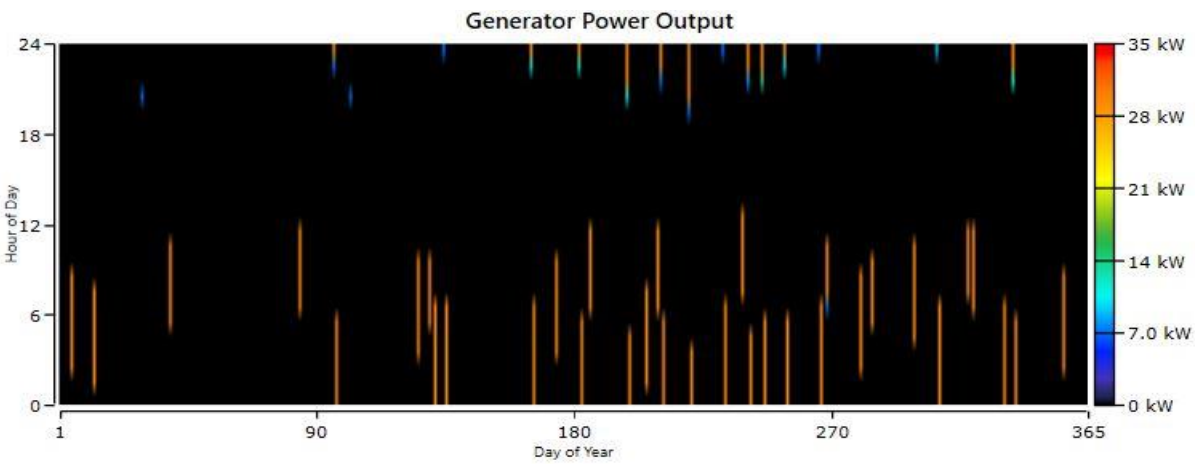


Figure 4. 17: Figure showing power output from DG for SD.

4.3.1.4 Battery

Homer simulated the battery bank requirement for the hybrid system to be 68 batteries, with a nominal capacity of 335kWh and a string size of 17 batteries, implying the number of batteries in a serial connection is 4, thereby constituting a system voltage of 48V. Battery autonomy represents the number of hours the demand load can be supplied entirely with energy stored from the battery bank. For the hybrid system, homer simulated the battery autonomy to be 34hours with an expected lifetime of 3.91 years, and annual throughput of 45,049kWh/yr. The sum of energy inputs into, and output from the batteries are 45,538kWh/yr and 44,369kWh/yr respectively, and the battery storage accounts for a figure of 1,369kWh/yr loss in the total energy stored. The capital cost of the 68 batteries is $23,800, and the average cost of energy is $0.0214/kWh.

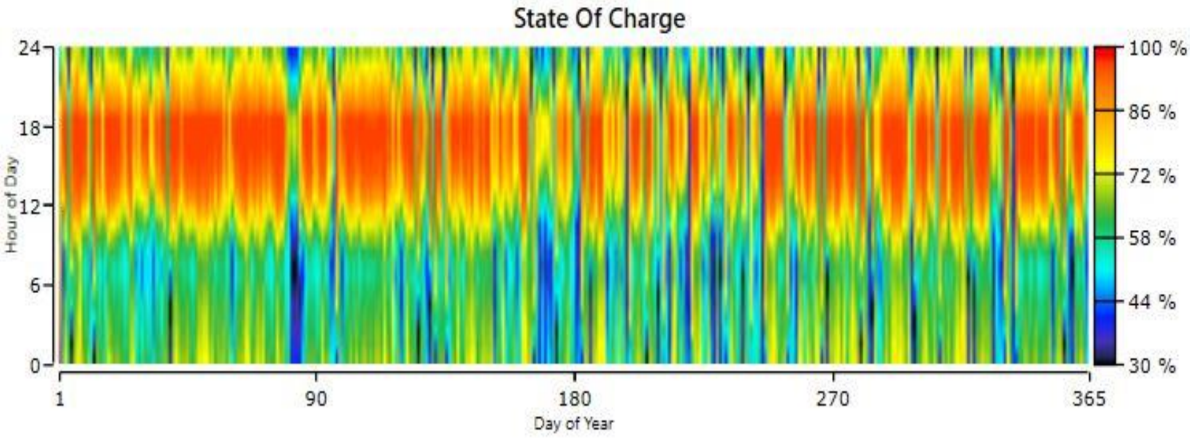


Figure 4. 18: Figure showing power output battery state of charge for SD.

