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(Including CLIMATE CHANGE)

ENERGY ENGINEERING

MASTER THESIS

Optimal Sizing and Techno-Economic Analysis of a Stand-alone Photovoltaic–Wind Hybrid System: A Case Study of Busitema Health Centre III in Busia District, Eastern Uganda

Student Name: Onesmas GUMISIRIZA

BSc. Textile Engineering

Supervisor: Prof. Olayinka S. OHUNAKIN

SUBMITTED ON: 30-09-2020

CERTIFICATE OF APPROVAL

I attest that GUMISIRIZA ONESMAS is the one who has written this report on the account of his Master's research under my supervision, and that it has been submitted on this day with my approval.

Name: ……………………………………………………………

Signature: ……………………………………………………

Date: ………………………………………………

DEDICATION

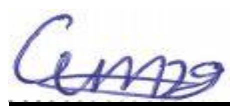
I dedicate this report the Glory of the Almighty God, and to my wife Glorious Nyamigisha.

STATEMENT OF THE AUTHOR

I, Gumisiriza Onesmas declare that this research entitled: Optimal Sizing and Techno-economic Analysis of a Stand-alone Photovoltaic–Wind Hybrid System: A Case Study of Busitema Health Centre III in Busia District, Eastern Uganda, is entirely my original work and has never been submitted to any higher institute of learning for any academic award.

It is submitted in partial fulfilment for the requirements of a Master of Science in Energy Engineering, at the Pan African University of Water and Energy Sciences including Climate Change (PAUWES).

I affirm that I have cited and referenced all sources used in this document. I have also made every effort to avoid plagiarism.



Mr. Gumisiriza Onesmas		27-09-2020
Name	Signature	Date

BIOGRAPHICAL SKETCH

Onesmas GUMISIRIZA was born and raised in Bushenyi District, Western Uganda, on February 26, 1992. He holds a Bachelor of Science in Textile Engineering from Busitema University in Eastern Uganda. He attended Kyamuhunga Secondary School for both his Ordinary and Advanced Level education. He has previously worked as a production manager in a plastic manufacturing company, the China LESSO Holding Company Limited. His Master's program included 5-week summer internship at Ndejje University Energy Research and Development Center, Luwero-Uganda.

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ABBREVIATIONS AND ACRONYMS

ABC – Artificial bee colony algorithm

AC – Alternating Current

ACA – Ant colony algorithms

AEC –Atomic Energy Council

AGECC - Advisory Group on Energy and Climate Change

AI – Artificial Intelligence

ANFIS – Artificial Neuro-Fuzzy Inference System

ANN – Artificial Neural Network

AU – African Union

AWS – Automatic Weather Station

BFO – Bacterial Foraging Algorithm

BOS –Balance of the system

CAES – Compressed air energy storage

CC –Cycle-charging

CdTe – cadmium telluride

CdTe –Cadmium Telluride

CIGS) – copper-indium-gallium-diselenide

CS – Cuckoo Search

CSP – Concentrating Solar Panel

DC – Direct Current

Democratic Republic of Congo (DRC)

DG – distributed generation

DN – Direct Normal Irradiance

EAC – East African Community

EDT – Electricity Disputes Tribunal

ERA – Electricity Regulatory Authority

FF – Fill Factor

FIT – Feed-in-Tariff

GA – Genetic Algorithms.

GDP – Gross Domestic Product

GHG – Green House Gases

GHI – Global Horizontal Irradiation

GOU – Government of Uganda

HAS – Harmony search algorithm

HAWT – Horizontal Axis Wind Turbines

HDI – Human Development Index

HOGA – Hybrid optimization by genetic algorithm

HOMER – Hybrid Optimization for Multiple Electric Renewables

HRES – Renewable Energy Systems

Imp – Maximum power operating current

IRENA – International Renewable Energy Agency

Isc – Short Circuit Current,

LCOE –Levelised cost of energy

LF – Load-following

MAAIF – Ministry of Agriculture, Animal Industry and Fisheries

MEMD - Ministry of Energy and Mineral Development

MPP Maximum Power Point

NEMA – National Environment and Management Authorities.

NEPAD – New Partnership for Africa’s Development

NFA – National Forestry Authority

NPC – Net Present Cost

NREL –National Renewable Energy Laboratory

NREL –National Renewable Energy Laboratory

PPA) – Power Purchase Agreement

PSO – Particle Swarm Optimization Technique

PV - Photovoltaic

RAPSim – Remote Area Power Simulator

REA – Rural Electrification Agency

REB) – Rural Electrification Board

SA –Simulated annealing

SHC – solar heating and cooling

SMES – Superconducting magnetic energy storage

SOLSIM – Simulation and optimization model for renewable Energy Systems

SOMES –Simulation and Optimization Model for Renewable Energy Systems

UBOS – Uganda Bureau of Standards

UECCC – Uganda Energy Credit Capitalization Company

UEDCL – Uganda Electricity Distribution Company Ltd

UEGCL – Electricity Generation Company Ltd

UETCL – Uganda Electricity Transmission Company Ltd

UN – United Nations

USA – United States of America

USD – United Stated Dollars

VAWT –Vertical Axis Wind Turbine

Vmp – Maximum Power Voltage

Voc – Open Circuit Voltage

WT –Wind Turbine

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ABSTRACT

The total power generation in Uganda stands at 1,777 MW which is below phase two target of 2,325 MW of the National Development Plan (NDP II). To achieve the NDP II target while ensuring sustainable development, requires the utilization of renewable energy particularly solar photovoltaic (PV). Although photovoltaic technology in Uganda is relatively expensive due to high upfront cost, the need to diversify the energy mix of the country thereby enhancing security of supply is necessary, and forms the subject of this study. Uganda is endowed with solar energy resource which can be used to generate electricity for isolated sites in rural areas, and can be combined with the other available resources in the country in the form of hybrid renewable energy systems. Eastern Uganda possesses minimal level of global solar irradiance (GHI) for PV deployment, and approximately 5.15 kWh/m^2/day. This study deals with the optimal sizing and techno-economic analysis of PV/Wind hybrid system for Busitema Health Centre III. The load demand for the health Centre was 3.979 kWh. The meteorological data used in this study was obtained from the National Meteorological Centre. The Net Present Cost (NPC), as well as energy output and Levelized Cost of Electricity (LCOE) of the optimal system was determined through simulations using HOMER PRO x 643.13.2 software. For the design of an optimal system, various combinations were obtained with solar PV, wind turbines, batteries, converters and diesel generator from the HOMER optimization simulations. The sensitivity analysis revealed that as electricity price increases, the NPC and LCOE increases for optimal system. The NPC also increases with an increase in the electrical load demand due to the need for expansion of the system. The results show that a solar PV-diesel hybrid system having configuration of 15.75 kW Solar PV, 10 kW diesel generator, and 9 batteries, with a renewable energy fraction of 85.5% solar, and a total electrical energy output of 26,231kWh/yr, gives the optimal configuration. The system had a NPC of $22,427 with LCOE of $0.256/kWh. It was recommended that future research be considered in extending such work to other similar potential sites. Overall, this study revealed that location at coordinates of 0°28'01.0"N and 4°05'24.0"E is preferable for the PV deployment and a hybrid power system can optimally serve Busitema Health Centre III.

Keywords: Renewable Energy, HOMER PRO, Hybrid Electric Systems, Off-Grid System, Health Centre, Uganda

1. INTRODUCTION

1.0 Background of the Study

Energy is the engine for the economic progress and development of any given society or country. Access to energy is therefore a key factor in the socio-economic transformation of every country. The Advisory Group on Energy and Climate Change (AGECC) defines energy access as: access to a basic minimum threshold of modern energy services for consumption and productive uses. Access to these modern energy services must be reliable and affordable, sustainable and where feasible, with low GHG-emitting sources [1]. It is estimated that many people, particularly in the developing world, lack access to modern energy services. Over 620 million people (almost two-thirds of Africans), do not have access to electricity and nearly 730 million rely on traditional solid biomass for cooking [2]. The proportion of the populace having access relies on a very expensive, low-quality supply [3]. The principal goal of African countries is to meet the growing energy demand to cater for the rising population, and to ensure universal access to modern energy services with respect to the environment.

Hybrid energy systems such as photovoltaic (PV)–wind systems, offer the most adequate solutions for the electrification of remote areas; the combination and the ratio of the types of energy technologies depend greatly on the resources locally available in each geographical area. These resources can be evaluated only after a period of monitoring of the basic parameters such as wind speed, solar radiation, and temperature, that are necessary for sizing and implementing renewable energy systems. Optimization of the sized stand-alone photovoltaic–wind hybrid systems guarantees the lowest investment with the use of renewable energies. Photovoltaic generators are silent, inexhaustible, pollution-free and size-independent electric conversion efficiency. The PV generators are excellent replacements to fossil fuels because of their non-effect on the environment, but the power outputs are susceptible to variations in solar radiations. Therefore, the intermittent nature of solar radiation limits the use of only PV power generators for off-grid applications. In order to solve this problem, PV generators are hybridized with other energy technologies such as wind, battery, diesel or fuel cell etc. Combining PV generators, wind turbines and storages ensure a continuous supply of power.

1.1 Energy Situation in Uganda

Uganda has the lowest per capita electricity consumption rates in the world [4]. The Ugandan Power Sector Investment Plan estimates that a cumulative investment of about USD 9 billion (7.2 billion Euros) in funding, is needed between 2009 and 2030 to accommodate the rising electricity demand, and to achieve universal access to electricity [5]. Uganda is richly endowed with diverse energy resources which are fairly distributed throughout the country and namely: biomass, hydropower, solar energy, geothermal energy, wind energy, thermal energy, and fossil fuels (crude oil). Uganda has an energy mix with a significant contribution of approximately 95% from biomass while Electricity and petroleum products contribute 4% and 1 % respectively [6]. The cost of power produced to the final user is approximately US$0.11/kilowatt-hour, and is a high rate in the East African Community [7]. According to World Data Atlas in 2017, the total primary energy consumption of Uganda was 0.01 quadrillion Btu. The energy consumed is being sourced from different energy sources ranging from fossil fuels, biomass, solar power, and hydro power among others. Over 90% of the total consumed energy comes from biomass resources such as firewood (78.6%), charcoal (5.6%), crop residue (4.7%) and electricity with only 1.4%, and the remaining 9.7% is from petroleum products used to power vehicles and thermal power plants [8].

1.2 Health Care System in Uganda

The Ugandan health sector is a decentralized system composed of national and district levels. The health facilities are farther classified into seven levels based on the services they provide and the catchment area they are intended to serve. The health facilities are designated as Health Centre level one (HC I) to Health Centre Level four (HC IV); General hospital, Regional Referral hospital, and National Referral hospital. The respective services provided at each of the levels and the desired catchment area / populations are as in Table 1. There are Special clinics which are health facilities with specialised services like The AIDS Support Organization (TASO) Sites offering HIV related services only [9].

Table 1.1: Service Delivery by Each Level of Health Facility

Level	Target	Serves Provided
Health Centre I (Clinics)	1,000	Community based preventive and Promotive Health Services. Village Health committee or similar status.
Health Centre II	5,000	Preventive, Promotive and Outpatient Curative Health Services, outreach care, and emergency
Health Centre III	20,000	Preventive, Promotive, Outpatient Curative, Maternity, inpatient Health Services and Laboratory services.
Health Centre IV	100,000	Preventive, Promotive Outpatient Curative, Maternity, inpatient Health Services, Emergency surgery and Blood transfusion and Laboratory services.
General Hospital	500,000	In addition to services offered at HC IV, other general services will be provided. It will also provide in service training, consultation and research to community based
Regional Referral Hospital	2,000,000	In addition to services offered at the general hospital, specialist services will be offered, such as psychiatry, Ear, Nose and Throat (ENT), Ophthalmology, dentistry, intensive care, radiology, pathology, higher level surgical
National Referral Hospital	10,000,000	These provide comprehensive specialist services. In addition, they are involved in teaching and research.

1.3 Demography of Uganda

1.3.1 Geographical Location and Size of Uganda

Uganda is a landlocked country located in the East African Region. It is bordered by Kenya to the East, South Sudan to the North, Democratic Republic of Congo (DRC) to the West, Rwanda to the South West, and Tanzania to the South. Uganda lies across the equator at latitude 4°12’N & 1°29’S and longitude 29°34’E & 35°0’E. It covers a total surface area of 241,550.7 km^2 out of which the area under land is 200,523.2 km^2. Uganda has a minimum altitude is 620 m above sea level while the maximum altitude is 5,111 m above sea level [10], this is shown in Figure 1.1.

Figure 1.1: Location and Physical Features of Uganda [4]

1.3.2 Climate

Most regions of Uganda experience four well-marked seasons every year namely, two dry seasons and two wet seasons. The variations in mean temperature and annual rainfall are experienced across the country as a result of differences in altitude, landscape, as well as proximity to water bodies [11]. Lying at the equator, Uganda has a warm climate. Average temperatures vary little throughout the year, ranging from 20–27 °C depending on location and altitude. Temperatures are highest from December to March and lowest from June to October. Most part of Uganda receives an annual rainfall of at least 1,000 mm, but as with temperature this varies by location [12].

1.3.3 Demography of Uganda

The population censuses in Uganda have been conducted after every ten years since 1911. The population of Uganda was estimated as 40.3 million in 2019, as opposed to the 34.6 million in the recent population census of 2014 with a population density of 174 persons per km2 and the annual population growth rate between 2002 and 2014 censuses of 3.03 percent [10]. The 2019 Human Development Report shows that Uganda has a Human Development Index (HDI) value of 0.528, and is ranked 159 out of 189 countries and the life expectancy at birth is 63 years [13].

1.3.4 Economic Development of Uganda

Uganda has a GDP of 27.9 billion USD and per capita GDP of 666.6 USD while the estimated growth rate is 5.8% according to 2018 National Budget of Uganda. Agriculture is the backbone of Uganda's economy and contributes about 26% to the national GDP. The total budget of Uganda was UGX 32.7 trillion for 2018/2019 financial year and out of which Energy & Minerals sector was allocated 9.7% (i.e., UGX 2.438 trillion). The major economic activity is agriculture, which employs about 68% of the population; most of the agricultural practices are however, carried out on a subsistence scale [14].

1.4 The Policies and Institutional Framework of Uganda's Power Sector

Energy Policy of Uganda as set up in September 2002, shows the government's commitment to the development and use of renewable energy resources for both small- and large-scale applications. The goal of this policy is to meet the energy needs of Uganda's population for social and economic development in an environmentally sustainable manner. The key objectives of this policy are to: (i) publish a standardized Power Purchase Agreement (PPA) with feed-in-tariffs determined periodically, (ii) create a renewable energy department, (iii) promote collaboration with the National Forestry Authority (NFA) and Ministry of Agriculture, Animal Industry, and Fisheries (MAAIF), the growing of energy crops, (iv) develop appropriate legislation, and (v) provide financial incentives for the production of biofuels [15]. Renewable Energy Policy for Uganda released in March 2007, set out the government's policy vision, goals, principles, and objectives for promoting sustainable utilization of renewable energy in Uganda. The vision of the policy for renewable energy is to make modern renewable energy a substantial part of the national energy consumption [16]. The Government of Uganda regulates power policy which is impartially liberalized with room for private players to provide other related services. However, the transmission segment remains a government preserve under Uganda Electricity Transmission Company Limited. The main players in the energy sector of Uganda are the government through the Ministry of Energy and Mineral Development, development partners, and the private sector. The government provides overall policy direction, while implementations take place at different agency level such as the: Electricity Regulatory Authority (ERA), the Atomic Energy Council (AEC), Electricity Disputes Tribunal (EDT), Rural Electrification Board (REB), Rural Electrification Agency (REA), Uganda Electricity Generation Company Ltd (UEGCL), Uganda Electricity Transmission Company Ltd (UETCL), Uganda Electricity Distribution Company Ltd (UEDCL), Uganda Energy Credit Capitalization Company (UECCC) [17].

1.4.1 Energy Act of Uganda

The Electricity Act 1999 of Uganda establishes the Electricity Regulatory Authority (ERA). By virtue of the Electricity Act of 1999, different statutory instruments have been issued which include: The Electricity Regulations for Installation Permits of 2003, the Electricity Regulations for License Fees of 2003, the Electricity Regulations for Primary Grid Code of 2003, the Electricity Regulations for Quality of Service Code of 200,3, the Electricity Regulations for Safety Code of 2003, and the Electricity Regulations for Tariff Code of 2003. The Uganda's Petroleum Act of 1964 governs the downstream industry in the petroleum sub-sector, while the Petroleum Exploration and Production Act of 1985 regulate the upstream activities in the petroleum sub-sector [16]. According to the UBOS report of 2019, the total installed capacity of electricity power sources increased by 5 % from 937.8 MW in 2017 to 984.5 MW in 2018, while the national on grid energy generated increased by 6.2 percent from 3,801.4 GWh in 2017 to 4,038.8 GWh in 2018. Article 56 of the Electricity Act 1999 obliges the authorities to publish standardized tariffs based on the avoided cost of the system for sales to the grid, of electricity generated from renewable energy systems of up to a maximum capacity of 20 MW [16]

1.4.2 Rural Electrification Master Plan

In Uganda, rural electrification is the mandate of a semi-governmental Rural Electrification Agency (REA), which was set up under the Ministry of Energy and Mineral Development (MEMD) and has been operational since 2003. The government has targeted the year 2022 to achieve 26% electricity access in rural areas of Uganda, which is about 1,300,000 grid consumers and 140,000 PV connections [18]. The main objective of Uganda's Rural Electrification Strategy and Plan (RESP) 2013-2022 is to achieve an accelerated pace of electricity access and service penetration to meet national development goals during the planning period and beyond. The strategy of the Government is to achieve a rural electrification access of 26% by 2022. The pace of acceleration expected in the RESP also projects access to be at 51% by 2030, and100% by 2040 [19]. The RESP identifies the need to develop standardized procedures for small power producers, as small systems can play a key role in rural electrification, especially due to the dispersed nature of demand in Uganda, thus suggesting that mini-grids are the least-cost solution. The strategy is being implemented through a combination of approaches such as grid extension, mini-grids in concentrated settlements, and PV standalone systems in dispersed and isolated settlements.

1.4.3 Feed-in Tariff Policy

To promote the development and use of renewable energy sources in Uganda, the government developed a feed-in-tariff (FIT) structure. A Feed-in-Tariff is an instrument for promoting private sector generation of electricity from renewable energy sources. The standardized FITs are established in accordance with the provision of the Electricity Act 1999. Under the Renewable Energy Policy (2007), a Renewable Energy Feed-in-Tariff (REFIT) was initially established in Uganda which ran from 2007 to 2009. It was reviewed in 2010 and a new tariff was developed based on updated Levelized costs of production that was also later reviewed in 2012. The REFIT applies to small-scale renewable energy systems of prescribed priority technologies, up to a maximum installed project capacity of 20 MW and greater than 0.5 MW as defined by the Electricity Act 1999. The REFIT is managed and implemented by ERA as part of its mandate under the Electricity Act of 1999. The ERA board approved 0.11 USD/kWh as the FIT for solar power in April 2014 [20].

1.5 Problem Statement

Efforts to improve access to green and sustainable energy in developing countries have generated a lot of attention in the recent past. Globally, ensuring access to affordable, reliable sustainable and modern energy for all is Sustainable Development Goal 7 of the 17 SDGs adopted under the United Nations' post-2015 development agenda. At a national level, many countries have adopted similar initiatives to encourage and speed up access to, and use of modern energy services. In Uganda, energy access objectives, strategies, and interventions have been included in previous and current National Development Plans. The government of Uganda has set her objectives in the energy and renewable energy policies, which are: to meet the energy needs of Uganda's population for socio-economic development in an environmentally sustainable manner and to increase the use of modern renewable energy sources from the current 4% to 61% [21]. However, even with such efforts, millions of people in the country still lack access to reliable and modern energy services. The uncontrollable nature of renewable energy resources, high initial investment costs, and dependency on weather conditions result in combining different renewable resources to form a 'hybrid system' which can be flexible, cost effective, reliable and efficient. Although, the government of Uganda has tried to increase the electricity access, there is still a problem of power blackouts which needs to be addressed by using a hybrid power system, since the country is endowed with solar and also with moderate wind energy potential. Hence, the techno-economic analysis of hybrid systems will ensure that a right combination of resources is chosen.

1.6 Research Hypothesis

An optimally designed solar PV–wind hybrid system can supply electricity to meet the power needs of Busitema Health Centre III, sustainably and at low cost.

1.7 Research Questions

Answers to the following questions will help in achieving the objectives of this research.

1. What is the energy demand of Busitema Health Centre III?
2. Is it possible to design a hybrid PV-wind system for Busitema Healthy Centre III?
3. What is the suitable hybrid power system configuration that sustainably and optimally meets the energy needs of Busitema Healthy Centre III, considering the available energy potential?
4. Can the electricity from the suggested hybrid energy system be able to compete with the one from the national grid?

1.8 Aim and Objectives

The aim of this research is to design an optimally sized cost-effective PV–wind hybrid system to meet the electricity demand of Busitema Health Centre III (in Eastern Uganda), in an affordable, reliable, and sustainable way. In meeting this aim, the following specific objectives are to be examined:

1. To investigate the energy demand of Busitema Health Centre III in Busia Eastern Uganda.
2. To model the different physical components that build up the hybrid power system.
3. To simulate and optimize various Renewable technologies using HOMER Pro software.
4. To perform a techno-economic analysis of the hybrid electricity generation system of the case study.

1.9 Significance of the Study

Renewable energy and energy efficiency are critical for stabilizing climate change and to reach universal access to energy, through an integrated approach [22]. To ensure that global warming remains below 2°C, it is critical to accelerate deployment of renewable energy (RE) and energy efficiency (EE) techniques to de-carbonize energy supply. This is thus one need to focus this research on RE technologies. An optimally designed solar PV–wind hybrid system will be a reliable solution for providing power to Busitema Health Centre III. This work is of utmost importance to the country due to the fact that it will reduce the heavy reliance on the power from the national grid that is characterized by continuous blackouts. This will also help in supplying power at reasonable costs and in an environmentally friendly way. This research will improve knowledge in the field of power generation and register a way forward towards more affordable green power generation technologies. The results from the analysis of the system will be used for conducting similar designs across different hospitals in rural communities of the country.

1.10 Scope of the Study

The research was limited to modelling and optimization towards finding the optimum hybrid energy system (HES) configuration for the techno-economic analysis of stand-alone solar PV–wind power system. An optimization process was carried out using HOMER pro software. Busitema Health Centre III, in Busia district Eastern Uganda was used as the case study.

2. LITERATURE REVIEW

2.1 Introduction

This chapter will include current information on energy production and energy/renewable energy resource assessment of Uganda. An overview of energy access in Uganda will be conducted alongside the rural electrification plan of Uganda. An extensive literature review will be conducted on Hybrid Renewable Energy System (HRES) and its components, their working principles and existing technologies. Mini-grid and micro-grid systems will also be explained. Finally, this chapter will review different relevant energy modelling tools, their application in different hybrid projects and applications of Artificial Intelligence in HRES modelling.

2.2 Energy Resources in Uganda

Uganda is endowed with substantial and diverse energy resources of both renewable and conventional in nature, that are equitably distributed throughout the country. The prominent resources include: biomass, hydro-power, solar energy, geothermal energy, wind energy, peat, and crude oil/petroleum (recently discovered). Recent estimates put Uganda's hydropower potential at about 2000 MW spreading across large, small, and mini-hydro sites across the country. Uganda has an average solar irradiation of 5.1 kWh/m^2/day on a horizontal surface; this quantity is very suitable for photovoltaic applications. Solar energy potential is highest in the semi-arid areas in the north-east and lowest in the mountain ranges of south-west [23]. The biomass potential for Uganda is estimated to be over 284 million tonnes of standing biomass stock. Biomass cogeneration potential is also estimated to be 1650 MW. Other resource potentials include geothermal (450 MW), peat (800 MW), and an approximate 3 billion barrels of crude oil [17].

2.2.1 Conventional Energy Resources

2.2.1.1 Crude Oil

In 2006, the government of Uganda confirmed the existence of economically viable petroleum reserves in the Albertine Region. In 2014, it was estimated that there were 6.5 billion barrels of oil in the Albertine Region; the recoverable oil was predicted to lie between the range of 1.8 and 2.2 billion barrels. The oil production was projected to reach heights of between 200,000 and 250,000 bpd based on present discoveries. Peak production is projected to last for ten years and commercial production will have a lifespan of 30 years based on present discoveries and prevailing technology.

Unfortunately, since the initial discovery of the oil in 2006, Uganda has struggled to make the Final Investment Decision.

2.2.1.2 Natural Gas

After discovering oil in 2006 at the Albertine region, natural gas reserves were also discovered. Natural gas can be associated gas (found in combination with oil), or non-associated (i.e., independent natural gas reservoir). The associated gas recognized in Uganda as at 2017 was projected to reach 170 billion cubic feet (bcf), while non-associated gas was projected to be 500 billion cubic feet [24].

2.2.1.3 Peat Resources

A significant amount of peat resources also exists in Uganda, of which about 25 million tons is viable for power generation and corresponding to 800 MW of potential capacity for 50 years. Using the best commercially available Circulating Fluidized Bed (CFB) technology with 16% conversion efficiency, the power generating potential from peat in Uganda would amount to about 10,300 GWh [6].

2.2.2 Renewable Energy Resources

Uganda has various renewable energy resources that are widely available in different parts of the country, and with different potentials.

2.2.2.1 Solar Energy

Solar energy can be converted to electricity on and off-grid through photovoltaic or concentrated solar power (CSP) technology. Uganda is endowed with favourable solar radiation ranging from 1,825 kWh/m^2/year to 2,500 kWh/m^2/year. About 200,000 km2 of Uganda's land area has solar radiation exceeding 2,000 kWh/m^2/year (5.48 kWh/m2/day) this is a high potential for solar power investment. According to available solar data, it is shown that the solar energy resource in the country is high during the whole year which is so because of Uganda lies at the equator. Figure 2.1 shows the solar map of Uganda. The solar radiation is found to be very high in the North-East and very low in the mountainous areas especially in the east and South-West. However, as you move away from the Equator, solar radiation varies up to a maximum of 20%. Uganda has an estimated 200 MW potential of electrical capacity from solar [25].

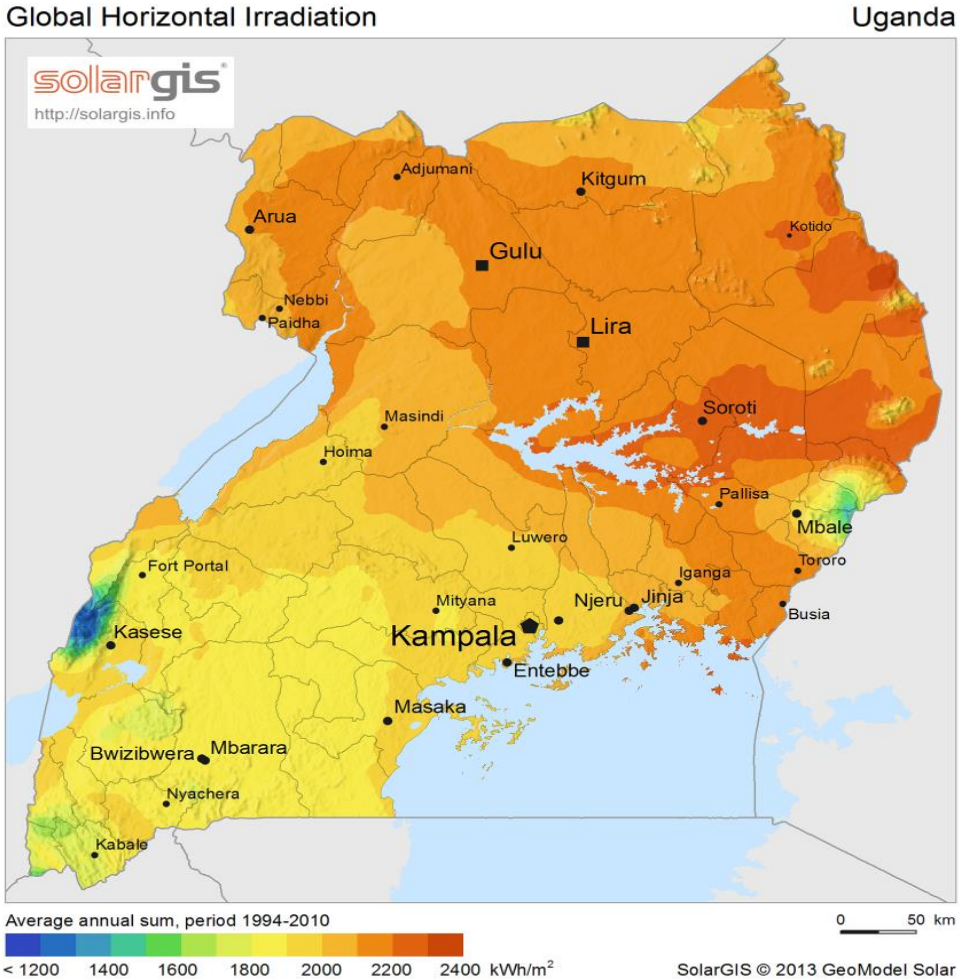
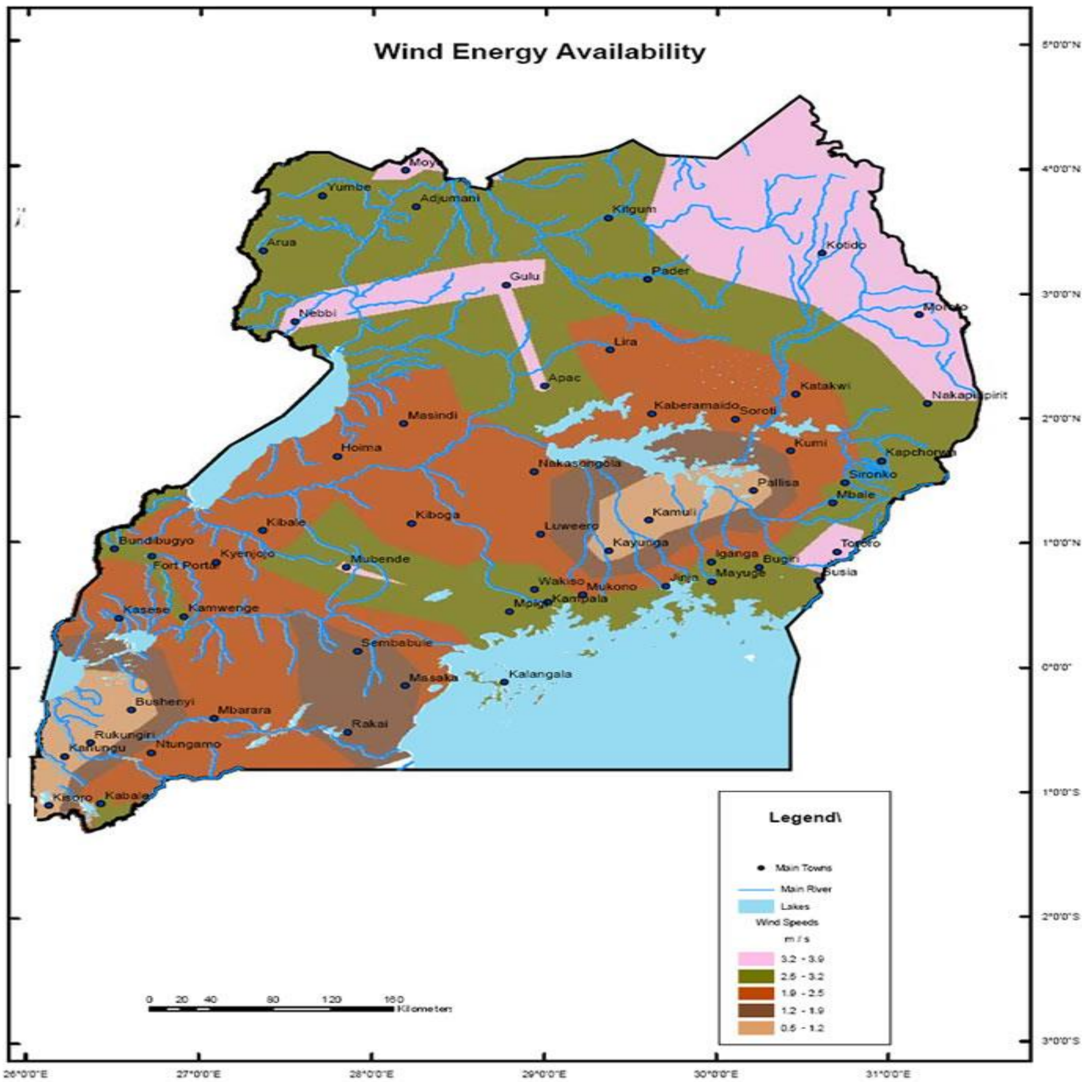


Figure 2.1: Solar Map of Uganda [26]

2.2.2.2 Wind Energy

From meteorological records, most areas in Uganda have moderate wind speed ranging from 2 m/s to about 4 m/s, and with an average of about 3 m/s. In flat surfaces like around Lake Victoria and the Karamoja region, including tops of hilly areas, the speed varies and may reach about 6 m/s, which is sufficient to run wind generators. Wind map of Uganda is shown in Figure 2.2. However, the contribution of wind energy to national energy needs is often downplayed by government technocrats arguing that the lower wind speeds are the ones most predominant in the country and therefore making wind energy less resourceful. Also, the wind speeds were recorded at low meteorological heights and not the standard 10 meters, hence, the wind speed may be much higher than indicated [27]. Commercially available wind speeds are found in Tororo, Soroti and Busia (Eastern Uganda), Pader (West Nile) and Nakapiripirit (North-Eastern Uganda).



Source: The Renewable Energy Policy for Uganda, November 2007

Figure 2.2: Wind Map of Uganda [28]

2.2.2.3 Hydropower

Currently, hydro power contributes 85% electricity to the country’s national grid. Discrepancies in water flow cause substantial variations between installed capacity (683 MW) and actual generation (300 to 350 MW). The hydro-power potential in Uganda is estimated to be about 2,000MW, and located mostly along the Nile river [29].

2.2.2.4 Geothermal

Uganda is in the East African Rift Valley; this location gave the country a potential advantage for geothermal energy exploitation. The country has more than 40 geothermal sites that have been assessed. The geothermal capacity of Uganda at this investigation phase is predicted to be 450 MW. Geothermal exploitation is expected to commence soon at three sites including Katwe-Kikorongo, Buranga, and Kibiro (Figure 2.3), in the Western part of the country [6], [17].

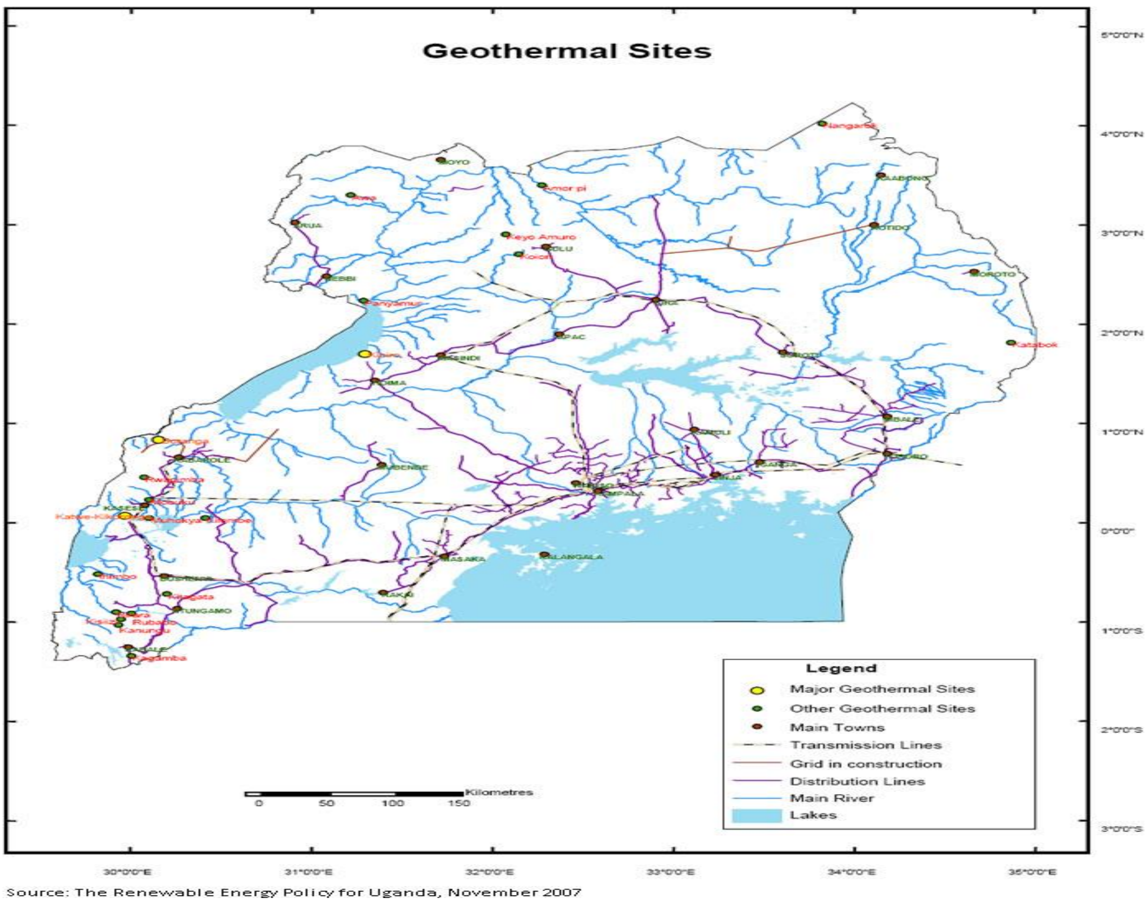


Figure 2.3: Existing Geothermal Sites in Uganda [28]

2.2.2.5 Biomass

Biomass (firewood, charcoal, crop residues, and bagasse) is the major energy source used in Uganda. It has an average demand of 44 million tonnes per year; this accounts for 94% of the total energy consumption in the country, thereby contributing approximately 6% to the country's Gross Domestic Product (GDP). Charcoal is largely used in towns for cooking; its utilization increased from 245 ktoe in 2000 to 1,552 ktoe in 2015. Firewood, agro-residues, and wood wastes are widely used in the villages. The total biomass stock is 284.1 million tons, but the sustainable potential supply of the entire biomass is 45 million tons [30]. The major sources are hardwood plantations, which consist of eucalyptus (50%), pine trees (33%) and cypresses (17%). Fuel wood is the greatest consumed primary fuel, with yearly consumption of approximately 28 million tonnes. The accessible sustainable wood biomass is 26 million tons [31]. Currently, biomass in the form of wood is exploited unsustainably. About 44 million tonnes/year of woody biomass is harvested but the available forests can only produce 26 million tonnes of biomass/year in a sustainable manner [32].

2.3 Existing Energy Technologies and Projects in Uganda

2.3.1 Solar Energy Technology

Three solar technologies are currently available, including photovoltaic (PV) cells, concentrating solar panel (CSP) and solar heating and cooling (SHC) technology.

2.3.1.1 Solar Heating and Cooling (SHC)

This technology is mainly preferred for large-scale plants with clear skies, i.e., under an intense sun. SHC directly extracts thermal energy straight from the sun to heat and cool residential or commercial buildings.

2.3.1.2 Concentrated Solar Power (CSP) Technology

Concentrated Solar Power (CSP) system utilizes concentrating lenses and mirrors to focus direct solar irradiation on a small area. The concentrated radiation can be applied to generate electricity indirectly. The absorbed heat from solar irradiation is used via thermodynamic cycles to produce electricity. Electrical power is produced when the concentrated heat drives a heat engine (usually a steam turbine) connected to an electrical power generator. It is possible to generate electricity even in the absence of the sun, which serves as the main advantage when compared to PV technologies. The conversion efficiency of CSP ranges from 20% to 24%. This technology is mainly ideal for comparatively large-scale plants.

2.3.1.3 Photovoltaic Solar Energy Technology

Photovoltaic (PV) solar cells directly convert sunlight into electricity, using the photovoltaic effect [33]. A PV system consists of PV cells that are grouped together to form a PV module, and the auxiliary components (balance of system - BOS), including the inverter and controls among other. A PV array used in the PV system is the complete power-generating unit, consisting of any number of PV modules and panels. A PV module consists of PV cell circuits (Figure 2.4) sealed in an environmentally protective laminate; panels include one or more PV modules assembled as a pre-wired, field-installable unit.

Figure 2.4: Photovoltaic Cell [34]

The PV modules are connected in series and in parallel to scale-up the voltage and current, in order to obtain the expected power output levels. The maximum power point tracking system is used to extract the maximum power from the PV arrays. The PV market is largely dominated by crystalline silicon solar cells (monocrystalline or polycrystalline, shown in Figure 2.5) with a rate of almost 80%. Other than this, many other technologies are already available or under research. For example, thin film solar cells (Figure 2.6) are making their way to the PV market due to the low cost of manufacturing and ease of production.

2.3.1.3.1 Types of Photovoltaic Solar Cells

2.3.1.3.1a Crystalline Silicon-Based Solar Cell

Crystalline silicon (c-Si) modules account for 85 to 90% of the actual global annual market [35]. The availability and low cost of silicon make it a prominent choice of material. In addition, it is characterized by its low coefficient of absorption, and low energy band gap. Crystalline silicon is divided into monocrystalline and polycrystalline.

2.3.1.3.1b Monocrystalline Silicon

This is the base material used in all electronic equipment today; its cells are characterized by a high purity and obtained by Czochralski process and zone melting methods. The silicon used is cut from one large crystal. The internal structure is highly ordered, which allows electrons to move easily through it. This type of silicon makes it possible to produce high efficiency PV cells (26.1% in laboratory). The practical conversion efficiency of these cells ranges from 13% to 17% and with lifespan of 25 to 30 years[36].

2.3.1.3.1c Polycrystalline Silicon

This is cheaper since it is of a lower quality, and generally obtained by directional or progressive solidification of silicon ingots. It contains more impurities (metal impurities, oxygen, carbon, etc.). It is made from the combination of many silicon crystals [37]. Consequently, the conversion efficiency is lower than the monocrystalline silicon technology. Polycrystalline silicon cells have an efficiency ranging from 10% to 14% and lifespan between 20 and 25 years [36]. The multi-junction solar cells have a much higher efficiency of 46% at laboratory level.

2.3.1.3.1d Amorphous Silicon

These solar cells belong to the category of silicon thin-film, where one or several layers of photovoltaic material are deposited onto a substrate; their low power output limits their use to small applications only. The first generation of thin film solar cells produced was a-Si. To reach higher efficiencies, thin amorphous and microcrystalline silicon cells have been combined as thin hybrid silicon cells. With II-VI semiconductor compounds, other thin film technologies have been developed, including cadmium telluride (CdTe) and copper-indium-gallium-diselenide (CIGS). Cadmium Telluride (CdTe) and Perovskite PV cells have witnessed an increase in efficiency, reaching 22.1% and 22.7%, respectively [38].

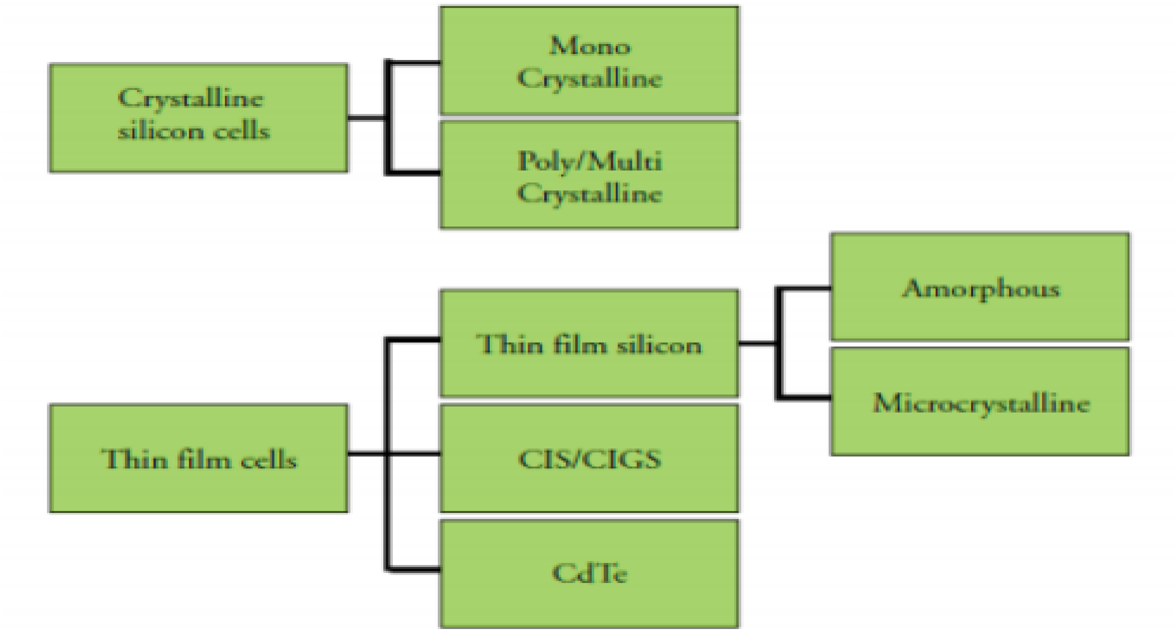


Figure 2.5: Photovoltaic Technology classes [39]

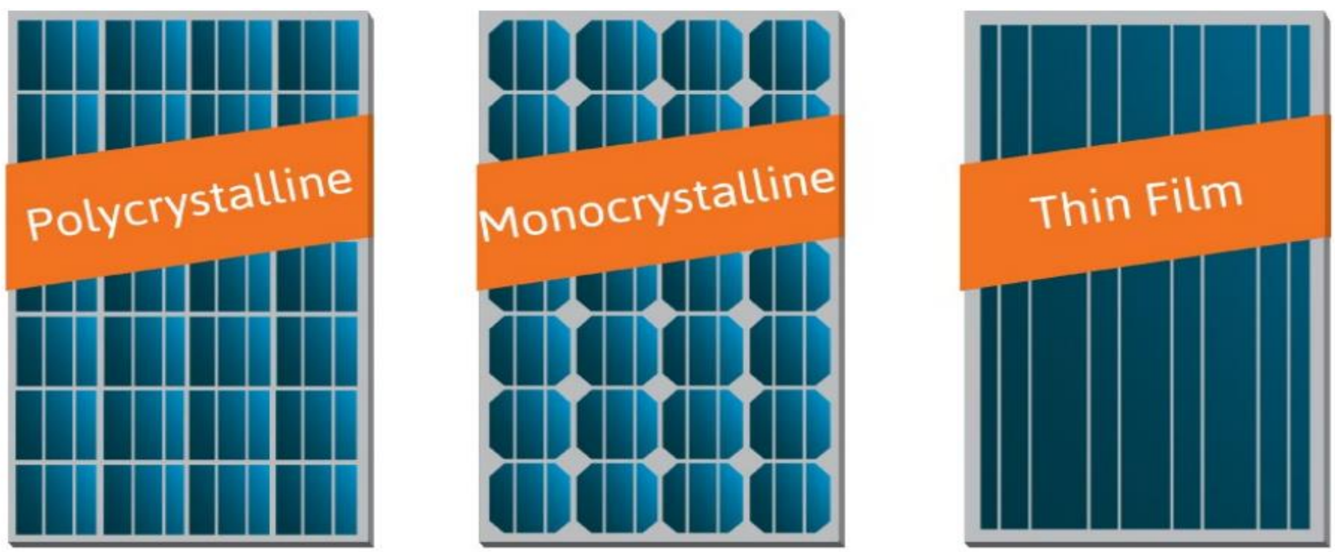


Figure 2.6: Different Types of Solar Panels [40]

2.3.1.3.2 Photovoltaic Module Performance

The total energy output (Wattage) of a photovoltaic module equals its output voltage multiplied by its operating current. Unlike voltage sources such as batteries which produce current at relatively constant voltage, photovoltaic modules may produce current over a wide range of voltages. The output characteristics of a module are characterized by performance curve called an I-V Curve that shows the relation between current and voltage output as shown in Figure 2.7 [41].