4.3.1.4 Converter

The converter consists of an inverter, and a rectifying unit. The inverter converts DC input power into an AC output power, whereas the rectifier achieves the reverse. The capacity of the converter, the maximum output, obtained from the simulation results was 28.7kW. The inverter unit is expected to operate for 8,531 hours per year and has an energy input of 62,230kWh and an output of 59,118kWh per year. The number of operation hours of the rectifier is 229 hours per year with an energy input and output of 62,230kWh and 59,118kWh per year respectively.

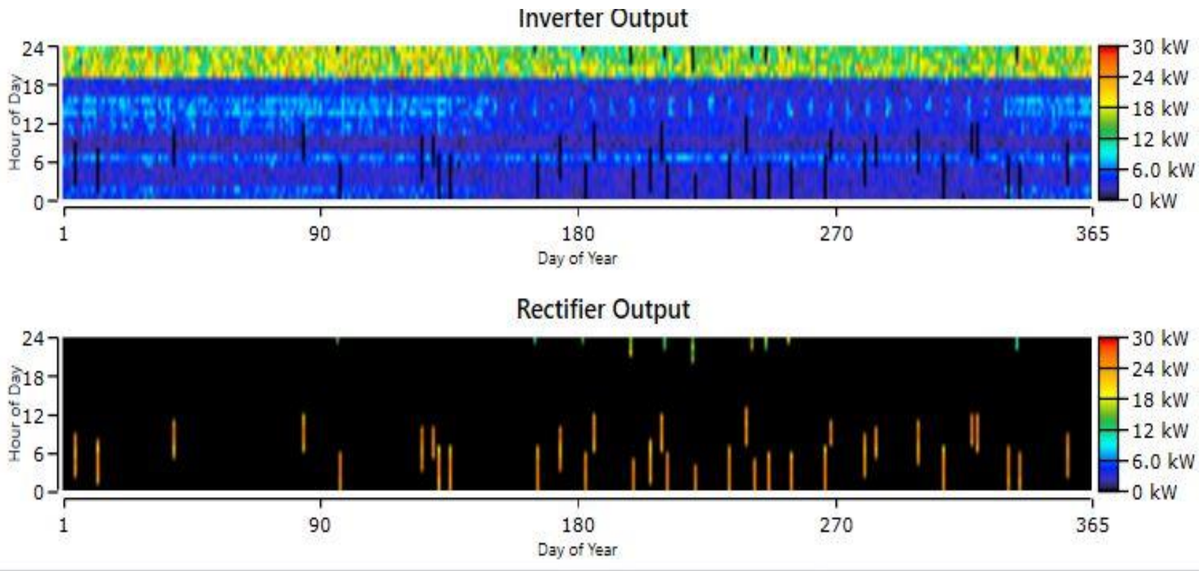


Figure 4. 19: figure showing converter power output for SD.

4.5 Sensitivity analysis

4.5.1 Inflation rate

The inflation rate represents the rate of price change in commodities. The macro-economic situation Sierra Leone is subject to and experiences a continuous change in the rate of inflation. For this study, the national inflation rate of 10.2% was as of June 2021 was selected to be used in the optimization of the system. To check for sensitivity of a change in the inflation rate on the project's economic output variables, three other inflation rates were selected for assessment; 3%, 6%, and 13%. Inflation rates higher and lower than the original rates were chosen to observe the results of an increase or decrease in the particular variable. The observations are discussed as follows.

With an inflation rate of 10%, discount rate of 24%, and the price diesel fuel at $1 respectively, the NPC, CC, and LCOE of the system obtained for the system were; $157,447, $98,130, and $0.345/kWh respectively. A decrease in the inflation rate to 6%, obtained a 10% reduction in the NPC, to $142,083, and CC by 3%, to $95,504. An increase in the inflation rate to 13% obtains an increase of 9% and 19% in the NPV and CC respectively. With an inflation rate of 6%, the LCOE increases to $0.408/kWh, and decreases to $0.306/kWh when the inflation rate is increased to 13%. In general, the results showed that LCOE decreases with an increase in the inflation rate, while the CC and NPC increase with an increase in the same. Fig.4-17 shows the sensitivity output for a change in inflation rate on the NPC, CC, and LCOE.