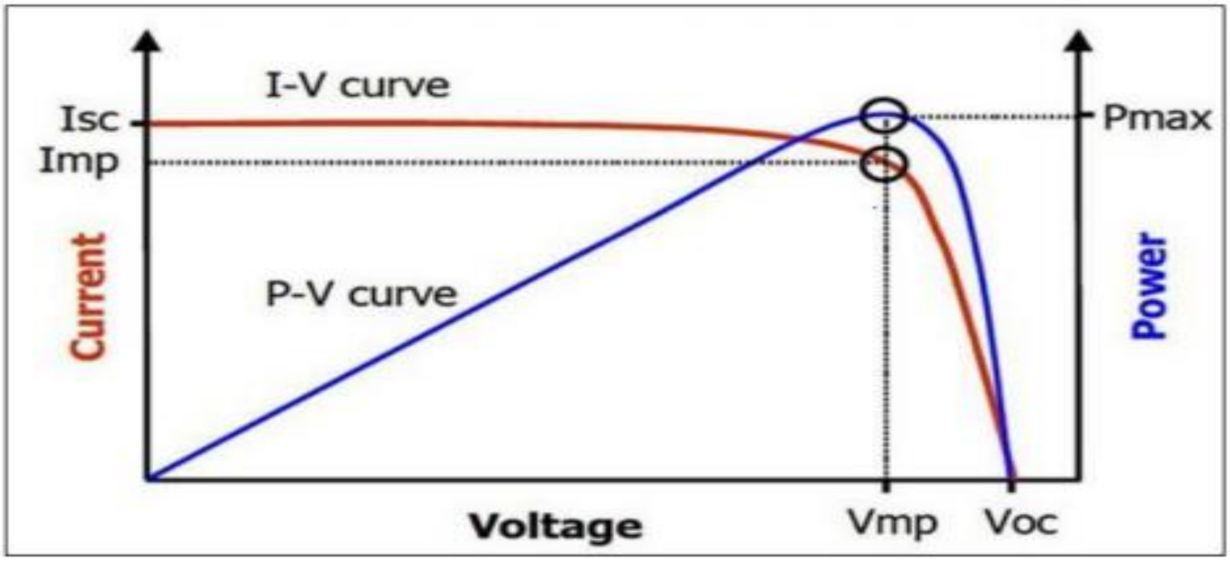


Figure 2.7: The Characteristic Curve of a PV Module [42]

Characteristics of the I-V curve:

1. Maximum Power Point (MPP/ Pmax): labelled Vmp, Imp on the I-V curve; this is the operating point at which the maximum output will be produced by the module at operating conditions indicated above i.e. **Pmax** = **Imp** × **Vmp**

2. The Open Circuit Voltage (Voc): The maximum potential voltage achieved when no current is being drawn from the module. As shown in Figure 2.7, the open circuit voltage (VOC) occurs when there is no current passing through the cell i.e., V (at I=0) = V_{OC}; V_{OC} is also the maximum voltage difference across the cell for a forward-bias sweep in the power quadrant.

V_{OC}= V_{MAX} for forward-bias power quadrant.

3. The Short Circuit Current (Isc): The maximum current output which could be reached by the module under the conditions of a circuit with no resistance. The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low. and calculated when the voltage equals 0 i.e., I = ISC at V=0

4. Maximum power operating current (Imp): The current for the cell corresponding to the

maximum power point on the array's current-voltage (I-V) curve.

5. Maximum power voltage (Vmp): The voltage at the maximum power point on the array's current voltage (I-V) curve.

6. Fill Factor (FF): A measure of the quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (PT) that would be output at both the open circuit voltage and short circuit current together i.e., $\boldsymbol{FF} = (\boldsymbol{Imp} \times \boldsymbol{Vmp})/ (\boldsymbol{Isc} \times \boldsymbol{Voc})$.

7. Efficiency (η) is the ratio of the electrical power output corresponding to the maximum power (Pmax), compared to the solar power input (Pin). To get maximum efficiency, solar cell should be operated at its maximum power i.e., $\eta=\boldsymbol{Pmax}/\boldsymbol{Pin}$.

2.3.1.3.3 Effect of Irradiance on PV Module I-V Characteristics

The solar irradiation, which is the measure of the sun's energy, has an influence on performance of PV cell due to its time variation. The quantity of irradiance decreases in hazy (cloudy) days and becomes reduced on overcast days. The solar cell current, which is directly proportional to the solar irradiance is the most affected parameter. In contrast, the voltage varies slightly and is usually ignored [43]. The biggest influence on the power output of a solar panel is naturally caused by the variation of sunlight; hence, output power is almost linearly proportional to incident solar irradiation. Therefore, irradiation directly affects the short circuit current (Isc) of the PV cell; it has little/no impact on the open circuit voltage (Voc).

2.3.1.3.4 Effect of Temperature on PV Module I-V Characteristics

Temperature affects the electricity flow in the electrical circuit. This is done by changing the speed at which electrons move. The voltage parameters are affected by the module temperature. As temperature increases, the open circuit voltage of the photovoltaic cell decreases and the short circuit current slightly rises. Both the open-circuit voltage (Voc) and the maximum voltage (Vm) decrease when the module temperature decreases. This can be explained by the increase in the circuit resistance. The decrease in the silicon solar cell is around 2 mV/°C and the temperature effect on the Maximum Power Output (Pmax) is -0.005 mW/°C. Under the STC, the conversion efficiency of the PV panel is decreased by about 0.40 - 0.50 % for each degree rise in temperature [44].

2.3.1.3.5 Solar PV Orientation and Tilt Angle

The tilt angle or slope of the PV array varies depending on the location of its mounting. Previous studies demonstrate that the basic routine that regards to mounting sunlight-based modules is to have them at a fixed angle with reference to the ground since it is the least complex and least expensive alternative (Table 2.1). Angle of tilt equals to the latitude of the location, and the correct azimuth will empower the solar array to extract maximum radiation when irradiance is high between 10 AM and 4.30 PM in many areas [45].

Table 2.1: Recommended Fixed Angles for Solar Modules

Latitude Angle	Recommended Angle
Latitude < 15 degrees	15 degrees
15 degrees < Latitude < 20 degrees	Latitude
20 degrees < Latitude < 35 degrees	Latitude +10 degrees
35 degrees < Latitude	Latitude + 15 degrees

2.3.1.3.6 Effect of Humidity

The efficiency of the PV module is affected by relative humidity. Relative humidity has an impact on the current, voltage, and power output. When the relative humidity drops, the power and efficiency increase. Furthermore, Monocrystalline panels, compared to other technologies, deliver the highest efficiency in situations where relative humidity decreases [46].

2.3.1.3.7 Major Solar Energy Projects in Uganda

In 2016, the Electricity Regulatory Authority licensed two major solar power stations, each having capacity to generate 10MW. The Soroti solar power plant is a fixed tilt solar PV power plant; the project is a partnership between the government of Uganda and the Netherlands Development Bank, and cost USD 19 million. The project is estimated to reduce carbon emissions of Uganda by 264,355 tons per annum. The Tororo PV Solar Plant was built in 2017 in eastern Uganda (10 km from the border of Kenya) on an area of 14hectares. The project was funded by the Dutch development bank and consists of 32,240 photovoltaic panels with a capacity of 10MW to provide energy needs for 35,838 households. The Plant is promoting clean industrial development in the town of Tororo, and at the same time reducing global warming by saving more than 7,200 tons of CO_2 emissions into the atmosphere per year. The project cost was a USD 19.6 million investment [25]. In January 2019, a 20MW Kabulasoke PV power plant with 68,000 solar modules was commissioned in Gombe district. Apart from these utility scale solar plants, there are other small PV mini- and micro-grid projects as shown in Figure 2.8.

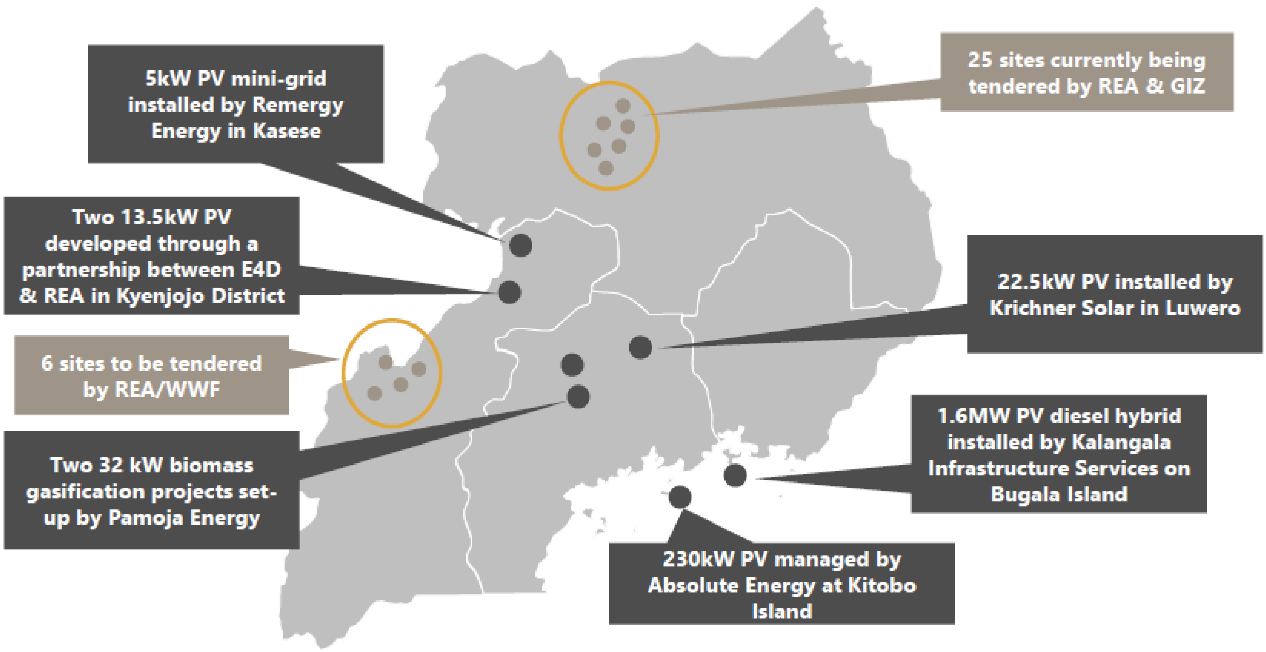


Figure 2.8: Small PV Projects in Uganda [47]

2.3.2 Wind Energy Technology

The amount of energy in the wind available for utilization by the turbine increases with the cube of wind speed; therefore, a 10% increase in wind speed corresponds to a 33% increase in available energy [48]. A wind turbine plays a crucial role in wind energy technology. A wind turbine is a machine which converts wind power into electricity, and it consists principally of a rotor, an electric generator, and a gearbox. The energy conversion in current wind turbines is done in two processes: (i) the rotor first extracts the kinetic energy of wind by means of friction between the air and its blades, (ii) with the help of a shaft, the rotor converts the kinetic energy into mechanical torque, while the generator then converts the mechanical energy into electricity [49]. Although this working principle sounds rather straightforward, wind turbines are complex systems and require knowledge of aerodynamics, mechanical, civil, electrical and control engineering. Given the working principle of wind turbines, the power generated is inherently dependent on the wind speed [50]. The theoretical mechanical power extracted from the wind can be calculated using Equation (2.1):

$$P = \frac{1}{2}\rho_{\alpha} A_T v^3 \tag{2.1}$$

The actual electrical power that is obtainable from a wind turbine is given in Equation (2.2):

$$P = (C_p \varepsilon_g \varepsilon_b)\frac{1}{2}\rho_{\alpha} A_T v^3 \tag{2.2}$$

where,

P = Power in Watts (646W = 1hp) (1,000W = 1kW)

ρ_{α} = air density (about 1.225Kg/m^3 at sea level, decrease with altitude)

A_T = rotor swept area, exposed to the wind (m^2)

C_p = Coefficient of performance, also called power coefficient

v = wind speed in m/s (20mph = 9m/s)

ε_g = generator efficiency

ε_b = gearbox/bearings efficiency

The wind speed is important for operation of a wind turbine. When the wind speed exceeds the cut-in value, the wind turbine generator will start generating power. If the wind speed exceeds the rated speed of the wind generator, it generates constant output power, and if the wind speed exceeds the cut-out value, the wind turbine generator stops running to protect the generator.

2.3.2.1 Types of Wind Turbines

Wind turbines can be classified in terms of the axis around which the turbine blades rotate; this includes: the horizontal axis wind turbines (HAWT) and the vertical axis wind turbine (VAWT).

2.3.2.1.1 Horizontal Axis Wind Turbines (HAWTS)

These machines are called HAWTs because the rotor’s rotation axis is horizontal, parallel to the wind direction. They generally comprise propellers with two or three blades, or multi-blade propellers for water pumping (Figure 2.9). They are the most widespread machines due to: (i) their superior performance to that of all other machines, (ii) they have a high efficiency, and (iii) they are simple to design. Turbines can have two or more number of rotor blades groups in their propeller.

Figure 2.9: HAWTs with three Rotor Blades [51]

2.3.2.1.2 Vertical Axis Wind Turbines (VAWTs)

They were the first to be developed for electricity production, and their axis of rotation is vertical and perpendicular to the wind direction. They have a main advantage over HAWTs by having the control devices and the generator on the ground, which means they are easily accessible for maintenance activities. Moreover, they are suitable for all wind speeds and do not require orientation. Savonius and Darrieus are the two most known VAWTs (Figure 2.10).

2.3.2.1.2a Savonius

The Savonius wind turbine mainly comprises two half-cylinders whose axes are offset with respect to each other. Like paddle machines, it uses basically the drag to turn. This machine has two advantages:

1. It is simple to manufacture.
2. It starts with wind speeds of around 2 m/s.

2.3.2.1.2b Darrieus

The Darrieus wind turbine was named after its inventor, it is basically a rotor whose shape is reminiscent of an eggbeater. This machine is well adapted for electricity supply. However, its main drawback is the fact that it cannot start alone.

a)

b)

Figure 2.10: Vertical Axis Wind Turbine (a) Darieus, (b) Savonius [52]

2.3.3 Hydro Power Project

The government of Uganda is investing in hydropower infrastructure to meet the increasing demand for energy, thereby lowering production costs, improving on the country's competitiveness and increasing access to electricity. Some of the developed hydropower plant in Uganda include: Nalubaale (formally known as Owen Falls Hydropower Station) is 180 MW, Kiira (200 MW) and Bujagali (250MW); these are the large hydropower plants before 2018, before the commissioning of 183 MW Isimba hydropower project and the 600 MW Karuma hydropower plant. Several small hydropower sites with a potential of about 210 MW have also been identified through different studies (NPA, 2015). Some of the small-hydro power stations are: Kuluva (120 kW), Kagando (60 kW), Mubuku I (5.4 MW), Mobuku II (14 MW), Mobuku III (10.5 MW), Kanungu (6.4 MW), Mpanga (18 MW), and Kisiizi (300 kW). These small hydro plants supply electricity to remote hospitals and small isolated communities [17]. Studies on a 600 MW Ayago hydropower project is ongoing. Other potential sites for hydropower that are expected to be established soon include the Kalangala with a potential capacity of 450 MW, Oriang with a potential capacity of 400 MW, Kiba with a potential capacity of 300 MW, and Murchison Falls with a potential capacity of 600 MW.

2.4 Electrification Access Rates and Prices in Uganda

The National electrification access rate of Uganda is about 26.1%, with 54.8% in urban and 19.9% in rural areas [6]. The national development plan of the government of Uganda targets to bring grid access to 30% of the population by 2020 and 80% by 2040, with a goal of increasing per-capita electricity consumption to 578 kWh by 2020 and 3,668 kWh by 2040 [17].

2.5 Off-grid Electrification

2.5.1 Hybrid Renewable Energy Systems (HRES)

A hybrid renewable energy system (HRES) is a combination of multiple types of renewable energy sources such as solar, wind, biomass, geothermal, hydropower and other auxiliary power components like inverter and battery. The basic working principles of HRES components are briefly described as shown in Figure 2.11. The description is limited to a selection of the most important components that are used in this work, namely: PV systems, wind turbine, and energy storage systems. A hybrid energy system integrates different energy sources to form a single system such that the weakness of some energy sources is complemented by the strengths of other energy sources. For instance, a PV hybrid system, wind hybrid system, and PV–wind hybrid systems are employed to meet the load demand. Once the power resources (solar and wind energy) are sufficient, the excess power generated is supplied to the battery until it is fully charged. Thus, the battery comes into play when the renewable energy sources (PV–wind etc.) power is not able to satisfy the load demand until the storage is depleted. In order to evaluate the maximum output from each component of the PV – wind hybrid system, the single component is first modeled, thereafter the combination needed to meet the required need, can then be evaluated.

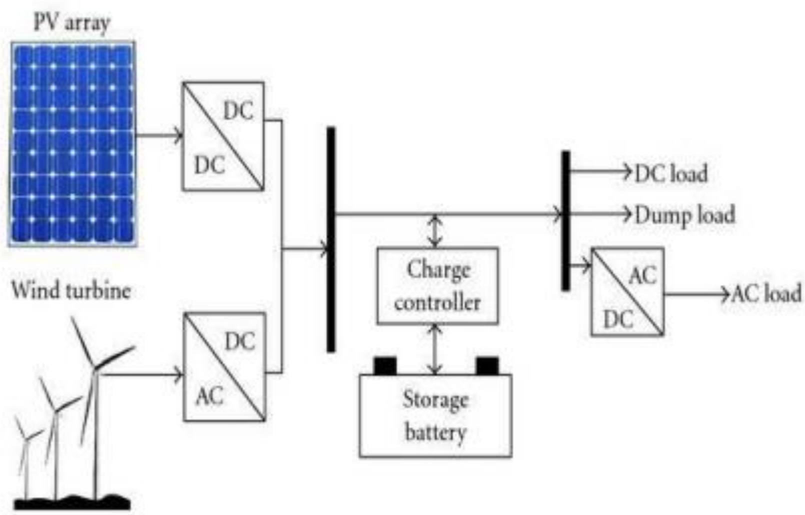


Figure 2.11: A Schematic Diagram of Solar Wind Hybrid System [53]

2.5.1.1 Photovoltaic System

In a photovoltaic (PV) system, the sunlight is converted into electricity without the use of any heat engine. Solar PV systems can be classified based on the end-use application of the technology. There are two main types of solar PV systems namely; grid-connected (or grid-tied) and off-grid (or stand-alone) solar PV systems [54]. They are used as a power source for remote buildings, communications, satellites, water pumping, space vehicles, reverse osmosis plants, and for even utility-scale power plants. A solar PV system consists of various PV modules that are interconnected in series and/or parallel circuits to produce higher voltages, currents and power levels, being complemented by other components such as inverters, Maximum Power Point Trackers (MPPT), and charge controllers.

2.5.1.2 Wind Turbine

A suitable wind-turbine model is very important for wind power output simulations. Usually, a wind turbine power - speed curve shown in figure 2.12 is used to describe the performance of wind turbines, namely the power output of a wind turbine at a specific wind speed [55]. The power – speed curve is given by the manufacturer and usually describes the real power transferred from the wind generator to AC bus [56]. When wind speed V is less than the cut-in wind speed Vcut−in, the wind turbine will not work, and no wind power will be generated. When V is located in between Vcut−in and rated wind speed Vrated, the output power increases as the wind speed increases and finally the output power reaches a constant which is the rated wind power Prated. when the wind speed is larger than the rated wind speed but less than the cut-out wind speed, then the wind turbine will be shut down to avoid defects and damage when the wind speed is larger than Vcut−out [57].

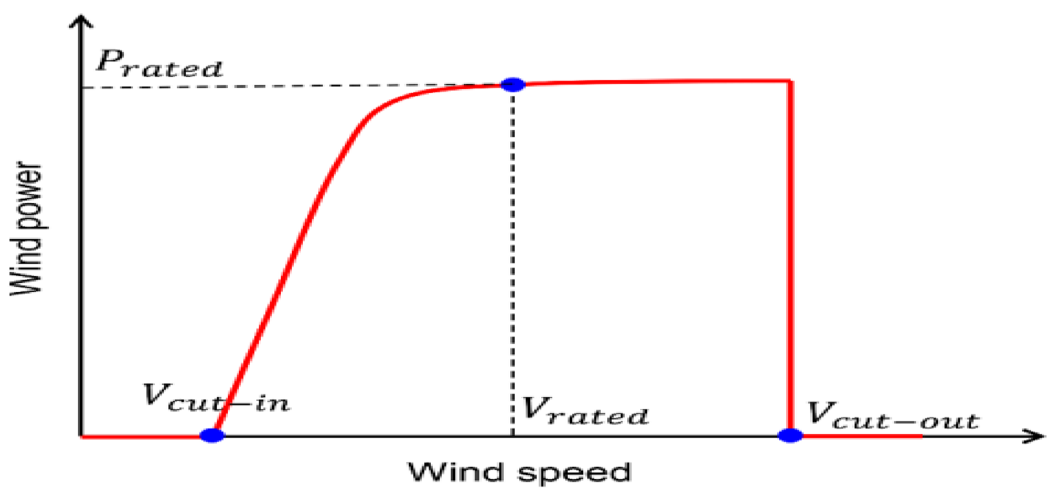


Figure 2.12: A Typical Wind Turbine Power Curve [57]

2.5.1.3 Energy Storage System

Wind and PVs are intermediate sources of power. Hence, it is highly desirable to incorporate energy storage into such hybrid power systems. Energy storage can smooth out the fluctuation of wind and solar power and improve the load availability. When the power generated by the PV and wind turbine is greater than the load demand, the surplus power will be stored in storage batteries for future use. On the other hand, when the power generated by the solar and wind is insufficient, the stored power will be supplied to the load, thereby enhancing the reliability of the system. There are various storage technologies depending on their application, their capacity and the duration of storage:

- Electrochemical batteries (Pb, Li, etc.),
- Heat pumps,
- Hydrogen fuel cells,
- Compressed air energy storage (CAES),
- Flywheels,
- Capacitors and
- Superconducting magnetic energy storage (SMES) [58].

2.5.1.4 The Power Inverter

The power electronic circuit (inverter) is used to convert DC into AC form at the desired frequency of the load. The DC input to the inverter can be from any of the following sources: DC output of the variable speed wind power system, and the DC output of the PV power system.

2.5.1.5 Mini-grid Systems

A mini-grid system can be defined as the system with one or more electricity generators that sometimes has a storage system and connected to a distribution network serving multiple customers. Min grids can accelerate access to electricity in remote rural communities that would otherwise have to wait years, if not decades, for a grid connection. They can operate in isolation from the national transmission networks or be connected to a central grid [59], [60]. The generation capacity of the mini-grid varies with definitions ranging between 50 kW and 1 MW; In some cases may go as high as 10 MW [61]. Mini-grids can have three basic configurations: alternating current (AC) coupled, direct current (DC) coupled or hybrid (both AC and DC). Different energy generation technologies are appropriate for different configurations. Hydropower, geothermal energy, diesel power and biomass-based power generate AC, hence, they generally use AC configurations. Solar PV systems produce DC and therefore appropriate to use DC configuration, but wind turbines can be configured to produce either AC or DC [62].