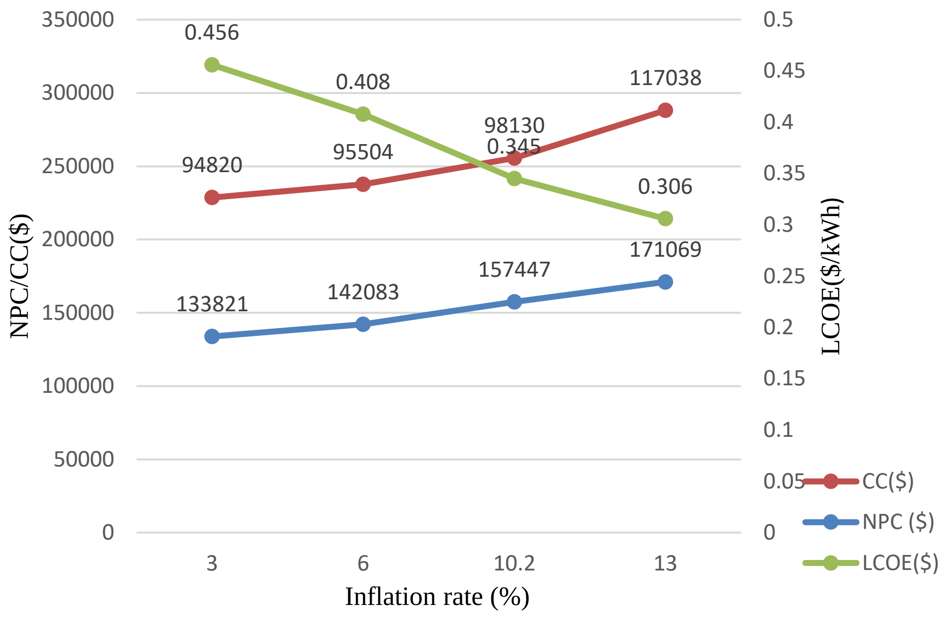


Figure 4. 20: Sensitivity output for inflation rate on NPC, CC & LCOE.

4.5.2 Discount rate

The original discount rate used for this study was 24%. Three other discount rates were used to simulate the sensitivity of the variable: 4%, 15%, and 30%, and the results are as follows.

At a 24% discount rate, and with the price of diesel at $1, and an inflation rate of 10.2%, the NPC, CC, and LCOE were; $157,447, $98,130, and $0.345/kWh respectively. A reduction in discount rate from 24% to 15% increases the NPC and CC, by 29% and 20% to $204,234 and $117,918 and respectively. For the same reduction in the discount rate, LCOE is reduced by 35% to $0.225/kWh. By increasing the discount rate to 30%, the NPC and CC reduce to $139,657 and $97,481 respectively, while the LCOE increases to $0.422/kWh.

In general, the result for the sensitivity analysis showed that an increase in the discount rate for such a system decreases the NPC and CC, and increases LCOE, while a reduction of the same obtains the reverse.

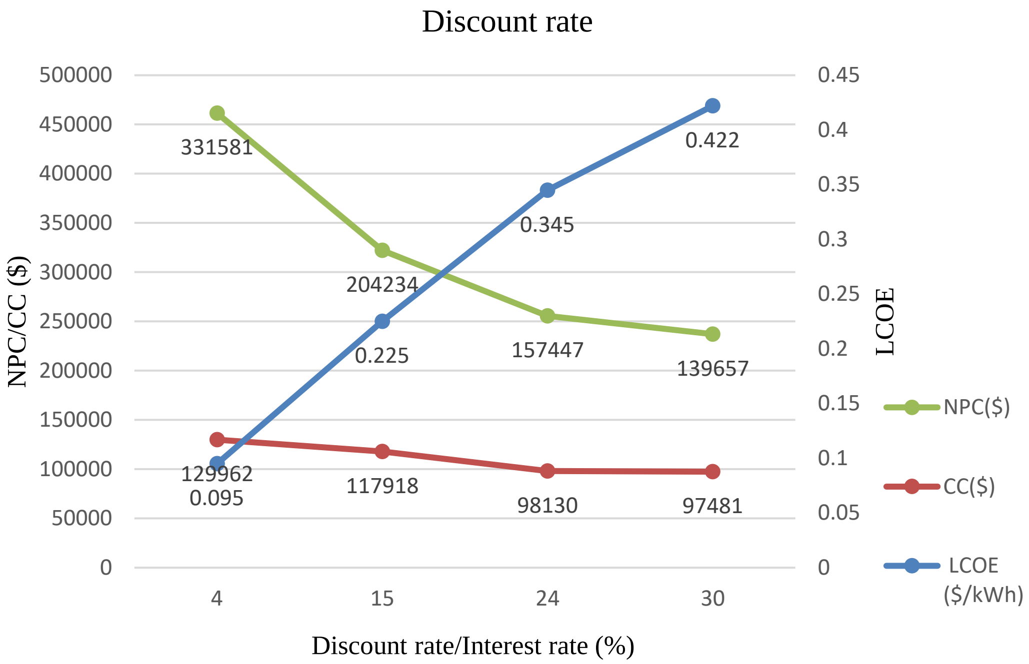


Figure 4. 21: Sensitivity output for the interest rate on NPC, CC & LCOE.