Currently mini-grids in Uganda are mainly driven by the public sector but managed by the private sector or community. REA identifies suitable sites for mini grid projects and tenders to developers.

There are some private sectors which initiate certain projects by applying for a license from the Electricity Regulatory Authority with a letter of support from Rural Electrification Agency. Mini-grids, unlike stand-alone power systems require more planning and institutional context. Since mini-grids serve a community of users, they rely on local governance frameworks or some other existing infrastructure that can provide a framework for their development. Different models for mini-grid deployment exist, and can be classified into the following categories: utility operated, privately operated, community operated or hybrids that combine a mix of the others. However, the best model depends on local circumstances [63].

2.5.1.6 Micro-grid systems

A micro-grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [64]. Micro-grids are similar to mini-grids but operate at a smaller size and generation capacity (1 to 50 kW) [61]. Micro-grid systems operate at a low voltage distribution and have several distributed energy resources. Microgrid system also has the capacity to operate connected to the grid (on grid) or disconnected to the grid (off-grid/islanded).

2.5.1.6a Components of the Micro-grid

Micro-grid components consist of power generation technology, storage, distribution, micro-grid control, and load demand (customers) as shown in Figure 2.13. The microgrid structure consists of several types of distributed energy sources such as solar PV, wind turbines, micro-hydro turbines, diesel generators, and thermal power plants, with each in the form of distributed generation (DG), including distributed storage.

Figure 2.13: Main components of Micro-grid [61]

2.6 Energy Modelling Tools

Various energy modeling tools in the form of software tools and programs are currently available for analyzing and designing of renewable energy-based systems. These tools are commercially available, and some are open source.

2.6.1 HOMER

The Hybrid Optimization for Multiple Electric Renewables (HOMER) is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micro-power systems and to facilitate the comparison of power-generation technologies across a wide range of applications. HOMER and HOGA (Hybrid Optimization by Genetic Algorithm) are the most applied software tools for optimization of hybrid power systems. HOMER, shown in Figure 2.14, performs three principal tasks including: simulation, optimization, and sensitivity analysis. In Simulation process, HOMER simulates the operation of a system by making energy balance calculations in each step time (interval) of the year. The Optimization process determines the optimal value of the variables over which the system designer has control. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control e.g., the average wind speed or the future fuel price [65].

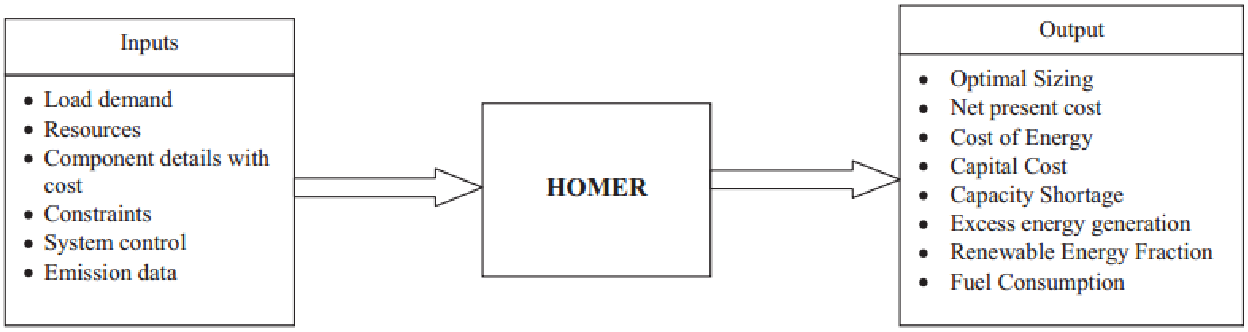


Figure 2.14: Schematic Representation of HOMER [66]

An off-grid wind/PV/battery based HRES was proposed in the work of [67], and the techno-economic analysis performed using two different platforms of HOMER and MATLAB; the system architecture lacked a smart monitoring component. A technical and economic analysis of wind/solar hybrid system performance in West-Coast area of Saudi Arabia was presented based on electricity production and energy cost in [68]. However, it was observed that it is important to select the best size of the wind/solar hybrid system components in order to ensure that all electricity demands are served with minimum cost of energy production [68]. A hybrid power generation system for an ATM machine was optimized using HOMER. All the optimization systems were listed based on NPC and other economic values. The optimized initial capital cost, net present cost, and cost of energy were calculated by HOMER [65].

2.6.2 RETScreen

RETScreen is a feasibility study tool and is freely downloadable software developed by the Ministry of Natural Resources, Canada, for evaluating both the financial and environmental costs and benefits of different renewable energy technologies in any given location in the world. This procedure is shown in Figure 2.15. It has a global climate data database of monthly solar irradiation and temperature data for the year, for more than 6000 ground stations, energy resource maps, hydrology data, and details of product data like solar photovoltaic panel and wind turbine power curves. It also provides a link to NASA climate database. The comparison between a ‘base case’ (conventional technology), and a ‘proposed case’ (clean energy technology) is fundamental in

RETScreen. The comparison includes all costs and a number of economic indices i.e. internal rate of return (IRR) and net present value (NPV) [69]. RETScreen is ultimately not concerned with the absolute costs but rather the costs of the proposed case that are in excess of those for the base case. The program is accessible in more than 30 languages and has two separate versions: RETScreen 4 and RETScreen Plus. RETScreen 4 is a Microsoft excel based energy project analysis software tool that can determine the technical and financial viability of renewable energy, energy efficiency, and cogeneration projects RETScreen Plus is a Windows-based energy management software tool to study the energy performance [70]. RETScreen has a number of worksheets for performing detailed project analysis including energy modeling, cost analysis, emission analysis, financial analysis, and sensitivity and risk analyses sheets. It conducts detailed financial analysis for projects and compares a base scenario that uses traditional energy sources to a RET scenario when calculating energy savings and payback estimates [71]. The pre-feasibility analysis of grid connected PV system using various modes of solar tracker system was evaluated using RETScreen; it was found that dual axis tracker mode represents more feasible output results when compared to fixed and one axis tracker mode [72]. [73] used RETScreen for effective selection of renewable energy projects in constructed facilities in Ohio.

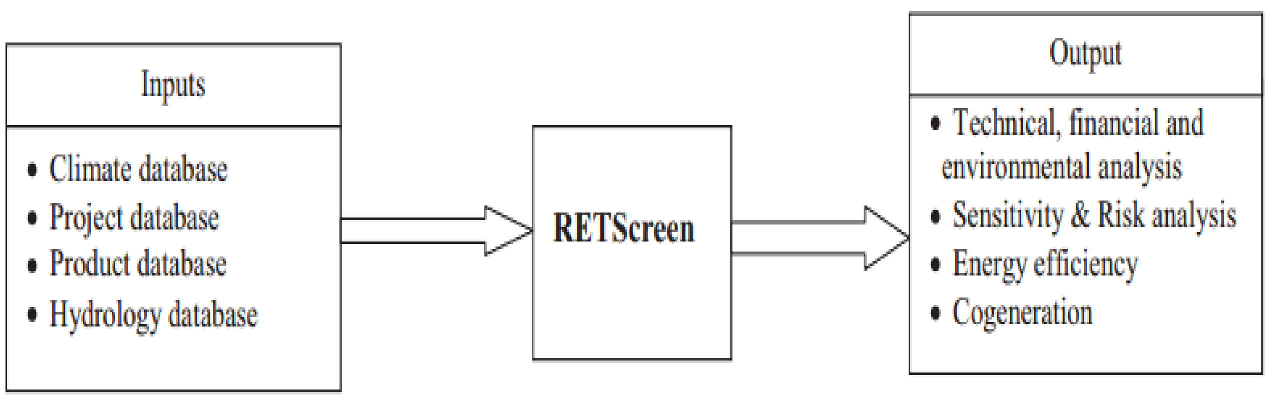


Figure 2.15: Schematic Representation of RETScreen [66]

2.6.3 Remote Area Power Simulator (RAPSim)

Remote Area Power Simulator (RAPSim) is a window-based open-source software package for hybrid system models which was developed in 1996 at Murdoch University Energy Research Institute (MUERI), Australia. The software can simulate the performance of a range of hybrid power systems consisting of PV arrays, wind turbines, and diesel generators with battery storage. The main inputs required by the software are solar radiation, wind speed, ambient temperature, and system load [66].

2.6.4 Simulation and Optimization Model for Renewable Energy Systems.

The Simulation and Optimization Model for Renewable Energy Systems (SOMES) was developed in 1987 at Utrecht University in Netherlands. This model can simulate the average electricity production from the renewable energy generators on an hourly basis. The model has the capacity to perform optimization tasks for searching lowest electricity costs within defined constraints. It requires inputs such as weather data, load demand, among others to get technical and economic performance of a particular system configuration [74]

2.6.5 HYBRID 2

HYBRID 2 is an open source simulation tool that provides a versatile model for the technical and economic analysis of hybrid renewable energy systems. The tool was developed in 1993 by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts. This software uses both the time series and a statistical approach to evaluate the operation of a renewable hybrid system. It is a user-friendly tool and can determine long-term performance while still taking into account, the effect of short-term variability of climatic data [75].

2.6.6 Simulation and Optimization Model for Renewable Energy Systems.

Simulation and Optimization Model for Renewable Energy Systems (SOLSIM) was developed at Fachhochschule Konstanz, Germany in 1998. It enables users to design, analyze, and optimize off-grid, and grid-connected hybrid solar energy systems. SOMES has detailed technical models for PV, wind turbine, diesel generator, and battery components, including biogas and biomass modeling. SOLSIM software package consists of different tools such as the main simulation program, the unit to optimize the tilting angle of PV module, the unit to calculate life cycle cost, and the unit to simulate wind generators [75]

2.7 Artificial Intelligence in HRES Modelling

There are various optimization techniques for HRES sizing; nowadays, artificial intelligence (AI) has attracted a lot of attention for many researchers. The use of AI has seen a lot of relevance in modeling, design, and optimization of renewable energy systems [76]. Artificial intelligence can be defined as the application of science and engineering in making intelligent computer programs. In general, the AI techniques are appropriate methods and provide better optimization results [77]. Application of AI is being utilized for optimization of hybrid systems. There are numerous AI approaches reported in the literature including: genetic algorithms (GA), particle swarm optimization technique (PSO), harmony search algorithm (HSA), simulated annealing (SA), ant colony algorithms (ACA), bacterial foraging algorithm (BFO), artificial bee colony algorithm (ABC), cuckoo search (CS), or a hybrid of these techniques. These algorithms can handle the non-linear variation of system components of RES or intermittent nature of solar and wind energy sources. The key parameters for optimization of PV-wind systems using AI methods are average wind speed, and solar radiation data of each hour and month [78].

2.7.1 Genetic Algorithms (GA)

Genetic Algorithm (GA) is a search process that mimics the process of natural selection and was developed by John Holland between 1960–1970. GA optimization uses techniques inspired by natural evolution such as initialization, inheritance, mutation, selection, and crossover to ensure an optimal solution to a given problem [79]. GA has several advantages viz: it can solve problems with multiple solutions, easy to understand, and can easily be transferred to existing simulation and models [78]. It has some limitations like a tendency to converge towards local optima, or even arbitrary points rather than the global optimum of the problem and cannot assure constant optimization response time etc. [78]. An optimum match design sizing method for hybrid solar–wind system developed using GA, had the ability to attain the global optimum with relative computational simplicity (Yang et al., 2009). The work of [81], optimized a hybrid system consisting of PV panels, a wind turbine, batteries for energy storage, and diesel generator as a back-up system using a genetic algorithm. However, the system needed to be validated using measured data and price data of real installations.

2.7.2 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) applies the concept of social interaction to problem solving. It is a famous algorithm based on the population of swarms, originally proposed by Kennedy and Eberhart in 1995 [82]. This method is based on the social behavior of a flock of migrating birds or fish fooling. Each possible solution of any problem is termed as a particle in PSO. Each particle updates its position according to its own (local search) experience as well as the experience of other (global search) particles. The particles are positioned in the search space of the objective function. The objective function is evaluated by each particle at its current location. Then the particle's movement is determined through the search space by combining the aspect of the history of its own current and best (best-fitness) locations, with those of one or more members of the swarm, and with some random perturbations [83].

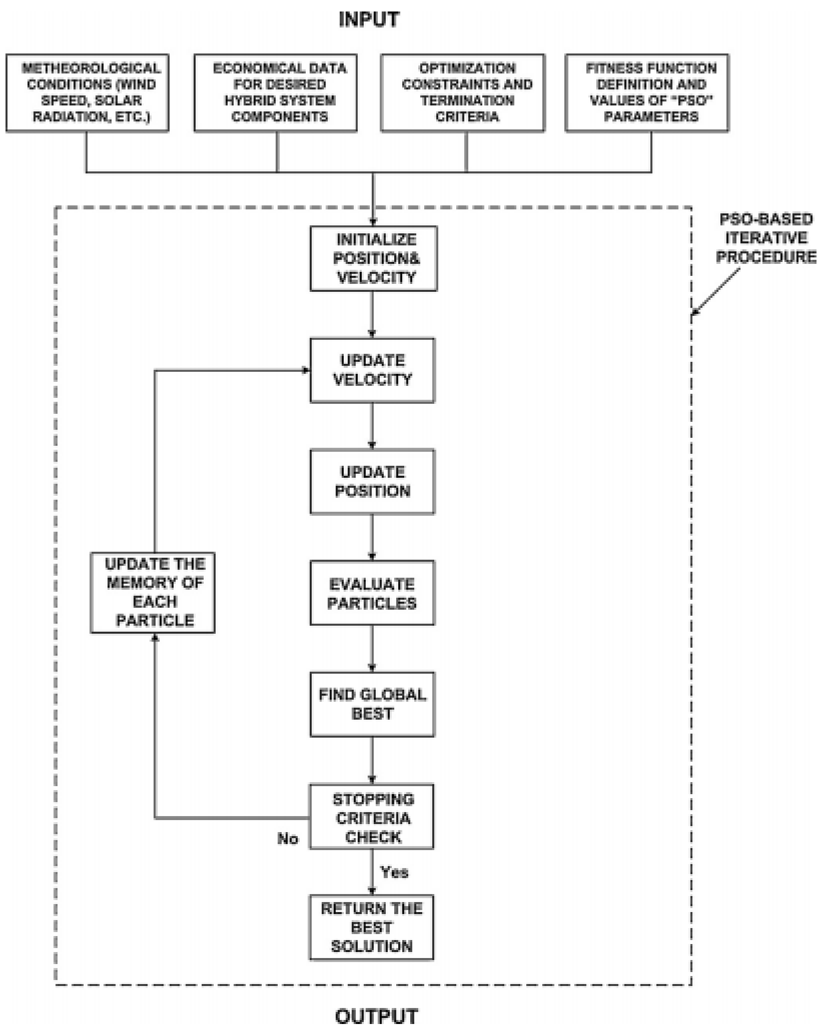


Figure 2. 16: Flow Diagram for PSO [84]

The techno-economic analysis, modelling and optimization of a PV/WT/diesel-based hybrid system with battery storage for electrification to an off-grid remote area located in Rafsanjan, for different diesel generator fuel price scenarios was studied in the work of [85]. The optimal sizing of the system was done using PSO algorithm [85]. A stand-alone PV-wind–fuel cell was optimally sized using a PSO Modified Algorithm. In the design, the net present value cost of the energy generation system was minimized while considering/and not considering reliability indices constraints. The reliability index used was Equivalent Loss Factor (ELF) [86]. PV-wind hybrid energy system was sized optimally by in the work of [87] using GA and PSO. The cost function which was the total cost of the system was minimized for cost analysis while the Loss of Power Supply Probability (LPSP) index was used as the criteria for reliability analysis. PSO was used to determine the optimal component sizing for the different configurations of the autonomous hybrid power system. A techno-socio-economic criterion was formulated to determine the optimum combination of resources. The economic criterion of Levelized cost of electricity was incorporated as an objective function which formed the basis of evaluating fitness of candidate solutions [88].

2.7.3 Artificial Neural Network (ANN)

Artificial Neural Networks (ANNs) are mathematical models with learning and parallel data processing abilities, that use computational neurons (nonlinear cells) organized in layers and connected to each other by weight factors. An ANN has a complex network composed of interconnected elementary processing units (neurons). Neurons are organized into layers and can be connected in different ways [89]. ANN is able to handle noisy and incomplete data, and once trained, can perform complex tasks such as prediction, modeling, identification, optimization, forecasting, and control [82]. Given the variable, intermittent, and non-dispatchable nature of solar and wind power, considerable effort has been made to develop accurate forecasts that meet the needs of micro-grid power providers. Forecasting the production of large solar arrays and wind farms allows power providers the time necessary to make changes to the production of base-load power plant to minimize peak power plant use. These forecasts often use ANNs that access multiple and varied data sources to estimate power changes in hours or days in advance. In the feasibility design and techno-economic analysis of HRES for the rural electrification in the work of Murugaperumal and Ajay D Vimal Raj, (2019), ANN technique was used to help in finding the future load growth for the system from historical load data. The optimum performance of the different configurations of solar PV, wind turbine, bio-generator, and battery system was then evaluated using HOMER software. ANNs were used in predicting the hourly electricity demand of households in US cities of Fargo and Phoenix. This was important in assessing the techno-economic and environmental sustainability of the microgrid for a residential community. The microgrid system was composed of several components including: solar PV, wind-turbines, lead acid batteries, biodiesel generators, fuel cells, electrolyzers, and H_2 tanks [91].

2.7.4 Artificial Neuro-Fuzzy Inference System (ANFIS)

Artificial Neuro-Fuzzy Inference System (ANFIS) is one of the most successful Neuro-fuzzy systems developed by Jang in 1993. It applies neural learning rules to identify and tune the parameters and structure of a fuzzy inference system, based only on the available data [92], [93] modeled and optimized the sizing of a hybrid standalone power system using a Neuro-Fuzzy approach [94] used ANFIS for the modeling of the different components of a PV power supply system and a global ANFIS model was developed to model the output signals of the system. In a solar/wind hybrid standalone system [95], used an ANFIS to foresee the voltage of the panel at which extreme power is obtained for a solar system and to ensure that the most extreme power is delivered by the non-uniform and unpredictable characteristics of solar and wind energy sources. [96] evaluated an ANFIS-based energy management system of a grid-connected hybrid system. The renewable energy hybrid system was composed of a wind turbine, and PV panels, hydrogen (fuel cells, electrolyzer, and hydrogen tank), and battery. Fuzzy-based modeling integrated with time series, neural networks, and regression in forecasting, has helped in improving the prediction accuracy of the concerned variables [97].

2.7.5 Ant Colony Algorithms (ACA)

Ant Colony Optimization (ACO) is a technique for optimization that was pioneered in 1992 by Marco Dorigo. The development of this algorithm was inspired by the observation of ant colonies. After several observations, it has been realized that as the number of colonies becomes larger using a specific path for finding food, the probability of utilizing that path in the future becomes higher. The best path (i.e., shortest path) towards the food is the highest possible value of the performance index in an optimization procedure [84]. ACO simulates this behavior of ants to find the most optimal solution for a given objective function [98], [99] used ACO to optimize the size of a stand-alone hybrid photovoltaic, wind turbine, battery and hydrogen system for reliable and economic supply. The minimum annual system cost was used for cost analysis and LPSP for the analysis of maximum system reliability.

2.7.6 Simulated Annealing (SA)

The SA is an iterative meta-heuristic optimization technique for solving combinatorial optimization problems that was introduced by Kirkpatrick Gelatt and Vecchi in 1983 [100]. It was inspired by the annealing technique used in metallurgy where controlled heating and cooling lowers defects and increases crystal size in a metal [101]. A search with SA begins with a temperature high enough to permit a search of a wide area and finishes with a lower temperature, so as to follow the steepest descent heuristic in moving downhill. The main advantage of simulated annealing is its ability to avoid being trapped in local minima. Simulated annealing is a robust and versatile technique that can deal with highly nonlinear models, chaotic and noisy data, and many constraints. The main weakness of SA is that the quality of the outcome may be poor [84], [102] used the SA algorithm to optimize the size of a PV-wind hybrid power system with battery storage. The system converged at the 127th iteration with the total cost of the hybrid energy system as 33283.6 USD. A hybrid system for renewable energy including electrochemical storage (battery) and chemical storage (hydrogen) was optimized using a SA algorithm. The decision variables for the optimization algorithm were the number of hydrogen tanks and number of batteries which are integers plus the PV surface area, and the area of wind turbine blades (m^2) that are continuous [103].

2.7.7 Harmony Search Algorithm (HSA)

Harmony search is a derivative-free, real-parameter optimization technique algorithm used for optimization, with several evolutionary meta-heuristic optimization techniques. HSA is a population-based algorithm that works on the basis of musicians' behavior. HSA is one of the most recent population-based optimization techniques that can be adopted in various fields of engineering applications [104]. HSA was used in energy storage system's charge scheduling of residential customers with renewable power generators. The schedules presented by the harmony search proved that it can reduce both peak power and purchase of electricity during on-peak time [105].[106]used HSA for comparing the results of Improved Harmony Search Algorithm for optimum sizing of hybrid solar systems with a battery storage unit. The minimum total life cycle cost (TLCC) was used to obtain the optimal solution for the system's LPSP concept, employed for system reliability.

2.7.8 Bacterial Foraging Algorithm (BFO)

Bacterial Foraging Algorithm is a swarm intelligence technique that models the individual and group foraging policies of the Escherichia coli [107]. It is the chemotaxis behavior of bacteria that will perceive chemical gradients in the environment and then move towards or away from particular signals [108]. BFO was used to optimally tune a PI control system for grid-connected wind energy conversion system based permanent magnet synchronous generator (PMSG) in [109]. This optimization technique was used to control both active and reactive current components of the PMSG so that maximum power from the wind can be extracted.

2.7.9 Artificial Bee Colony Algorithm (ABC)

The Artificial bee colony algorithm (ABC) is an optimization algorithm based on the intelligent foraging behavior of honeybee swarms. In ABC, the position of a food source represents a possible solution to the optimization problem, while the nectar amount of a food source corresponds to the quality (fitness) of the associated solution [78]. ABC optimization algorithm was used [110] in the selection of the optimal number and type of PV modules, chargers, the PV modules, tilt angle, battery type, and nominal capacity for supplying a residential household at Helwan city, Egypt. [111] employed ABC for optimal sizing and operation of battery storage to maximize the revenue in a Wind–Hydro hybrid power system. In [112], the total annual cost of the renewable energy system was minimized by determining appropriate numbers of wind turbine, solar panel, and batteries using ABC algorithm. The desired load was economically and reliably satisfied based on the given constraints. LPSP and the Energy Not Supplied (ENS) by the system were the reliability criteria used for the system.

2.7.10 Cuckoo Search (CS)

Cuckoo Search (CS) is a new meta-heuristic optimization algorithm developed by Yang and Deb [113]. It is developed based on the obligate brood parasitic behavior of some cuckoo species in combination with the levy flight behavior of some birds and fruit flies [114]. An optimized fuzzy logic controller was developed for operating a standalone hybrid power system based on CS algorithm. The optimized fuzzy logic controller was able to minimize LPSP, excess energy, and Levelized energy cost (LEC) for reliability analysis [115]. The CS optimization algorithm with enhanced local search was used with Tabu search for optimal energy scheduling in smart grid. The proposed approach was implemented in MATLAB R2018a with the micro-grid containing five-generation units that include three wind plants, two PV plants, and one combined heat power plant [116]. The CS algorithm was used to find the optimal PV panels area, wind turbines rated power, and batteries capacity of the grid-connected PV-wind-battery system, so as to minimize the total system cost and grid power absorption probability. A multi-objective minimizing function was used to optimize the system. The performance of the system was analyzed by conducting two case studies: one for a residential household, and the other for a cattle farm [117]. The work in [118] optimized the design of the hybrid power generation system using CS and Firefly Algorithm (FA). The results of CS and FA were compared with the original results obtained, using the PSO algorithm.

2.10 Identification of the Knowledge Gap

Numerous studies were conducted for HRES in different remote areas in the world, but limited work have been conducted for the remote regions in Uganda. According to the current electricity situation in Uganda, HRES systems will enable the government to plan for rapid development of electrification in rural areas, and the spread of clean energy to isolated communities in the country. Most of the work performed, uses conventional methods of optimization techniques. This study aims to contribute knowledge to the techno-economic and optimization of HRES for the electrification of villages in the country. The study also hopes to design a system that will sustainably improve the lives of the people in the rural community.

3. METHODS

3.1 Introduction

This chapter presents the methods and materials used to attain the aim of the Thesis and to obtain the appropriate results and conclusions. The Global solar insolation, Wind Speed, ambient air temperature data, and the collected for energy demand of Busitema Health Centre III are presented in detail. The model of different hybrid system components are presented in detail. HOMER Pro software tool used to model and optimize the hybrid system (HOMER Pro) is described in this section. The techno-economic analysis is presented in which the optimal solution is obtained.

3.2 Homer Pro Software

In this Thesis a Homer pro software is used for Techno – economic analysis of the hybrid system. It is a famous software that is heavily used for designing renewable energy systems worldwide. Homer pro software was developed by the USA NREL (National Renewable Energy Laboratory) in 1993 and in 2009 executed a commercial license [119]. HOMER performs main three tasks as explained in literature review namely: simulation, optimization and then sensitivity analysis. The software also provides detailed technical feasibility and life cycle cost analysis of the system. To optimize the proposed system, HOMER uses different configurations to find the one that is technically feasible with minimum life cycle cost. The HOMER Pro Microgrid Analysis Tool x643.13.2 installed in the computer lab of Ndejje University Uganda was used in this work.

3.3 Case Study Location and Description

Busitema Health Centre III is located in Busia district 171 km East of Kampala Uganda, at coordinates of 0°28'01.0"N, 34°05'24.0"E (Latitude:0.4669; Longitude:34.0900): 1,198 meters (3,930ft) above sea level. It was established in 1967 as a health Centre II, the facility serves patients from several sub-counties, including Busitema, Buteba and Sikuda among others. It was later expanded and elevated to Health Centre III status in 1981. The health center is for a rural community and has got the capacity to handle 2500 patients per month. It is critical to assess the energy demand of any health facility in order to select the most suitable energy resources. The basic rural health facilities like BHC are usually characterized with medical services such as: (i) treatment of minor illnesses or injuries, (ii) child deliveries and provision of basic immunization services. Energy need of such facilities can be considered to be relatively low, due to limited availability of medical equipment. According to the United States Agency for International Development (USAID) [120], healthcare facility can generally be categorized into three. The first (Category I) is applicable to rural setting and characterized with limited medical services and staff. The estimated load demand for this category range between 5 and 10 kWh/day. Busitema Health Centre II falls under this category. The second category (Category II), contains medical equipment that are similar to the first category, but can as well accommodate sophisticated medical diagnostic equipment with frequent usage when compared to facility in first category. The estimated energy demand in this category is in the range of 10–20 kWh/day. The third (Category III) usually serves as a primary referral center, because it can coordinate communication between several smaller facilities and major hospital in large cities.

Figure 3.1: Location of Busitema Health Centre III (Source: Google Maps)

3.4 Resource assessment and Data collection

To carry out this research, some specific data was required, that is solar insolation, wind speed, ambient temperature, site geographical position, and electrical load. The information on the case study Health Centre was gotten by site investigation. The meteorological data was collected from the national meteorological Centre at Luzira Kampala, it is recorded at the Automatic Whether Station located in Tororo which is the nearest weather station to the case study area. The power output of the PV array depends on the direct and diffuse solar radiation over a particular area. The insolation reaching the earth's surface depends on the cloudiness or clearness of the sky, which in turn depends on the season of the year [121]. Solar energy is one of the readily available renewable energy resources in Uganda. Uganda has average solar irradiation of about 5.1 kWh/m^2/day on flat surfaces with average sunshine duration varying between 4 and 9 hours daily [122]. Figure 3.2 shows the solar irradiation for Busia where BHC is located.

3.4.1 Solar Resource Data

Knowledge of irradiance on a collector's surface is critical for solar resource assessment. Most weather stations record the total irradiation on a horizontal surface also known as Global Horizontal Irradiation (GHI). In some instances, the Direct Normal Irradiance (DNI) is also available. DNI represents the sun's radiation striking the earth incident on the direction of the sun and is a vital parameter for the design of concentrated solar power systems (CSP) [123]. GHI on the other hand represents the sum of the sun's radiation directly incident on the surface of the earth and the diffuse horizontal irradiance (DHI) [124]. It is an important parameter for the design of panel based photovoltaic systems. Diffuse Horizontal Irradiance is the sun's radiation that doesn't strike the earth's surface directly but rather has been scattered by molecules, clouds, dust or other particles in the earth's atmosphere and comes equally from all directions [124]. The case-study area being located in Busia Eastern Region of Uganda, the solar resource of Busia district obtained from Tororo AWS was used. The weather station records data in time interval of 15minutes. The scaled annual average was found to be 5.15 kWh/m^2/day. The highest daily irradiation during the year is January and February which are also essentially among the hottest days in Eastern Uganda as shown in Figure 3.2. The highest clearness index experienced during the dry season is 0.759 in January. However, the lowest clearness index is 0.371 in June.

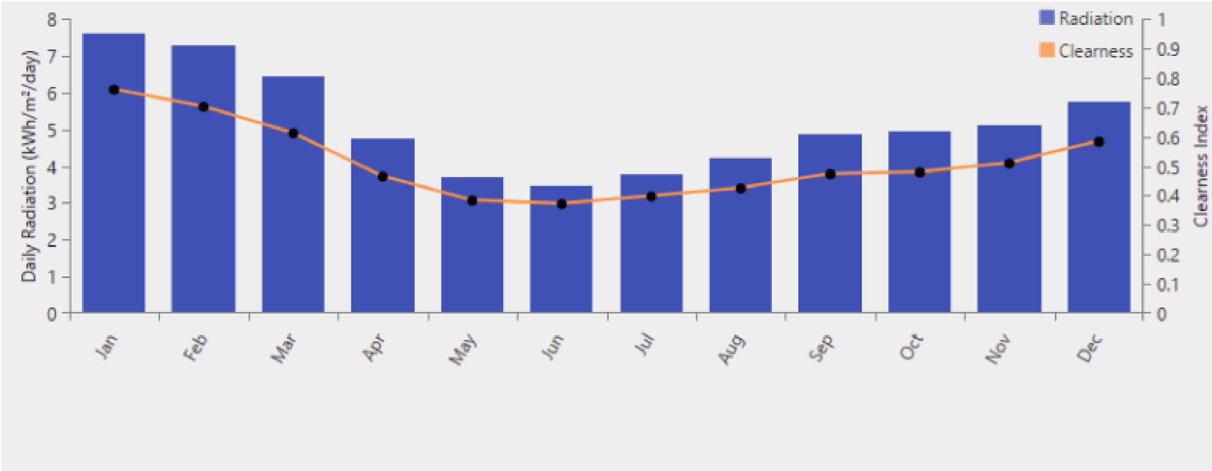


Figure 3.2: Daily Radiation of Busia (Source: Modified NASA Database of HOMER Pro .13. 2)

3.4.2 Wind Resource Data

Just like solar, to quantify wind potential in an area, wind speeds at certain hub heights are required. Wind data measurement at meteorological weather stations is usually done at a hub height of 10m and is intended mainly for weather prediction purposes. Busia district where the health Centre is located has an annual average wind speed of 2.41 m/s height of 10 m according to the AWS recording in Tororo weather station as shown in Figure 3.3. Electrical energy can be generated from wind energy when wind blow through a wind turbine. The kinetic energy of the wind at rated wind speed is converted into mechanical power by turning the turbine blade, thus producing electricity through the shaft connected to the alternator [125].

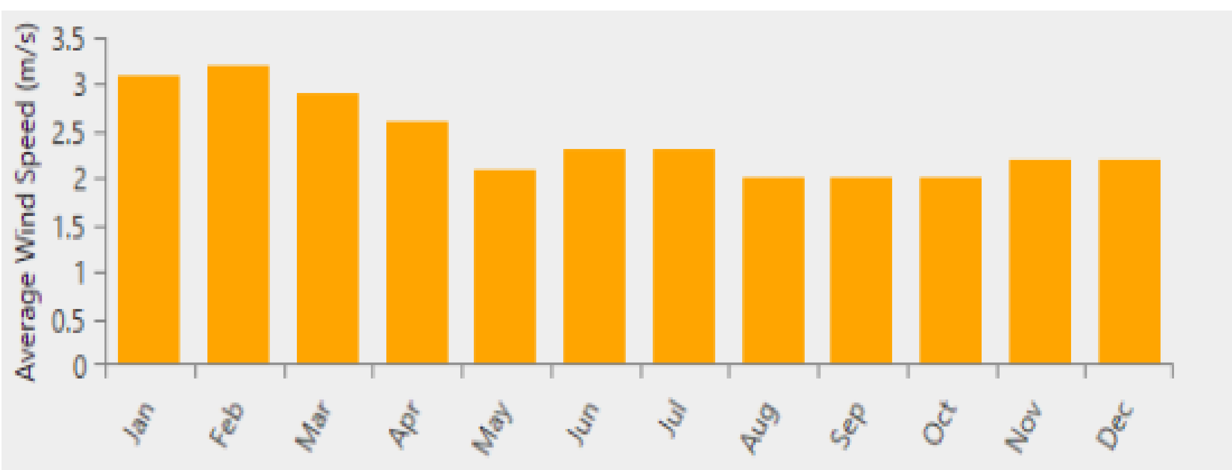


Figure 3.3: Monthly average wind speed received in Busia

3.4.3 Ambient Temperature

The ambient temperature (Figure 3.4) at the selected site where the Health Centre is also of great importance, this is because solar PV performance has a negative correlation with ambient temperature as seen in the literature review.

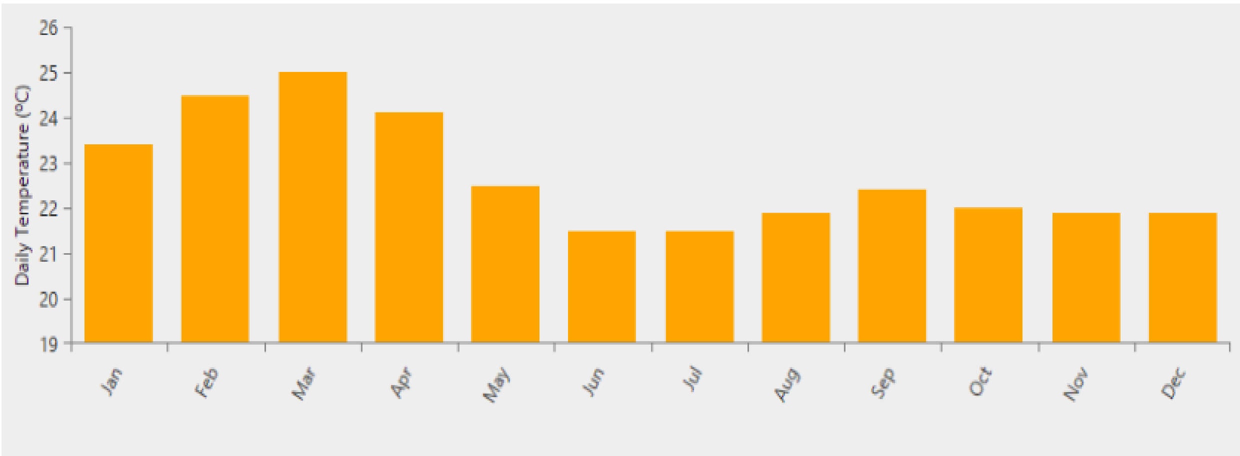


Figure 3.4: Monthly Average Ambient Air Temperature Received in Busia

3.4.4 Electrical Load Data.

The electrical load data for the Health Centre was obtained by site visiting and having an interview with the hospital technician and the "in charge" of the Health Centre. In this study, the category of load profile was community because the hospital is a community hospital. Measured hourly load profiles are not available for the selected the health Centre load data were thus synthesized by specifying typical daily load profiles and then adding 10% daily randomness, and 15% hourly noise. The demand was estimated for the whole year as shown in Table 3.1.

Table 3: 1 The Hospital Power Consumption

Load	Quantity	Rated power (W)	Watt Hour/Day	Duration (hr)	Total watts	Total Watts Hour (W)
Lighting Bulb	14	7	06:00pm 7:00am	13	98	1,274
Printer	1	696	8:00am - 3:00pm	7	696	4,872

Load	Quantity	Rated power (W)	Watt Hour/Day	Duration (hr)	Total watts	Total Watts Hour (W)
Monitor	1	360	8:00am - 3:00pm	7	360	2,520
Television	1	50	8:00am - 3:00pm	7	50	350
CPU	1	360	8:00am - 3:00pm	4	360	1,440
Vaccine Fridge	1	130	00:00am- 11:00pm	24	130	3,120
Microscope	1	60	8:00am - 1:00pm	5	60	300
Battery Backup	1	390	00:00am- 11:00pm	24	390	9,360
Landline phone	1	10	00:00am- 11:00pm	24	10	240
Cell Phone	6	5	8:00am - 3:00pm	7	25	175
Kettle	1	1800	8:00am - 11:00am	3	1800	5,400
Total (W)					3979	
Total (kW)					3.979	

3.5 Modeling of Hybrid System Components

The PV-Wind power hybrid system consists of several electrical components, which ensure necessary functions like production, storage, adaptation of electrical energy; and these components are PV array, wind turbine, battery storage, inverter, controller, and other accessory devices and cables. In order to understand the performance of a hybrid system, each component needs to be modeled separately. The modeling of hybrid system component is discussed under this section. Only the generation components, inverter and battery will be modelled in this study as they represent the key system components. The flowchart for the selection of optimal system configurations is given blow. The proposed hybrid systems consist of PV panels, wind turbines, Diesel generator and other system components such as batteries, converters. The PV panel and wind turbine are combined to compensate for the unpredictable variation in RE sources from one zone to another, whereas the generator acts as a backup. Effective utilization of renewable resources can reduce the Maintenance and replacement costs of the hybrid system [126]. The initial capital cost of a hybrid system is usually high; therefore, long-lasting, reliable, and cost-effective systems are needed to meet the entire project life. HOMER searches from the search space (Table 3.2) for the optimal system configuration, for the different components considered in the hybrid system.

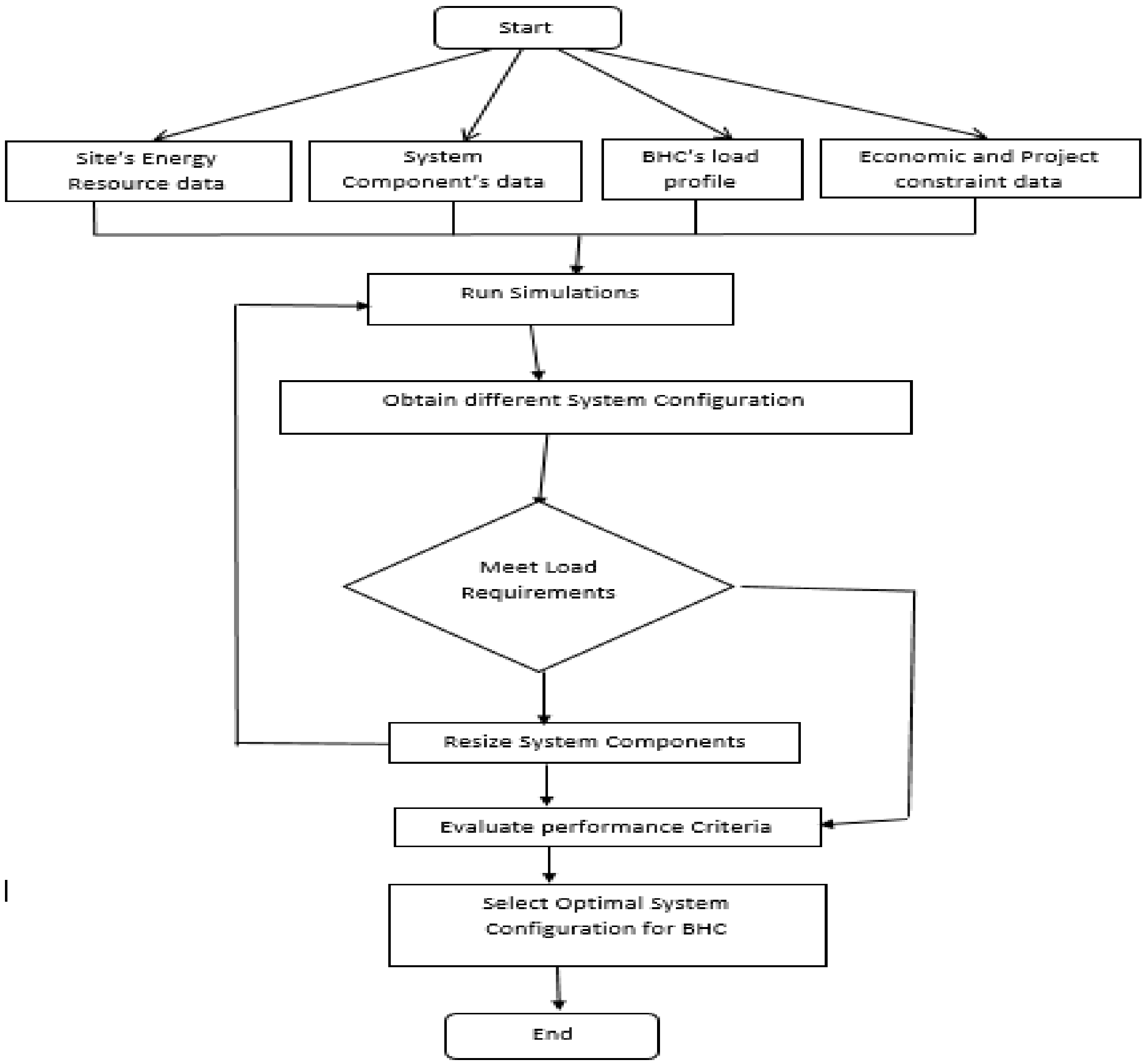


Figure 3.5: Energy System Configurations Selection Flowchart

Table 3.2: Search Space of Different Component Size in HOMER

Wind turbine (Quantity)	PV array (kW)	Battery (string)	Converter (kW)
0	0	0	1
1	0.33	1	1.15
2	0.35	4	2

4	0.36	8	100
6	0.4	10	200
8			
10			

3.5.1 Solar PV Array Modelling

Solar panels are a group of cells connected in parallel and series to generate the required electrical power based on meteorological factors such as solar radiation and temperature. A polycrystalline panel model Canadian Solar MaxPower CS6U-330P was used in the study because of its relative high efficiency 16.97, robustness, outstanding low irradiance performance: 96.0 % and relatively low price with specifications shown in the Table 3.3. The component was chosen to be the main electricity generator due to the abundant solar insolation in eastern Uganda. Tracking system was not considered in this work because of the terrain of Busia region, it is on flat ground with very few trees scattered over the expanse of land; thus, losses due to shading are not considered. With the right angle of inclination, the modules do receive sunshine throughout the day.

Table 3.3: Design Parameters for the Solar PV Modules

Parameter	Unit	Value
Capital cost	$/kW	150
Replacement cost	$/kW	150
Operation and maintenance cost	$/kW	50
Operating Temperature	°C	-40 ~ +85
Derating factor	%	88
Efficiency	%	16.97

3.5.2 Converter

The model designed in Homer Pro consists of both DC and AC power generators connected to an AC only load. A converter is therefore needed to maintain the flow of energy between the AC and DC components. A bi-directional CyboEnergy off grid CI-mini 1000N converter with specifications in Table 3.4 was chosen for the system, and HOMER Pro software used for optimization of the size. The size can then be reduced or increased according to the result of simulation.

Table 3.4: Design Parameters for the Converter

Parameter	Unit	Value
Capital cost	$	200
Replacement cost	$	200
O & M cost	$	0
Operational lifetime	Year	10
Efficiency	%	96

3.5.3 Wind Turbine Modelling

The wind is characterized by its speed and direction and is affected by factors, such as geographic position, meteorological factors, and height above ground level. Wind turbine as it rotates it intercepts the wind and thus captures a part of its kinetic energy and turns it into usable energy. Aeolos 1kW vertical axis wind turbine was used in this study because it is a low start wind speed (since the site is a low windy area), quiet, safe, and reliable vertical wind turbine. It also has high reliability in off-grid applications, can be used in 48V off-grid application or 110V grid tie application. The power curve for this turbine is shown in figure 3.6. To allow the software to find an optimum solution, provisions for using 0 (no turbine), 1, 2, 4, 6 8 and 10 units were used in the search space. The design parameters are shown in the Table 3.5.

Table 3.5: Design Parameters for the Wind Turbine

Parameter	Unit	Value
Capital cost	$	1,000
Replacement cost	$	1,000
O & M cost	$	0
Rotor Diameter:	m	2.0
Rated Power:	watts	1000
Cut-in Wind Speed	m/s	1.5
Rated Wind Speed:	m/s	10
Cut-out Wind Speed	m/s	50

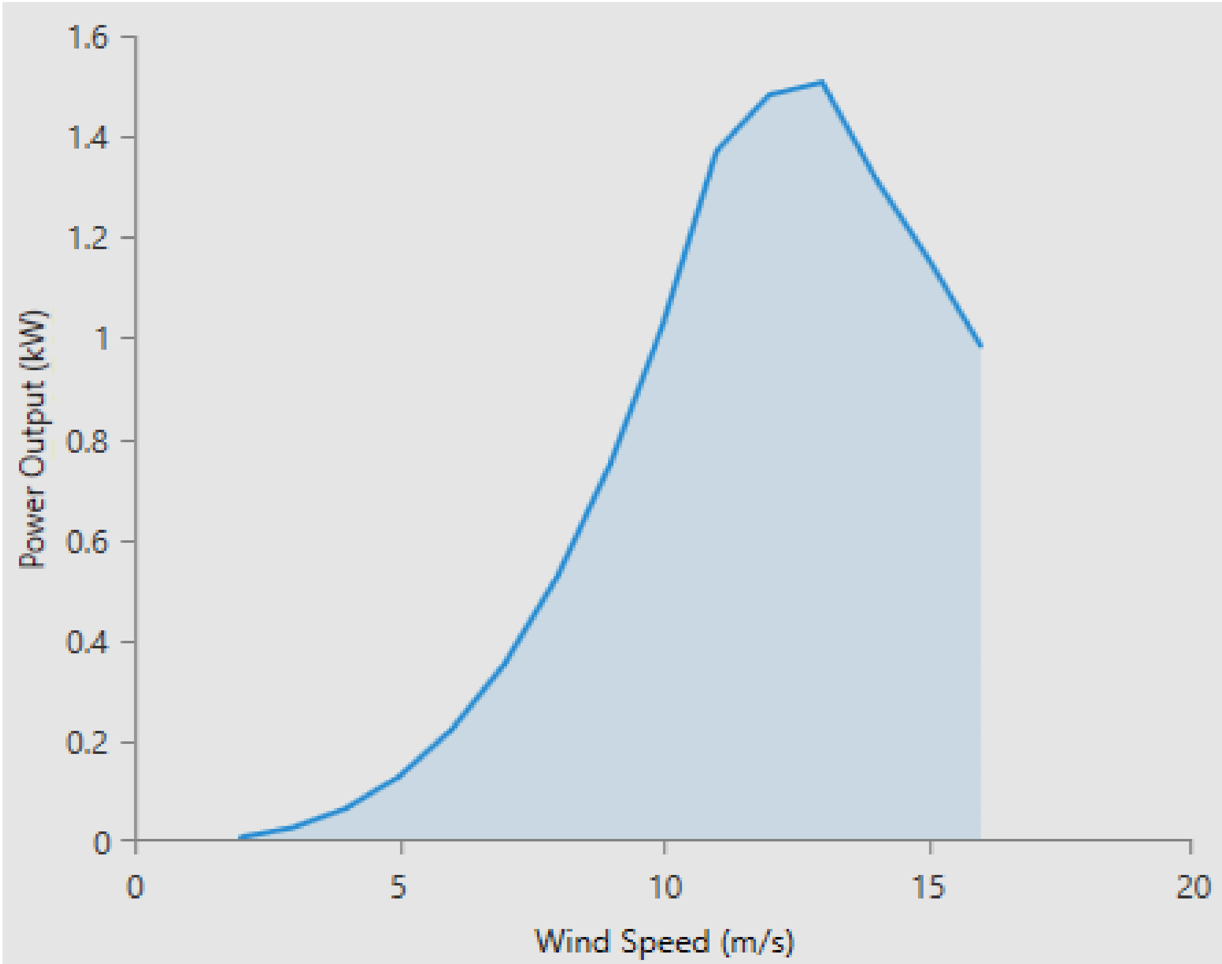


Figure 3.6: Wind Turbine Power Curve (Source: HOMER PRO x643.13.2)

3.5.4 Battery Modelling

When the power generated by Wind turbine and PV in a hybrid system is greater than the load demand, the excess energy will be stored in the batteries and provides electricity during the time solar PV and wind are unavailable in the future. The Battery Model S-480 from Surrete Battery Company was chosen for modeling of the system and the details are enlisted in Table 3.6. The number of batteries considered in the optimization study were determined by HOMER Pro optimizer, which decided on the total number needed. In case of any deficiency in the power generation, the stored power will be used to supply the load which enhances system reliability.