4.6.3 Diesel fuel price

Diesel fuel prices are susceptible to fluctuations in both the international and local markets in Sierra Leone due to several reported reasons. Since 2016, the pump-price of a liter of diesel fuel, at Le3,750 ($0.37) has increased by more than 170% to a current price of Le10,000. With the selected price of diesel for this study at $1, the NPC, CC, and LCOE were $157,447, $98,130 and $0.345/kWh respectively. A reduction in the price of the diesel fuel to $0.8 decreases the NPC, CC and LCOE to $154,035, $96,290 and $0.337/kWh respectively, increasing the price of the same to $1.25 increases the cost of the stated parameters to; $161,377, $98,896, and $0.353/kWh in their respective order.

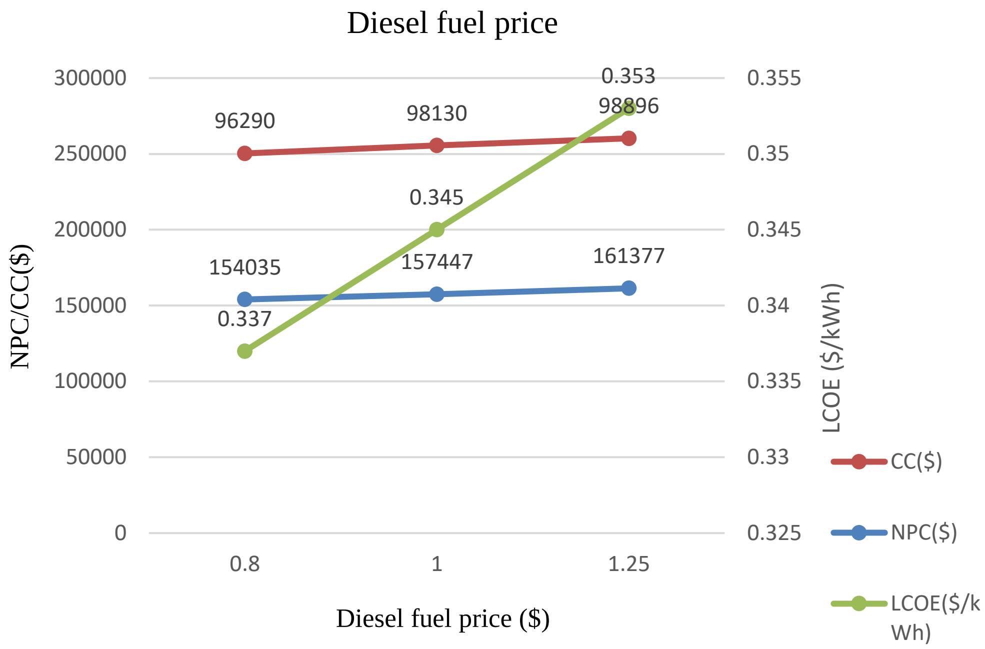


Figure 4. 22: Sensitivity output of diesel fuel on NPC, CC & LCOE.

Chapter five - Conclusions and recommendations

5.1 Recommendations

5.1.1 Specific recommendations

The system was sized for peak load by HOMER and as a result, there is a lot of excess of power produced which can be put into productive use by introducing some more productive activities during periods of excess in energy production, this creates an opportunity for a study in further energy management practices to optimize electricity production in such a system. A further study can also be carried out that can size a system based on future projections of an increase in the productive use of energy.

5.1.2 General

The sensitivity analysis showed that the NPC of the HS increased with an increase in the discount rate. The national discount rates in Sierra Leone at 24% is one of the highest relative to other countries in the sub-Saharan Africa region. Lowering the discount rate banks charge on lending towards projects involved in RET development can significantly lower the cost of the investment required to undertake such projects. As a recommendation supporting claims by previous similar studies on hybrid electricity systems across rural and remote communities in Africa, government policies and actions driven towards lowering interest rates on electricity projects that promotes access to rural and remote communities is vital to ensure the development of such technologies in these locations.