Table 3.6: Design Parameters for the Batteries

Parameter	Unit	Value

Nominal Voltage	Volt	6
Nominal Capacity	KWh	2.89
Round trip efficiency	%	80
Maximum capacity	Ah	375
Capital cost	$	300
Replacement cost	$	300
Max charge current	A	135
Max discharge current	A	135
O & M Cost	$/Year	50

3.5.5 Diesel Generator

The generator has a minimum load ratio of 25% which is the percentage of the total load of the system below which the generator is switched off so as not to support the connected electric load. If the connected load is below the minimum load ratio, the generator runs at a high load and the extra power produced is either used to charge the battery or dumped. When other energy sources in the system are powering the load, the generator is switched off. The diesel generator chosen for modeling of the hybrid energy system is a Generac 10kW. The power factor of the generator is 80% as shown in Table 3.7. The generator was added to the HOMER Pro library and later chosen because of its availability on the Ugandan market.

Table 3.7: Design Parameters for the Diesel Generator

Parameter	Units	Value
Capital cost	$/kW	600
Replacement cost	$/kW	600
Operation and maintenance cost	$/h	0.3
Operational lifetime	Hours	15,000
Fuel curve intercept	L/h	0.48
Fuel curve slope	L/h/kW	0.286
Fuel Price	$	1.0

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the load profile of Busitema Health Centre III and the load curve of the community. A presentation is given about the system configurations and assumptions taken during simulation in HOMER Pro.

4.2 Load Profile of the Hospital

From Table 3.1, the daily load data was generated. This daily load data serve as the load input data in the HOMER Pro software, utilized for the system analysis. From the synthetic load of HOMER, a community profile was chosen since the health Centre is for a community. The data for community profile was then edited with real load data to generate the daily load, monthly, seasonal and yearly profile for the health Centre, as shown in Figures 4.1, 4.2, 4.3, and 4.4 respectively. The day to day variability in HOMER was used to represent a realistic load pattern for the day. The day to day variability was set to 10%, which is the recommended value in HOMER. Random variability was set for the variation of the daily load from month to month. The time step for the simulation of the data was set as the default of 60 minutes with the time-step percentage of 20%. From the baseline data supplied to HOMER, the annual average power demand was calculated as 33.2 kWh per day. Figure 4.1 shows the overall modeled daily load profile for the aggregated electrical demand for the health Centre. From the figure, it can be observed that the peak period is in the morning (14:00-17:00) and estimated as 7.45 kW. The estimated average power demand is 6.77 kW with a load factor of 20 %. The mismatch in the peak value the and value shown in the schematic figure are due to the scaling process and the random variability introduced in HOMER, to make the load pattern more realistic. In addition, the seasonal load profile showing monthly averages of primary AC load for the health Centre is shown in Figure 4.4.

Figure 4.1: A Typical Daily Load Profile in HOMER Pro

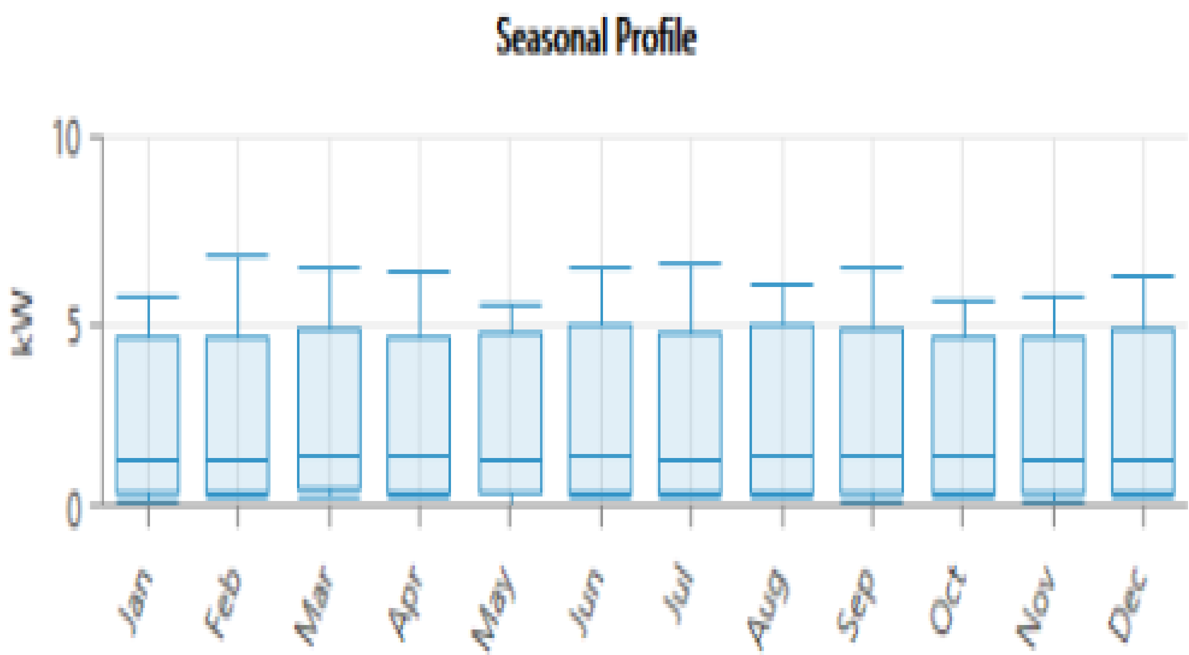


Figure 4.2: Monthly Load Profile of the Health Centre in HOMER Pro

It is clear that most of the load falls under the range of 6.77kWh.ie the average load for the whole year in the hospital is 65kWh.

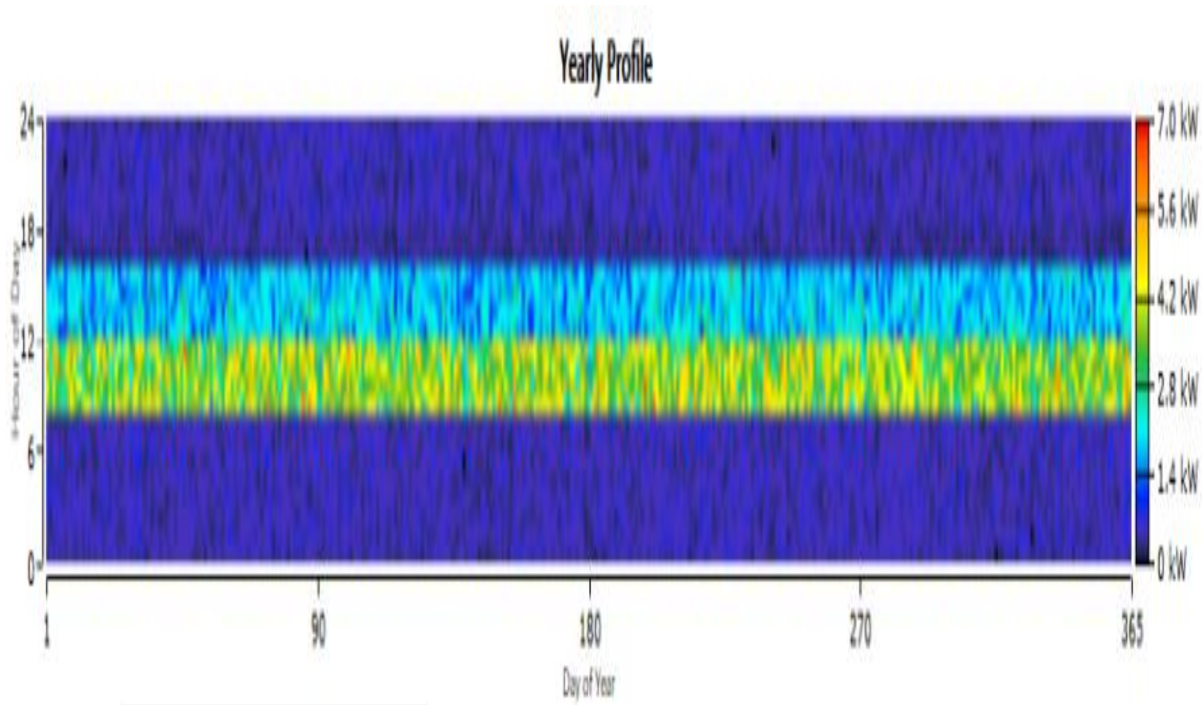


Figure 4.3: Diurnal Variation of Primary Load Profile in HOMER Pro

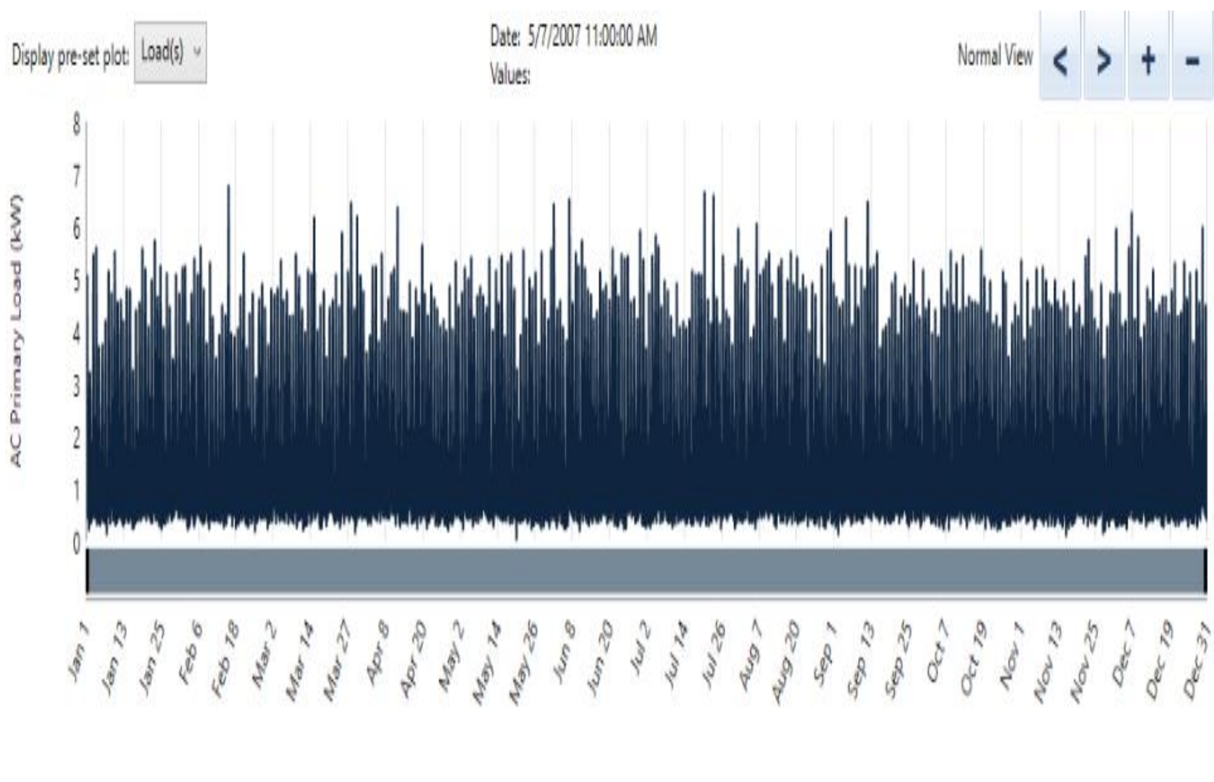


Figure 4.4: AC Primary Load for the whole Year in HOMER Pro

4.3. Modelling and Simulation Results from HOMER Pro

An off-grid system is modelled for the electrification of the Health Centre III of Busitema Community. The system designed is a standalone system with batteries for storage, and the energy generation sources as solar PV, wind turbine, and a 10-kW diesel generator for backup as shown in Figure 4.5. The sensitivity analysis was done on diesel price, inflation rate, annual average load, and average global solar irradiation, to understand their impact on the system optimal solution. The optimum configuration and components sizes that meet load requirements at the lowest costs, are found by using HOMER sizing tool. The inputs used by the software describe the solar and wind resource availability, the electrical load and energy demand, and the hybrid system components' (PV array, wind turbine, battery and converter) costs. The system's simulation was performed for each 8760 hours in a year, and the main economic output of the system configuration is based on the net present cost (NPV), levelized cost of energy (LCOE), and operating cost.

4.3.1 System Control Parameters, Economic Inputs and Constraints

4.3.1.1 Dispatch Strategy

Dispatch strategy is a set of rules used to control the operation of the power generator(s) and the storage bank whenever there is insufficient renewable energy to supply the load. HOMER models two types of dispatch strategies namely: cycle-charging and load following. In load-following dispatch (LF), renewable power sources charge the battery but generators only produce power to serve the load, and do not charge the battery bank; in cycle-charging dispatch (CC), whenever the generators operate, they produce more power than required to serve the load with surplus electricity to charge the battery bank. Both scenarios were modeled in this study but the optimal solution had load following dispatch. The optimal dispatch strategy for the proposed system depends on different characteristics such as the generator sizes, the diesel generator's operation and maintenance cost, the fuel price cost, the battery bank, and the renewable energy resources.

4.3.1.2 Technical and Economic Inputs and Constraints

HOMER software inputs for the economic analysis includes the nominal discount rate, expected inflation rate, the project lifetime in years, system fixed capital costs, system fixed operation and maintenance costs, and the capacity shortage penalty. According to Bank of Uganda, the nominal overall inflation rate for year 2019 was 3.94 %. The discount rate was modelled at 14 % for 25 years' project lifetime. Constraints are prerequisites which systems must fulfil; otherwise HOMER neglects those systems that do not conform with the defined constraints. In the proposed system, the maximum renewable fraction is considered as a range from 0 to 100 %, and the maximum unserved energy is assumed as 0 %, while the value for the maximum annual capacity shortage is taken as 0%; hence, the system is design to meet all the annual load demand. The techno-economic model was developed using HOMER software and a schematic overview of the designed simulated hybrid system is shown in Figure 4.5.

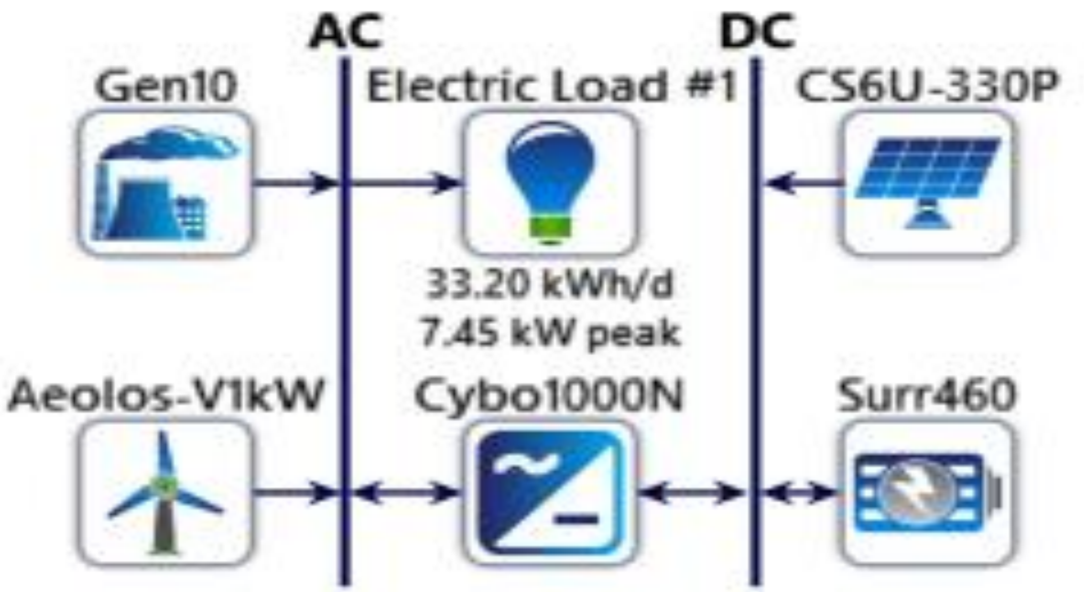


Figure 4.5: Schematic of the Simulated Hybrid System (Source: HOMER Pro)

Since the load is based on alternating current (AC), it is therefore connected to the AC bus. A bi-direction CyboEnergy 1000N converter is used to convert electricity from the direct current (DC) bus to AC power. Solar PV generates electricity in DC form that charges the battery, thereby necessitating connection to the DC bus. 194,568 solutions were simulated in HOMER Pro, of which 139,793 were found feasible according to calculation report shown in Figure 4.6. The 10 possible optimal solutions are presented in Table 4.1. The optimization results show both the categorized and overall list of configurations available, based on the input data, and ordered according to the lowest NPC. The categorized table presented the least cost-effective combinations from among all components' setup, whereas the overall optimization results displayed all of the possible system combinations based on their NPC. Power systems are selected after simulation and based primarily on minimum NPC. Furthermore, cost of energy, high renewable fraction, low capacity shortage, and low excess electricity generation parameters could be used for the comparison of power generating schemes in order to analyze their technical feasibility. In this work, NPC and the LCOE were used as the economic criteria to determine the feasibility of the system.

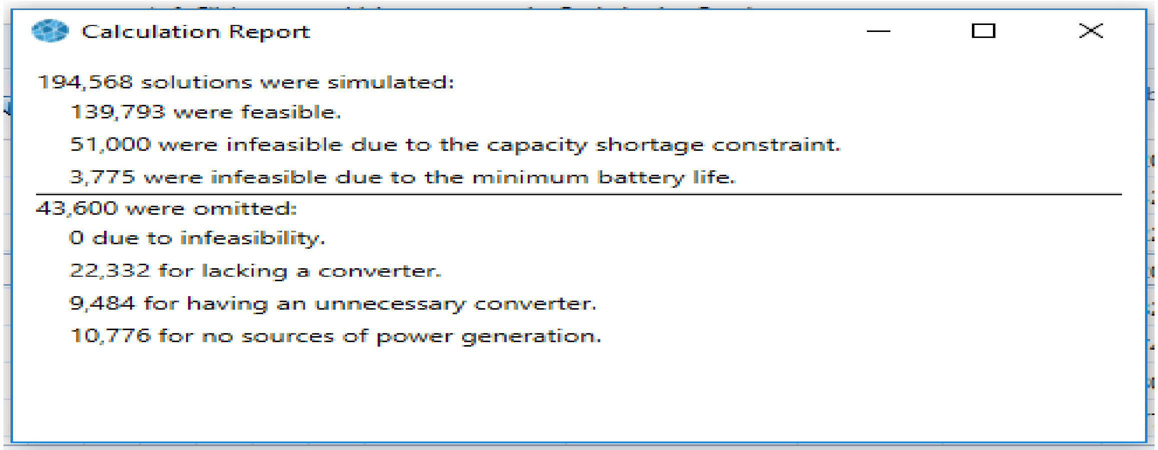


Figure 4.6: Calculation Report (Source: HOMER Pro)

Table 4.1: System Components and their Sizes

System Configuration		**Size of Solar PV (kW)**	**Number of Wind Turbines**	**Size of Diesel Generator (kW)**	**Size of Batteries (Units)**	**Size of Converter (kW)**
PV/Genset/ Battery	S1	15.78		10	9	6.20
PV/Wind/Genset/Battery	S2	15.29	1	10	9	6.17
PV/Battery	S3	33.17			26	7.37
PV/Wind /Battery	S4	35.13	1		24	7.36
Genset	S5			10		
PV/Genset	S6	0.05		10		0.06
Genset/Battery	S7			10	1	0.25

Wind/Genset	S8		1	10		
PV/Wind/Genset	S9	0.58	1	10		0.38
Wind/Genset/Battery	S10		1	10	1	0.19

The generating power of PV panels is about 7 hours during the day, while the remaining 17 hours will be from wind since a health facility needs power for 24 hours a day. The configuration without battery storage will not proffer the best solution, because wind resources may not necessarily be available for all the 17 hours because of its intermittent nature. Therefore, a battery is necessary to store energy for use when both sunshine and wind are not available. The battery is not allowed to discharge below 70 %, therefore it is necessary to have a backup diesel generator to account for fluctuations in the renewable energy resources. The system consisting of solar PV and battery (S1) stood out as the most appropriate optimal system having a capacity of 15.78 kW of solar PV, and 9 strings of Surrette S-480 battery connected in parallel with 11.3 hours of autonomy. The system also consists of 6.20 kW converter. The dispatch strategy for the configuration is load following. The configuration next to the best optimal solution is PV/Wind/Genset/Battery (S2) with the same number of batteries as system S1, but a slightly smaller size of converter and solar PV of 6.17 kW. The base case is a system of a 10-kW diesel generator having NPC of $72,698 and LCOE of $0.703 with cycle charging dispatch strategy. The Wind/Genset/Battery (S10) was considered as the most expensive option for electricity generation due to high NPC of $75,578. Figure 4.7 shows the categorized optimal system configurations from S1 to S10 of the optimization section of the software.

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost		
CS6U-330P (kW)	Aeolos-V1kW	Gen10 (kW)	Surr460	Cybo1000N (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)
15.8		10.0	9	6.20	LF	$27,427	$0.265	$2,405
15.3	1	10.0	9	6.17	LF	$29,243	$0.283	$2,510
33.2			26	7.37	CC	$42,644	$0.412	$3,327
35.1	1		24	7.36	CC	$44,499	$0.430	$3,464
		10.0			CC	$72,698	$0.703	$8,448
0.0494		10.0		0.0613	CC	$72,705	$0.703	$8,447
		10.0	1	0.250	LF	$73,525	$0.711	$8,504
	1	10.0			CC	$74,768	$0.723	$8,574
0.583	1	10.0		0.385	CC	$74,811	$0.723	$8,560
	1	10.0	1	0.188	CC	$75,578	$0.731	$8,629

Figure 4.7: Categorized Optimisation Result (Source: HOMER Pro)

4.4 Cost Analysis of the Systems

High capital costs are characteristic of renewable energy systems because of the upfront costs of equipment that need to install before the production of electricity. Most of the renewable energy sources have high costs of the balance of system equipment, often required for stabilization of the system. Renewable energy systems often need equipment installed over a large piece of land to harness the energy, especially solar and wind systems. It is therefore very essential to establish an optimal system for a particular location. The costs of the system configurations are broken down into different classes, from capital costs to salvage value. System configuration that consist of wind turbine for electricity production, have a relatively high initial capital cost as compared to that without it. Capital cost for the system S4 were $14,940.53 as compared to that of system S1, which is at $ 6905.67 (Figure 4.8). The high initial costs are mainly due to the balance of the system (BOS) equipment, apart from the solar panels. Although, the price of solar modules has reduced, most of the BOS are still expensive and not as affordable as the modules. The BOS costs for systems that have solar includes converter and battery costs, whereby the price varies according to the size and the capacity of the system. Although, system S2 has the same number of batteries like S1, it has in addition, a more expensive wind turbine.

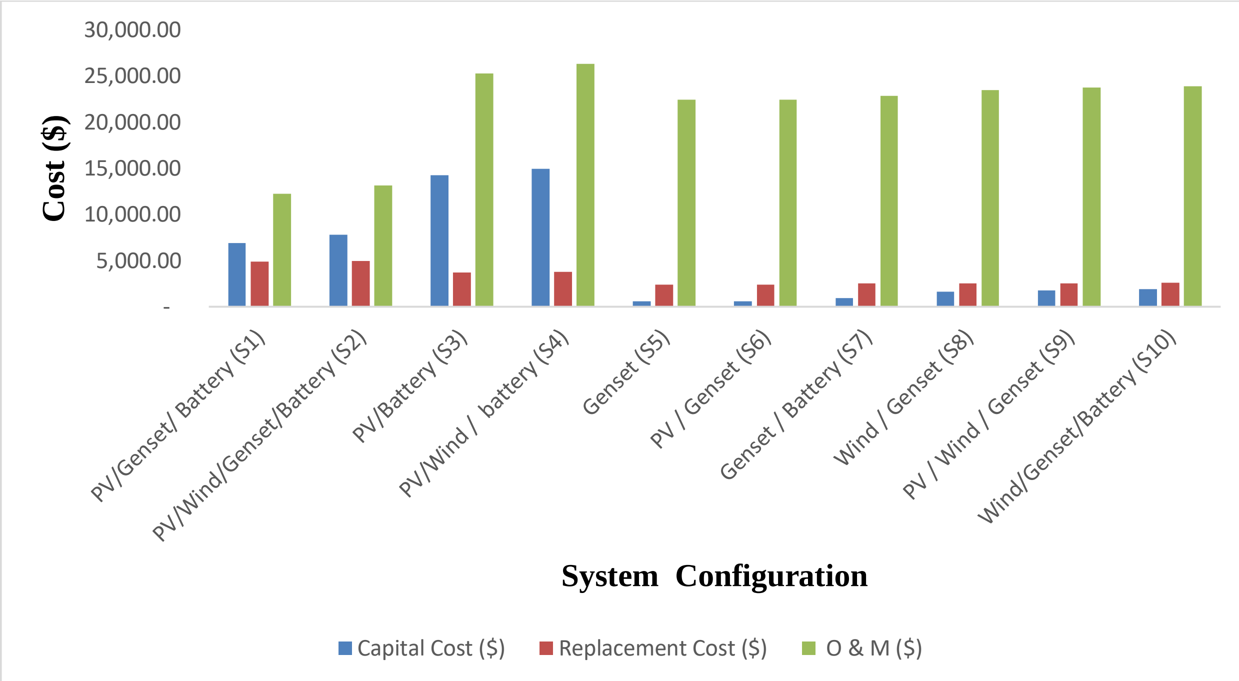


Figure 4.8: Capital Costs of Different System Configurations

As shown in Figure 4.8, the O & M costs of the system with diesel Genset and wind turbine is high; this is due to continuous expenses incurred in lubrication and spare parts associated with Genset and wind turbine, among others. In addition, the long operating hours of the diesel generator leads to wear and tear, and therefore require lubricants and repair in the event of breakdowns. For a diesel Genset, the more hours it has to run, the higher the operation and maintenance costs. Systems S3 and S4, have the highest salvage value at the end of the project life due to the minimum running time awarded to the Genset. System S5 and S6 have the lowest salvage value, that can be attributed to wear and tear from the continuous operation of the generator, thereby reducing the quality of the equipment at the end of the project. Figure 4.9 shows the salvage value of the different system types and their running hours. From the result, it is noted that systems that have a long period of operation of the diesel generator have a low salvage value when compared to those with low to non-operating hours.

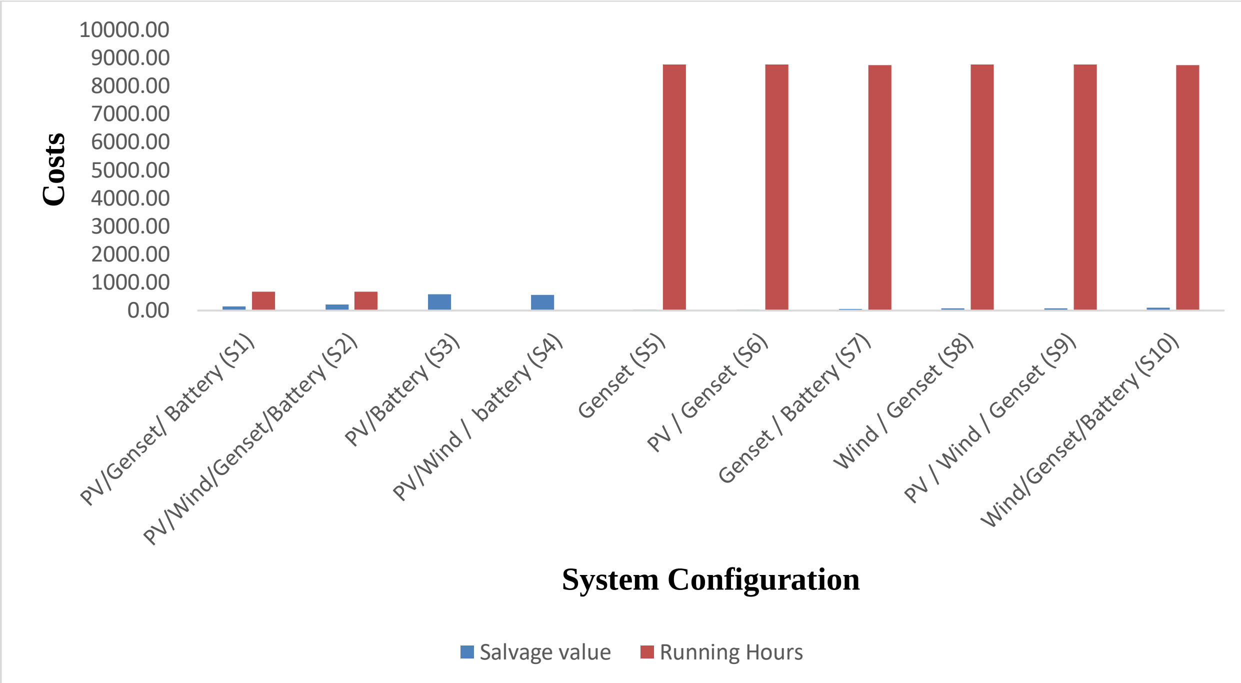


Figure 4.9: Variation of the Salvage Value with the Running Hours of Genset System

4.4.1 Fuel Costs

Fuel costs are essential expenses during the lifetime of system configuration with genset. They are determined by the amount of electricity produced and depends on the demand of health Centre. System S5has the highest fuel costs at $ 47,307.36 (Figure 4.10). System S1and S2 have closer and lower fuel costs due to the high percentage of energy being generated by PV and stored by the battery from the diesel generator. In both systems, the diesel generator has a low run time of less than 1000 hours a year.

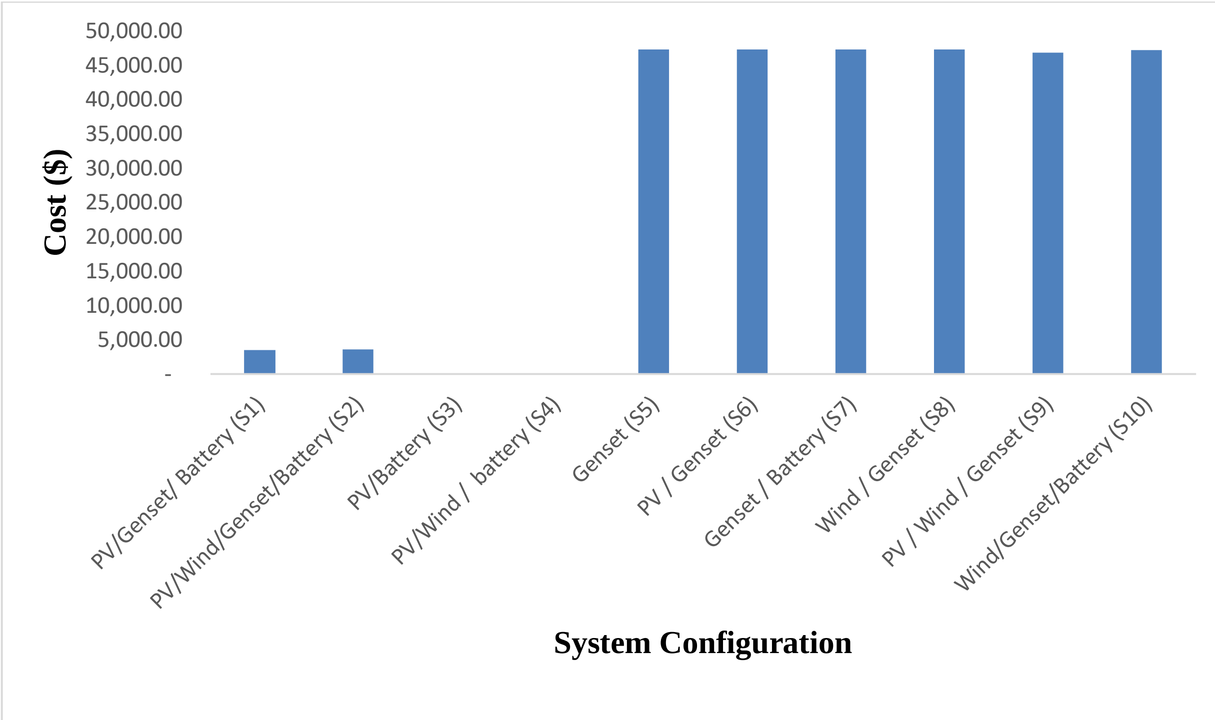


Figure 4.10: Fuel Costs Per System Type

4.4.2 Net Present Cost

System S10 has the highest NPC attributed to high fuel costs, O & M costs, when compared to S1 and base scenario (S5) (see Figure 4.11). The high costs are due to the high percentage of electricity being generated from the diesel generator. System S1 has higher initial costs of $ 6,906 attributed to many numbers of batteries, diesel, and solar PV modules, but has the lowest NPC at $ 27,427. This is found to be better than the rest of the configurations.

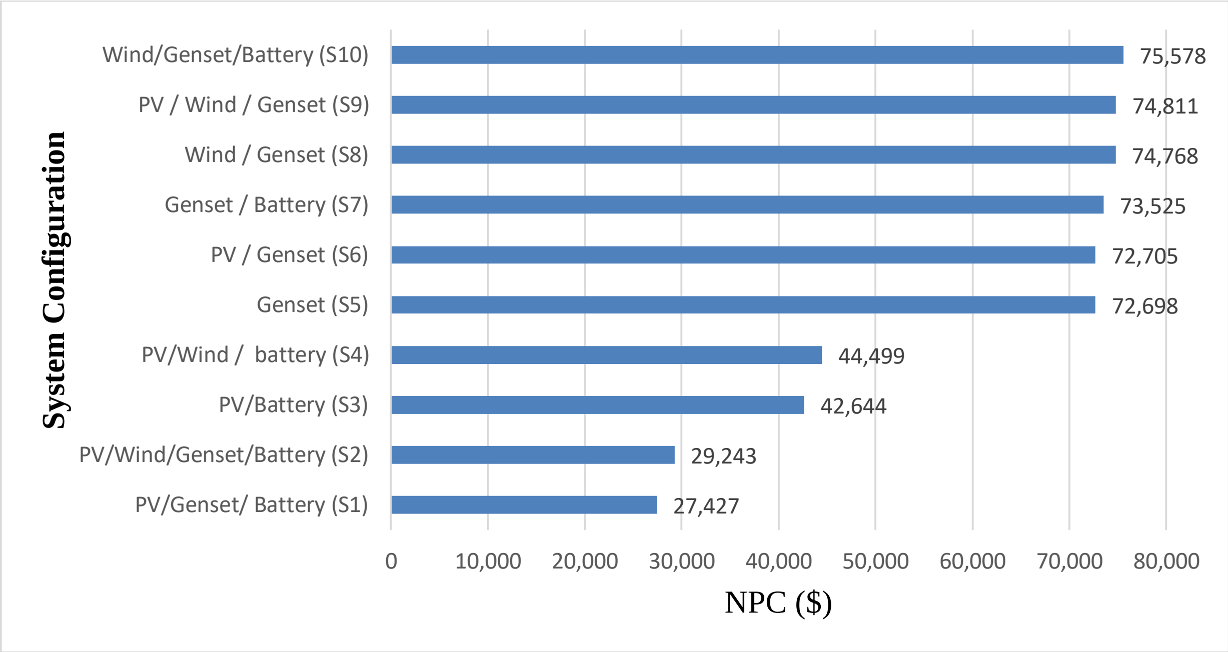


Figure 4.11: Net Present Cost Per System Configuration

4.4.3 Levelized Cost of Energy (LCOE)

System S1 gives the lowest cost of energy at $0.265, followed by system S2 at $0.285, as shown in Figure 4.12. Although Systems S2 and S3 have the same battery bank, system S2 is incorporated with the wind turbine(s) which increases the capital costs; this in turn makes the LCOE high. Systems S3 and S4 have a larger battery bank when compared to Systems S1 and S2 which significantly increase their capital costs. Systems S5 to S10 have higher LCOE, mainly because of the high fuel costs and the running time for the diesel generator. There is a 62 % reduction in the LCOE from a base case of $0.703, to the wining case of $0.265 due to the introduction of solar in the system energy mix. However, the LCOE from the optimal systems is higher than the average low voltage tariff charge from UMEME limited at 0.163$/kWh for business tariffs.

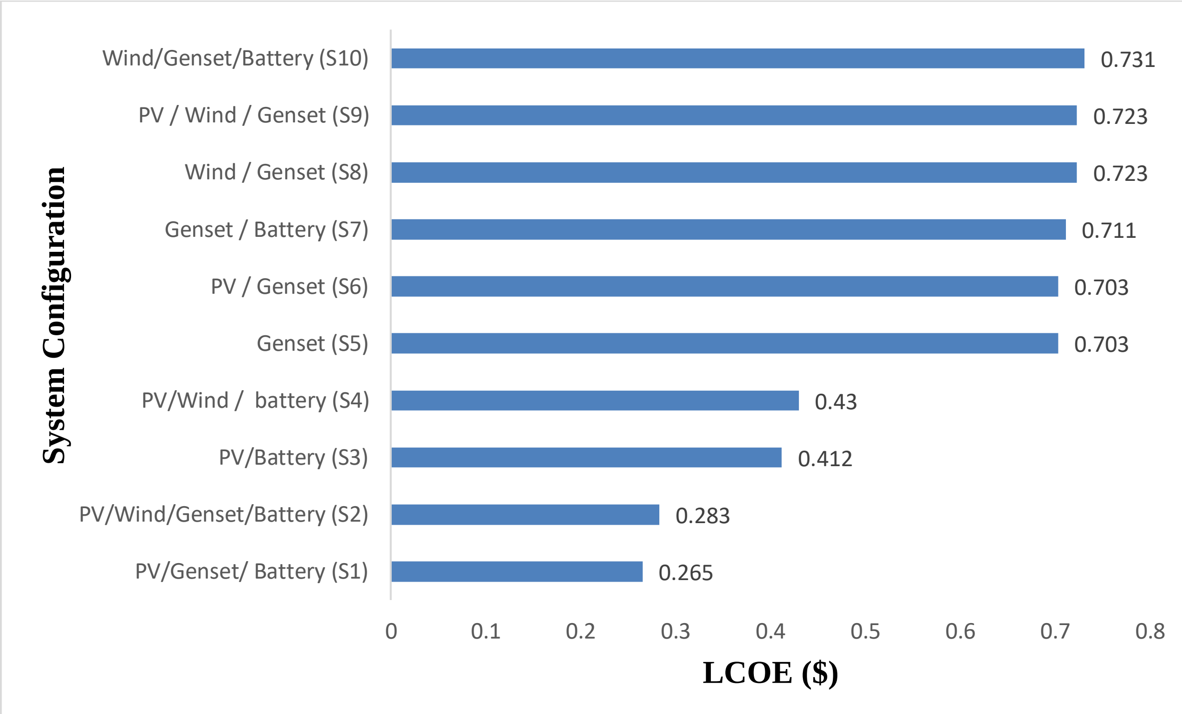


Figure 4.12: Levelized Cost of Energy Per System Configuration

4.5 Technical Analysis

4.5.1 Electrical Production

The configured systems in HOMER Pro have Solar PV, wind turbines, and a diesel generator for power sources (as presented in the energy resource assessment section above). According to the locally available resource, the configurations are expected to have production from either two or a single source. The results in Figure 4.13, indicates that the system S4 with solar PV and wind turbines, generates more power at 54,715 kWh/yr throughout the year, than any of the other system configurations. The optimal hybrid solar system S1 generates 26,231 kWh/yr that is enough to meet the AC consumption of the health Centre at 11,559 kWh/yr.

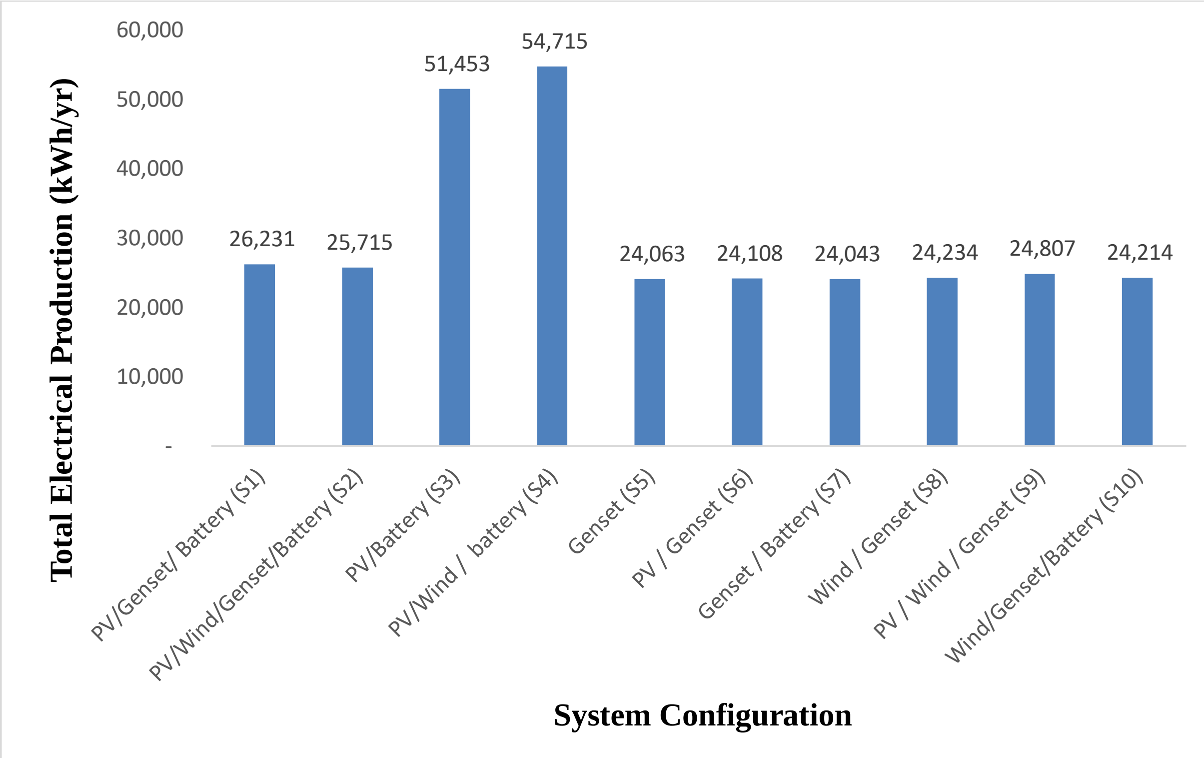


Figure 4.13: Total Electrical Production Per System

The percentage of power that is from a renewable energy source depends on the degree of penetration of the power consumed by the load generated by the PV and wind. Systems S3 and S4 have a high renewable fraction at 100 %, because they have solar PV and wind as the only power generator in the configuration. Systems S1 and S2 follow closely with a small fraction of the energy produced by the diesel generator at 14.5 % and 14.7 % throughout the year, as shown in Table 4. 2. Renewable fraction (RF) is the total amount of power generated by renewable energy sources compared to the total power generation from the entire hybrid system [127]. It is usually desired to have a RF as high as possible but bearing in mind its effect on NPC. The RF is obtained from Equation (4.1) below.

$$\text{RF (\%)} = (1 - \frac{\sum \text{Pdiesel}}{\sum \text{pren}}) \text{ x } 100 \text{)} \quad (4.1)$$

where, Pren is the power output of the connected renewable energy sources, i.e., PV and wind in this study.

Table 4:2: Electrical Energy Production Per Type of Source

System Configuration	Solar		Wind		Genset		Renewable Fraction (%)
	kWh/yr.	**%**	**kWh/yr.**	**%**	**kWh/yr.**	**%**	
PV/Genset/ Battery (S1)	24,476.0	93.300			1,755	6.69	85.5
PV/Wind/Genset/Battery (S2)	23,717.0	92.200	220	0.856	1,778	6.91	85.3
PV/Battery (S3)	51,453.0	100.000					100.0
PV/Wind/Battery (S4)	54,495.0	99.600	220	0.402			100.0
Genset (S5)					24,063	100.00	0.0
PV/Genset (S6)	76.6	0.318			24,031	99.70	0.0
Genset/Battery (S7)					24,043	100.00	0.0
Wind/Genset (S8)			220	0.909	24,014	99.10	0.0
PV/Wind/Genset (S9)	904.0	3.640	220	0.888	23,682	95.50	0.0
Wind/Genset/Battery (S10)			220	0.909	23,994	99.10	0.0

System configurations S1 and S2 have a slightly lower renewable penetration than S2 and S3, because of the diesel generators that generate electricity when the power stored in the battery is not enough to meet the demand. Also, th energy from the diesel Genset is only 6.69 % and 6.91 % of the total production; this indicates that a Genset is just a backup when the battery is down. The base case S5 and S7 have only Genset as the source of power, and therefore their RF is zero. The RF of S6, S8, S9, and S10 is zero even though they have a renewable resource, because almost all that electricity is given off as excess power. The configuration which has wind is not the best option because of the low wind speed at the site area.

4.5.1.1 Performance of the Solar PV

Table 4.3 shows the predicted performance indicators and power output respectively for the PV component of the optimal hybrid system for Busitema Health Centre III.