The LCOE of electricity obtained from the study was $0.345/kWh, a cost that is 23% greater than the average national grid price of electricity, at $0.28/kWh (SL electricity sector reform roadmap, 2017). Remote locations in Sierra Leone have been researched to consist of mainly low-income populations and this particular study considered one in that category (Statistics SL, 2017). Regardless of the perceived willingness of the inhabitants to be provided with electricity and their expressed desire to pay for the electricity, the high poverty rate amongst such communities is an inhibiting factor that hinders the cost-affordability of such systems. Therefore, subsidy and incentives interventions are necessary to help lower the LCOE of such an HPS which can eventually lead to cost-affordability amongst such communities.

Agriculture is a predominant practice, and it is the primary source of economic activities across rural Sierra Leone Academic studies that seek to research into areas of maximizing productive economic use of electricity in these communities are important to be carried out.

Renewable energy technologies are declining in cost in the global market, mainly due to advancements in production technologies which have significantly lowered the unit cost of production of these technologies. prices of these technologies available in the local market are relatively higher than those in the global market, this challenges the cost-affordability for many. Significant efforts must be made to develop policies that lower the price of RE products in the local market in Sierra Leone.

5.2 Conclusions

This research work carried out a techno-economic feasibility assessment for a hybrid PV/DG/BS to provide a reliable power supply to a remote village community called Masunthu, located in northern-Sierra Leone. At first, a resource assessment was conducted to determine the community's energy needs, and a further assessment was made to estimate the electrical load's demand for the village. Energy resource and load data obtained from the assessment was used as an input into HOMER software. HOMER software performs simulation, optimization, and sensitivity analysis to determine the technical and economic performance of a selected model of electrification. Four different models of electricity generation systems, referred to as scenarios; scenario A (SA), scenario B (SB), Scenario C (SC) and scenario D (SD), were considered for this study, and a comparative analysis on the technical and economic outputs obtained from the HOMER simulations was performed to determine and propose the most feasible option for electrification of the village, based on visual observation of specific criteria.

With a national rate of inflation of 10.2%, a discount rate of 24%, and a price of $1 per liter of diesel fuel, the results from the simulations showed that SD, the HES consisting of a solar PV array, DG, and a BS, was found to be the most feasible option for electricity generation for the remote location. The proposed system comprises a 45.5kW PV array, 31kW DG, 68 Lead-acid batteries are expected to provide a reliable power supply over a 25-year project lifetime. Economically, the PV/DG/BS HES presents the cheapest energy generation, with a total NPC of $152,491, over the 25-year project lifetime selected for this study. Technically, the system is expected to produce a reliable power supply with a high proportion of renewable energy generated, with solar PV accounting for 90% of the total energy 75,121kWh. In addition, the system accounts for the least loss of power produced during its operation. Furthermore, GHG emissions for the proposed system are lower (6,117kg) when compared to power generation using DG only (21,730kg) or a hybrid system combining PV and DG as sources of power generation.

In conclusion, this study proposes hybrid PV/DG/BS to be a feasible model for electrification of the case study area and other similar locations across Sierra Leone

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Appendix 1: Climate data for the location

Month	Air Temperature (ºC)	Earth Temperature (ºC)	Atmospheric Pressure (kPa)	Relative Humidity (%)	Wind Speed (m/s)	Daily Solar Radiation - horizontal ($kWh/m^2/d$)	Equivalent Number of No-sun days
January	26.000	25.9	99.4	73.3	3.600	5.600	4.31
February	28.170	26.8	99.4	77.0	3.640	6.130	2.22
March	29.510	27.0	99.3	80.3	3.880	6.440	2.13
April	29.420	26.9	99.3	83.0	3.950	6.300	1.57
May	27.980	26.4	99.5	85.9	3.540	5.480	2.92
June	26.190	25.4	99.6	87.7	3.760	4.740	6.48
July	24.880	24.3	99.7	87.5	4.710	4.340	5.08
August	24.530	23.9	99.7	88.0	5.150	4.060	4.57
September	25.020	24.5	99.6	88.0	4.140	4.560	4.35
October	25.630	25.1	99.5	87.5	2.990	4.760	4.31
November	25.640	25.4	99.4	85.5	2.570	4.890	4.27
December	24.940	25.1	99.4	80.1	3.340	5.280	3.5
Annual	**24.6**	**25.5**	**99.5**	**83.7**	**3.77**	**5.22**	**45.71**

Appendix 2 : Survey questionnaire for electrical load data survey

No:

FIELLD SURVEY QUESTIONNAIRE

SECTION 1 – PERSONAL DETAILS AND ENERGY NEED

1. Type of consumer
   a) Residential
   b) Commercial
   c) farmer
2. Name of Respondent...
3. Sex ....
4. Age...
5. House address.. ....
6. **mean of meeting electricity needs**

1. For cooking	
2. For lighting	
3. Heating	
4. Charging	
5. Internet	
6. Irrigation	

7. Monthly/annual electricity expense.

SECTION 2 - TECHNICAL SECTION – INCLUDING DEMAND LOAD ESTIMATION

Estimated load demand

Load type	**Number**	**Power**	**Daytime use(hr)**	**Night time use(hr)**	**Day-time wh**	**Night-time Wh**	**Total Wh**
Total amount of electricity required							

Appendix 3 : Load estimation data

COMMUNITY LOADS								
	CHURCH		HEALTH CENTRE					
Appliance	**LIGHT**	**FAN**	**LIGHT**	**FAN**	**FRIDGE**	**TV**	**PHONE**	**PC**
Power (w)	10	65	10	65	350	120	5	1
Number	3	2	12	5	2	1	5	1
Hour	12	9	13	8	23	8	10	11
00:00	0.02		0.12		0.35			
01:00	0.02		0.12		0.35			
02:00	0.02		0.12		0.35			
03:00	0.02		0.12		0.35			
04:00	0.02		0.12		0.35			
05:00	0.02		0.12		0.35			
06:00	0.02		0.12		0.35			
07:00	0.03		0.12		0.7			0.12
08:00					0.7		0.025	0.12
09:00					0.7		0.025	0.12
10:00				0.325	0.7	0.12	0.025	0.12
11:00				0.325	0.7	0.12	0.025	0.12
12:00		0.065		0.325	0.7	0.12	0.025	0.12
13:00		0.065		0.325	0.7	0.12		0.12
14:00		0.065		0.325	0.7	0.12		0.12
15:00		0.065		0.325	0.7	0.12		0.12
16:00				0.325	0.7	0.12		0.12
17:00				0.325	0.7	0.12		
18:00		0.13			0.7			
19:00	0.03	0.13	0.12		0.7		0.025	
20:00	0.03	0.13	0.12		0.7		0.025	
21:00	0.03	0.13	0.12		0.7		0.025	
22:00	0.03	0.13	0.12		0.7		0.025	
23:00	0.03		0.12		0.7			
Total (kWh/day)	0.3	0.91	1.44	2.6	14	0.96	0.225	1.2
% Total load	1%		45%					

	COMMNUITY LOADS CONTD.										
Appliance	**SCHOOL (2)**							**MOSQUE**		**ST. LIGHT**	**TOTAL kWh/day**
Power (w)	**LIGHT**	**FAN**	**FRIDGE**	**TV**	**DVD**	**PHONE**	**PC**	**LIGHT**	**FAN**	**LIGHT**	
Number	10	65	100	120	30	5	120	10	65	40	
Hour	8	8	1	1	1	3	1	3	2	15	
00:00	12	7	6	5	5	15	8				
01:00	0.16					0.03				0.6	1.28
02:00	0.1					0.03		0.01		0.6	1.23
03:00	0.1					0.03		0.01		0.6	1.23
04:00	0.1					0.03		0.01		0.6	1.23
05:00	0.1							0.03		0.6	1.22
06:00	0.1							0.03		0.6	1.22
07:00	0.1							0.03		0.6	1.22
08:00							0.24				1.21
09:00							0.24				1.085
10:00							0.24				1.085
11:00		1.04	0.2	0.24	0.06	0.03	0.24				3.1
12:00		1.04	0.2	0.24	0.06	0.03	0.24				3.1
13:00		1.04	0.2	0.24	0.06	0.03	0.24		0.13		3.295
14:00		1.04	0.2	0.24	0.06	0.03	0.24		0.13		3.27
15:00			0.2	0.24	0.06	0.03	0.24		0.13		2.23
16:00		1.04	0.2	0.24	0.06	0.03	0.24		0.13		3.27
17:00		1.04	0.2								2.505
18:00											1.145
19:00								0.03			0.86
20:00	0.16					0.03		0.03	0.13	0.6	1.955
21:00	0.16					0.03		0.03	0.13	0.6	1.955
22:00	0.16					0.03		0.03	0.13	0.6	1.955
23:00	0.16					0.03		0.03		0.6	1.825
Total (kWh/day)	0.16					0.03				0.6	1.64
% Total load	1.4	6.24	1.4	1.44	0.36	0.42	2.16	0.27	0.91	6.6	**42.835**
	31%							3%		15%	**24%**

	COMMERCIAL LOADS								
Appliance	**CINEMA**				**SHOP (3)**				
Power (w)	**LIGHT**	**FAN**	**TLEVISION**	**DVD**	**LIGHT**	**FRIDGE**	**FAN**	**RADIO**	**PHONE**
Number	10	65	120	30	10	100	65	30	5
Hour	5	3	3	3	2	1	1	1	1
00:00					11				
01:00					0.06				
02:00	0.03				0.03				
03:00	0.03				0.03				
04:00	0.03				0.03				
05:00	0.03				0.03				
06:00	0.03				0.03				
07:00	0.03				0.03				
08:00								0.09	
09:00								0.09	
10:00								0.09	
11:00								0.09	
12:00						0.3		0.09	0.015
13:00						0.3	0.195	0.09	0.015
14:00		0.13				0.3	0.195	0.09	0.015
15:00		0.13				0.3	0.195	0.09	0.015
16:00		0.13				0.3	0.195	0.09	
17:00		0.13				0.3	0.195	0.09	
18:00						0.3	0.195	0.09	
19:00								0.09	
20:00	0.05	0.195	0.36	0.09	0.06			0.09	0.015
21:00	0.05	0.195	0.36	0.09	0.06			0.09	0.015
22:00	0.05	0.195	0.36	0.09	0.06			0.09	0.015
23:00	0.05	0.195	0.36	0.09	0.06			0.09	0.015
Total (kWh/day)	0.05	0.195	0.36	0.09	0.06				
% Total load	0.43	1.495	1.8	0.45	0.48	2.1	1.17	1.44	0.12
	34%				43%				

	COMMERCIAL LOADS contd.					
Appliance	**TAILORING CENTRE**					**TOTAL**
Power (w)	LIGHT	FAN	PHONE	TV	DVD	
Number	10	65	5	120	30	
Hour	4	2	4	1	1	
00:00	10	7	7	8	8	
01:00	0.02					0.08
02:00	0.02					0.08
03:00	0.02					0.08
04:00	0.02					0.08
05:00	0.02					0.08
06:00	0.02					0.08
07:00	0.02					0.08
08:00						0.09
09:00						0.09
10:00				0.12	0.03	0.24
11:00		0.13	0.02	0.12	0.03	0.39
12:00		0.13	0.02	0.12	0.03	0.705
13:00		0.13	0.02	0.12	0.03	0.9
14:00		0.13	0.02	0.12	0.03	1.03
15:00		0.13	0.02	0.12	0.03	1.03
16:00		0.13	0.02	0.12	0.03	1.015
17:00		0.13	0.02	0.12	0.03	1.015
18:00		0.13	0.02	0.12	0.03	0.885
19:00						0.09
20:00	0.04					0.9
21:00	0.04					0.9
22:00	0.04					0.9
23:00	0.02					0.88
Total (kWh/day)	0.02					0.775
% Total load	0.28	1.04	0.16	1.08	0.27	**12.315**
	21%					**7%**

	HOUSEHOLD LOAD (91)								TOTAL DAILY CONSUMPTION (kWh/day)
Appliance	**RADIO**	**TV**	**DVD**	**PHONE**	**FAN**	**LIGHT**	**FRIDGE**	**TOTAL (kWh/day)**	
Power (w)	30	120	30	5	55	10	100		
Number	1	1	1	2	1	4	1		
Hour									
00:00					2.025	1.82		3.845	5.205
01:00				0.25	2.475	1.82		4.545	5.855
02:00				0.25		1.82		2.07	3.38
03:00				0.25		1.82		2.07	3.38
04:00						1.82		1.82	3.12
05:00						3.64		3.64	4.94
06:00	1.2			0.35		3.64		5.19	6.49
07:00	1.2			0.35		0.91		2.46	3.76
08:00	1.2			0.15				1.35	2.525
09:00	1.2			0.15				1.35	2.675
10:00	1.5			0.15			0.5	2.15	5.64
11:00	1.5			0.15			0.5	2.15	5.955
12:00	0.75			0.15			0.5	1.4	5.595
13:00	0.75			0.15	2.025		0.5	3.425	7.725
14:00	0.75			0.15	2.025		0.5	3.425	6.685
15:00	0.75			0.15	2.025		0.5	3.425	7.71
16:00	0.75			0.15			0.5	1.4	4.92
17:00	0.75			0.15			0.5	1.4	3.43
18:00	2.4			0.91			0.5	3.81	4.76
19:00	2.4	4.5	1.35	0.91	2.025	3.64	0.5	15.325	18.18
20:00	2.4	4.5	1.35	0.91	2.025	3.64	0.5	15.325	18.18
21:00	2.4	4.5	1.35	0.91	2.025	3.64	0.5	15.325	18.18
22:00	2.4	4.5	1.35	0.91	2.025	3.64	0.5	15.325	18.03
23:00	2.4	4.5	1.35	0.91	2.025	3.64		14.825	17.24
Total (kWh/day)	26.7	22.5	6.75	8.41	18.675	33.67	6.5	**123.205**	**178.355**
% Total load	**100%**							**69%**	

Appendix 4: - Result from sensitivity analysis

(a) Inflation rate

Discount rate = 24%	**diesel fuel price = $1**		
Inflation rate	NPC	CC	LCOE
3	133,821	94,820	0.456
6	142,083	95,504	0.408
10.2	157,447	98,130	0.345
13	171,069	117,038	0.306

(b) Discount rate

Inflation rate = 10.2%	**diesel fuel price =$1**		
discount rate	NPC ($)	CC ($)	LCOE ($/kWh)
4	331,581	129,962	0.095
15	204,234	117,918	0.225
24	157,447	98,130	0.345
30	139,657	97,481	0.422

(c) Diesel fuel price

Disc. Rate = 24%	**Inflation rate = 10.2%**		
Diesel fuel price	NPC ($)	CC ($)	LCOE ($/kWh)
0.8	154,035	96,290	0.337
1	157,447	98,130	0.345
1.25	161,377	98,896	0.353

Appendix 5: List of equations used by homer in system modelling the calculations

Solar PV	$$P_{output} = \gamma_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)[1 + \alpha_p(T_c - T_{C,STC})]$$ $$P_{output} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)$$ $$T_c = T_{amb} + \left[\left(\frac{\overline{G_T}}{0.8}\right)\right](NOCT - 20\,°C)$$ **Where:** **γ_{PV} – output power of PV module (kW),** **f_{PV} – PV module derating factor (%),** **$\overline{G_T}$ – Incident solar radiation on module (kW/m^2)** **$G_{T, STC}$ - Incident solar radiation under Standard test conditions (1000 W/m^2);** **α_p - Temperature coefficient of power (%/ºC);** **T_c - PV cell temperature (ºC) and** **$T_{c, STC}$ - PV cell temperature under STC (25 ºC),** **T_{amb} - Ambient temperature,** **NOCT - Nominal Operating Cell Temperature (ºC)** (**HOMER, 2016**)
Power Converter/Inverter	$$\eta_{inverter} = \frac{P_{inv\ AC}}{P_{PV\ output}}$$ $$P_{inv} = \eta_{inv} \times Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)$$ Where: $P_{inv\ AC}$ is the out power of the inverter in watt; $P_{PV\ output}$ = is the output power generated by the PV array in watt. (HOMER, 2016)
Diesel Generator	$$P_{DG} = \frac{Maximum\ energy\ demand}{Maximum\ operating\ hours\ per\ day\ \times Maximum\ load\ factor}$$ $$q(t) = aP_r + bP(t)$$ Where: q(t) - fuel consumption (l/h) P(t) - generated power in the time step (kW) P_r - rated power (kW); a - fuel curve interception coefficient in (l/kWh rated), b - fuel curve slope (l/kWh output). (HOMER, 2016)
Battery Bank	$$RB_{cap} = \frac{E_{AC\ load} \times A_d}{DOD_{max} n_{inv} C_t}$$ (Muh, 2017) $$SOC\ (t) = \frac{C_B\ (t)}{C_{B\ max}(t)}$$ $$\mathbf{0 \ll SOC\ (t) \ll 1}$$ $$Autonomy\ day = \frac{N_B \times V_{nor} \times C_{nor}\left(1 - \frac{q_{min}}{100}\right)(24\ h/day)}{L_{AC}(1000\ Wh/kWh)}$$ Where: RBcap – Required battery capacity in (Ah) EAC load – Total AC load in (Ah) Ad – Day of autonomy DODmax – Maximum depth of discharge (%) ηinv – Inverter efficiency (%) Ct – Temperature correction factor, SOC – Battery state of Charge,

	CB (t) — battery capacity at time (t) CB max(t) — is the maximum battery capacity at time t NB — Number of batteries in the storage bank Vnor — Nominal voltage of single storage (V) Cnor — Nominal capacity of single storage (Ah) qmin — Minimum state of charge of the storage bank (%) LAC — average AC primary load. (HOMER, 2016)

Appendix 6: Photo gallery

A solar system enterprise in the town of Kambia

Signpost of the Kambia district council

Masunthu village water supply facility

Village clinic using stand-alone SPV system

Three-stone fire-place used for cooking

alternative water supply facility for village

Village primary school

A stand alone solar pico-lantern