Table 4.3: Performance Indicator for a Model PV Component of the Hybrid System

Quantity	Value	Units	Quantity	Value	Units
Rated Capacity	15.8	kW	Minimum Output	0	kW
Mean Output	2.79	kW	Maximum Output	14.9	kW
Mean Output	67.1	kWh/d	PV Penetration	202	%
Capacity Factor	17.7	%	Hours of Operation	4,371	hrs/yr
Total Production	24,476	kWh/yr	Levelized Cost	0.0436	$/kWh

It can be observed from Table 4.3 that the PV would operate with a capacity factor of 17.7 %. With an installed capacity of 15.8 kW, the PV array could achieve a maximum power output of 14.9 kW. The LCOE of 0.0436 per kWh shown above is based on the total cost of the components. This is the LCOE for the installed costs of the PV panels alone without accounting for BOS. Figure 4.14 shows the average energy production from the Solar PV.

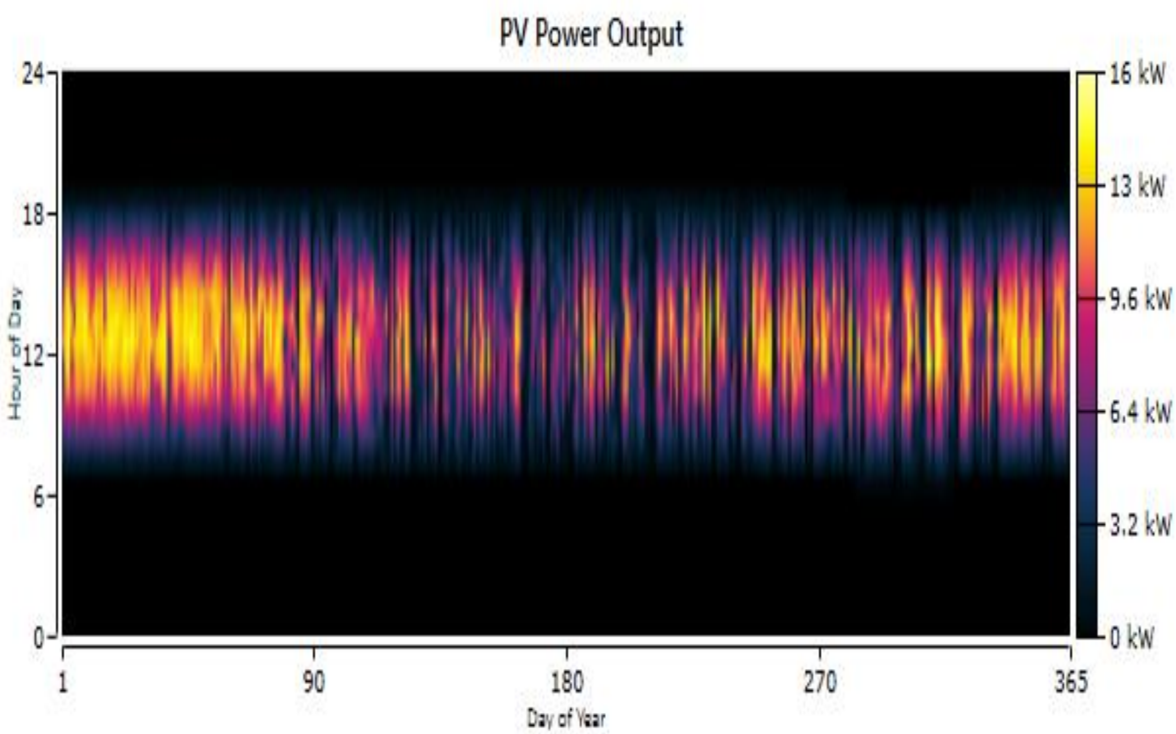


Figure 4.14: Average Energy Production from the Solar PV

4.5.1.1 Performance of Battery Bank

Table 4.4 shows a summary of performance indicators for the modelled battery storage, while Figure 4.15 shows the predicted variation in state of charge of the battery bank.

Table 4.4: Simulated Performance Indicators for Battery Bank

Quantity	Value	Units
Batteries	9.00	qty.
String Size	1.00	batteries
Strings in Parallel	9.00	strings
Bus Voltage	6.00	V

Quantity	Value	Units
Autonomy	11.3	hr
Storage Wear Cost	0.212	$/kWh
Nominal Capacity	26.0	kWh
Usable Nominal Capacity	15.6	kWh
Lifetime Throughput	14,220	kWh
Expected Life	4.37	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	3,634	kWh/yr
Energy Out	2,913	kWh/yr
Storage Depletion	6.65	kWh/yr
Losses	727	kWh/yr
Annual Throughput	3,257	kWh/yr

The system architecture contains 9 batteries, with a string size of 1.00 per battery, and 9 strings in parallel and a Bus voltage of 6.00 V. The battery sizing has autonomy of 14.3 hours with a nominal capacity of 26.0 kWh and a lifetime throughput of 14,220 kWh and expected life time of 4.37 years.

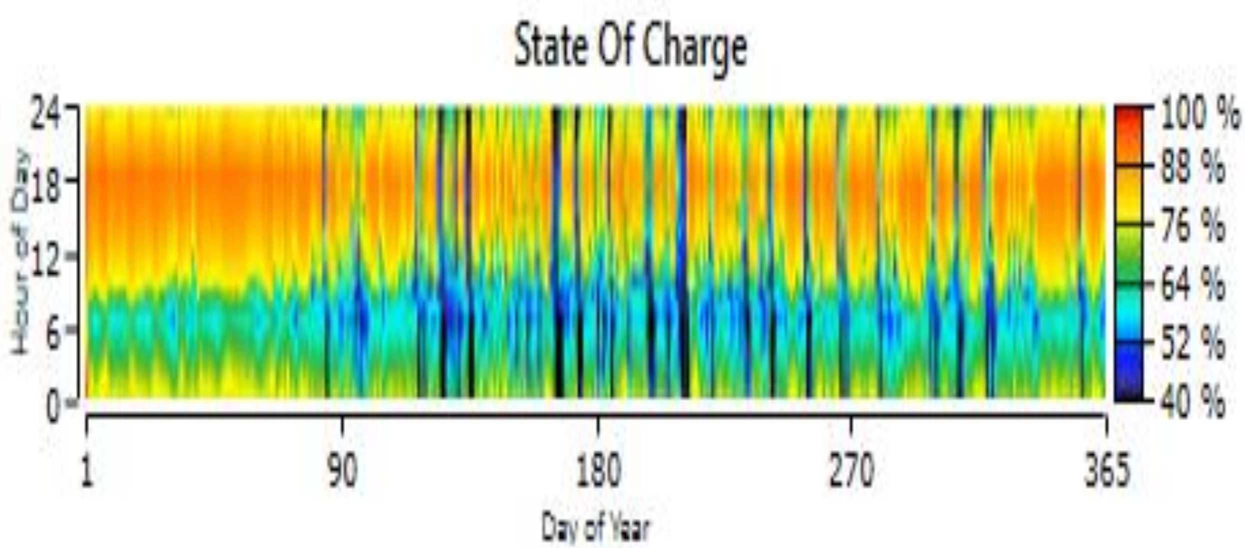


Figure 4.15: State of Charge of Battery Storage for a Year

It can be seen from Figure 4.15 that the battery bank's state of charge would vary between 40 and 100%. In Table 3.6, it can be shown that the efficiency of the battery bank is 80 %, i.e., having 20 % losses. However, the important parameter in the table is the expected life of the battery. The results show that the battery bank would need changing about every 4.37 years.

4.5.2 Excess Electricity

Most of the systems have a large quantity of excess power as shown in Table 4.5. However, it should be noted that the constraint for capacity shortage during the simulation was set at a maximum value of 0 %, meaning the system was designed to meet all the annual load demand without any shortage.

Table 4.5: Excess Electricity from different System Configurations

System Configuration	Excess electricity (kWh/yr)	Percentage of Excess Electricity (%)
PV/Genset/Battery (S1)	12,939	49.3
PV/Wind/Genset/Battery (S2)	12,446	48.0
PV/Battery (S3)	38,060	74.0
PV/Wind/Battery (S4)	41,359	75.6
Genset (S5)	11,945	49.6
PV/Genset (S6)	11,989	49.7
Genset/Battery (S7)	11,926	49.0
Wind/Genset (S8)	12,116	50.0
PV/Wind/Genset (S9)	12,675	51.1
Wind/Genset/Battery (S10)	12,097	50.0

In the Table 4.5, the results show that S3 has the highest quantity of excess electricity at 74.0 % of the total production per year from the solar PV producing energy during the day when the base load is low. S2 expresses the lowest excess electricity at 48.0 % due to lower capacity of Solar PV.

4.5.3 Fuel Consumption

The consumption of fuel depends highly on the number of hours that a diesel genset runs, and the load to be supplied. The generator size, set at 10 kW consumes enough fuel to power the full load of the health Centre, especially when it is the sole power producer. S5 consumes the most amount of fuel at 11,08 litres per year, since Genset is the sole supplier of power. Systems S1 and S2 have low fuel consumption at 818 liters and 829 litres respectively, as they do not depend on diesel generator as the sole producer of electricity needed to power the load. S3 and S4 have zero fuel consumption because the load is powered by only renewable sources namely Solar and wind as shown in Figure 4.16. Long hours of operation of the generator lead to high consumption of fuel.

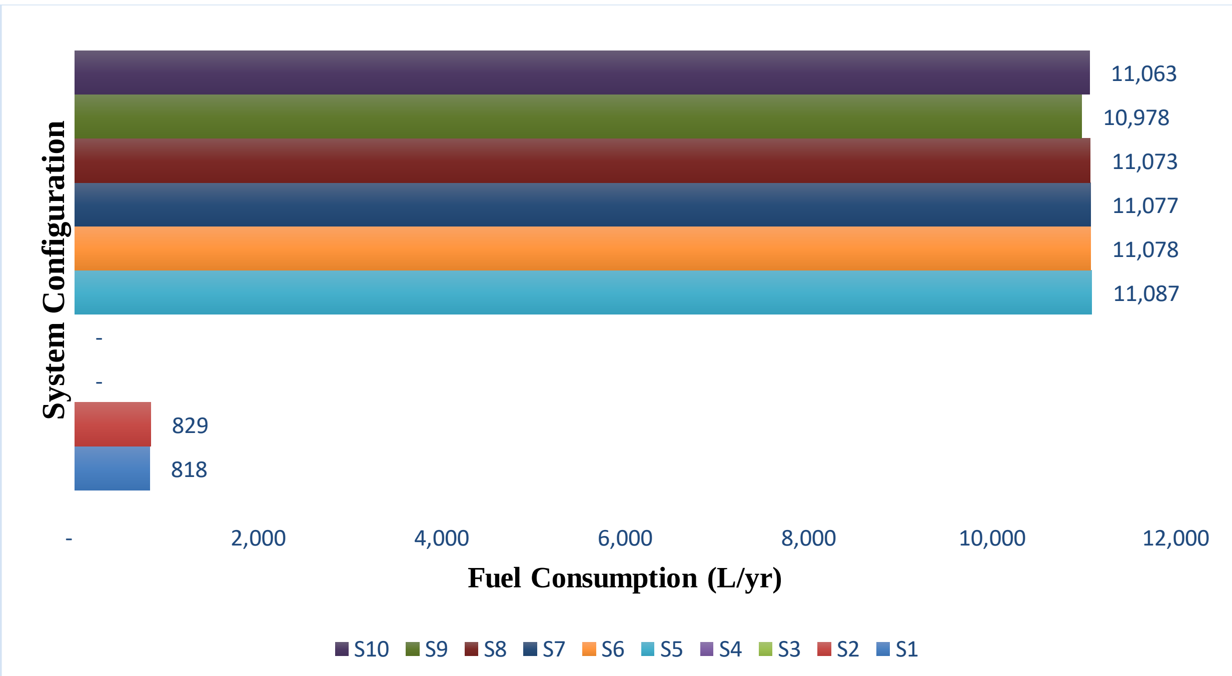


Figure 4.16: Fuel Consumption Per System Type

4.5.4 Carbon Emissions

The use of diesel generators for the production of electricity releases CO_2 and other pollutants to the atmosphere. In this analysis, the emphasis was put on CO_2 emissions per configuration. Although there are other emissions in the form of particulate matter, unburnt hydrocarbons, oxides of nitrogen, and carbon-monoxide, among others. The annual carbon emission is directly related to the amount of fuel consumed by the diesel generator per year.

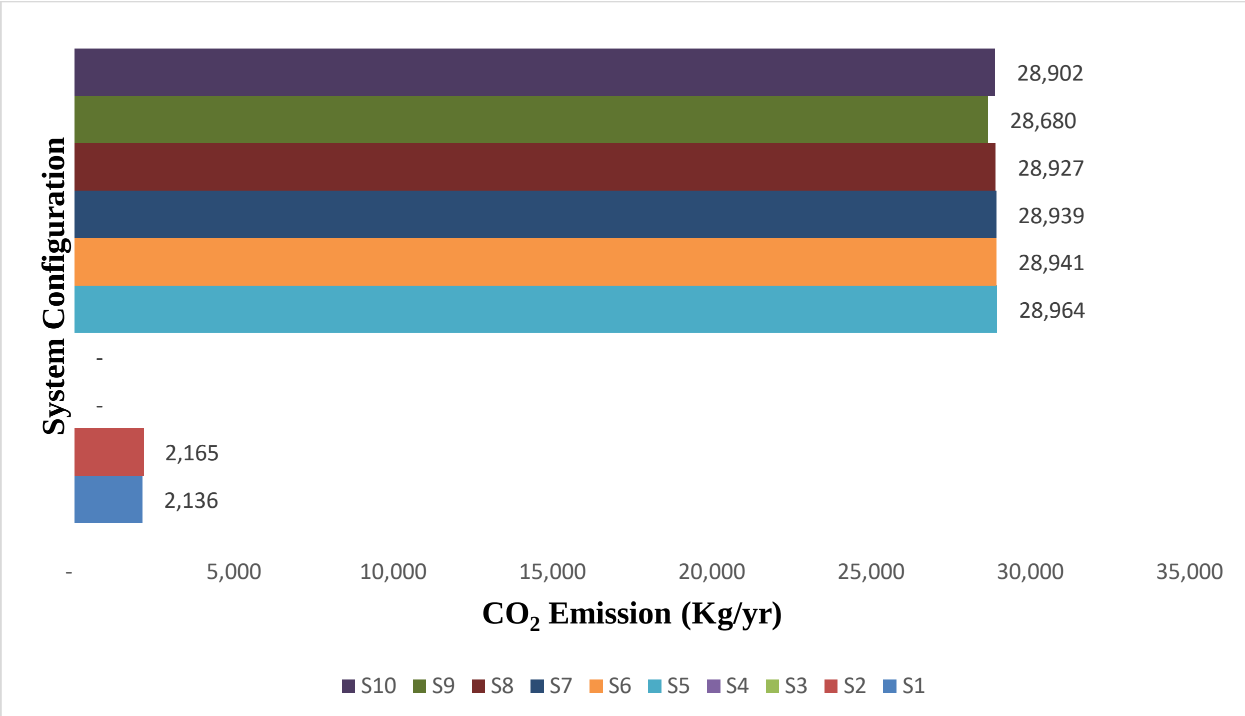


Figure 4.17: CO_2 Emissions Per System Configuration

A lot of CO_2 emissions are released from S5 up to S10. This is due to the long hours of running the diesel generator (a significant component in each of the system configurations above). S5 releases high levels of CO_2 emissions per year because it consumes more fuel as indicated in Figure 4.17. S2 and S3 have no CO_2 emissions during the operation of the system, while S1 and S2 release a negligible amount as compared to the other configurations. The diesel generator in the hybrid system contributes less towards the energy produced as a whole, thereby leading to the low emissions from the system. Carbon-dioxide emissions in this system thus reduce by 92.63 % from the S5 to a hybridized diesel generator with batteries (i.e., S1). The world is transitioning to a carbon-free energy structure; hence, a system with zero or negligible carbon emissions is desirable for diversification of the electricity mix.

4.6 Sensitivity Analysis of the System

The sensitivity result is the graphical representation of optimal systems. Basically, it shows the effects of a particular variable such as: diesel price, discount rate, inflation rate, average wind speed, annual average load, average solar irradiation, among others, on the hybrid system. A sensitivity analysis is essential in studying the effect of unknown variables and uncertainties on the performance of the designed system. It helps in answering the what-if-question. Sensitivity analysis is done by entering multiple values for a particular input variable in HOMER Pro. An input variable which has multiple values is called a sensitivity variable. The software repeats optimization process for each value of the variable and shows the sensitivity cases in the upper section of the results. Sensitivity analysis helps in discovering the effect of changes in the available resources and economic condition. Some of the variables are either unknown and a range of futures are used for estimate, or others are constantly changing the economy of the country, such as expected inflation rate and discount rates. In this work, a sensitivity analysis is used to understand the effect of changes in variables such as the diesel fuel price, inflation rate, average solar irradiation, and annual average load, on the economics of the optimal configuration.

Table 4.6: Sensitivity Variable Values

Diesel fuel price ($)	**Inflation rate (%)**	**Solar radiation ($kWh/m^2/day$)**	**Annual average load kwh/day**
0.5	2.87	5.15	33.20
1.0	3.94	5.9	36.52
1.5	4.85		

4.6.1 The Impact of Diesel Fuel Price and Inflation Rate on Optimal Solution

It can be observed in Figure 4.18 that increase in diesel price has a significant effect on the NPC of the optimal configuration. From a base price of $0.5/L when the NPC is $27,426.650, the NPC increases almost linearly as a function of the diesel price. At a price of $1.0/L, the NPC increases to $30,669.560, which is a 12 % increase in NPC for a 100 % increase in diesel price. An increase in diesel price from $0.5 to $1.0/L leads to an increase of energy cost by about 19 %. However, it may be noted that increase in diesel price can significantly reduce the emissions by altering the selection of energy supply options and shifting away from diesel to renewable energy generation. An increase in inflation rate from 3.94 % to 4.85 % leads to a decrease of energy cost by about 2 %. This results in a total net present cost of $31,187.04 (i.e., a rise of 6.3 % compared to the current state). The impact of varying fuel price and inflation rate on NPC and LCOE is shown in Figures

4.19 and 4.20 respectively.

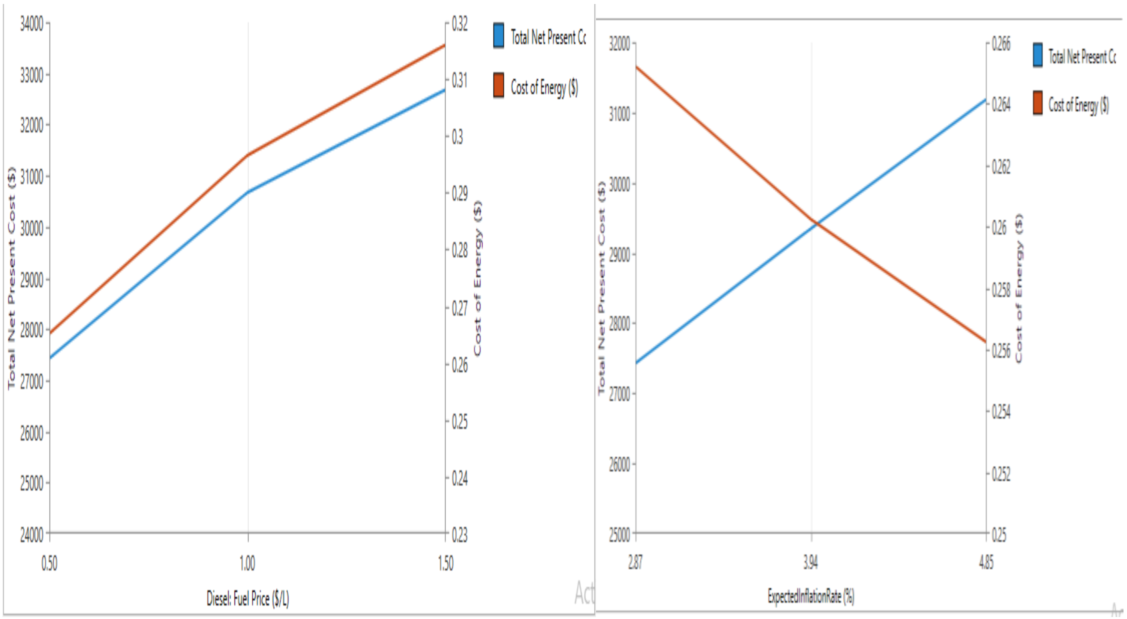


Figure 4.18: NPC and LCOE as a Function of Diesel Price and Inflation Rate

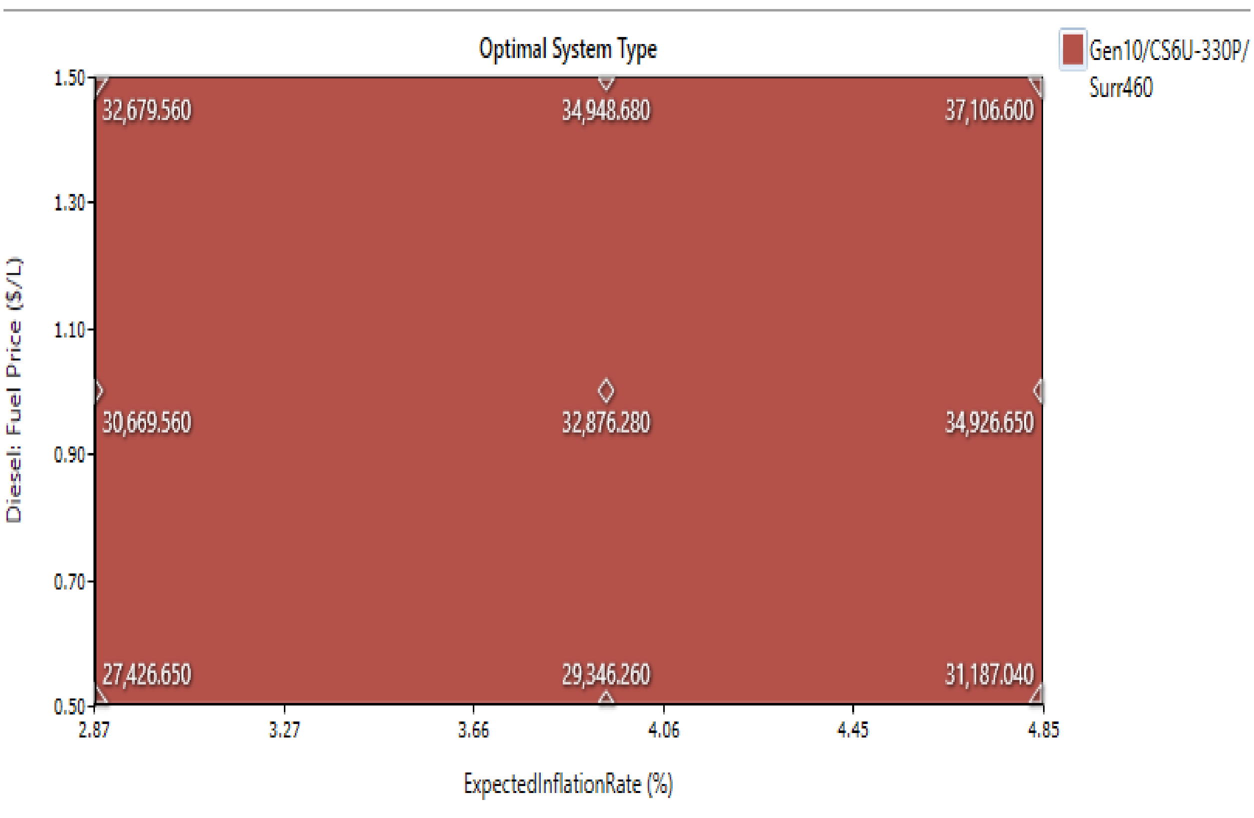


Figure 4.19: Impact of Varying Fuel Price and Inflation Rate on NPC

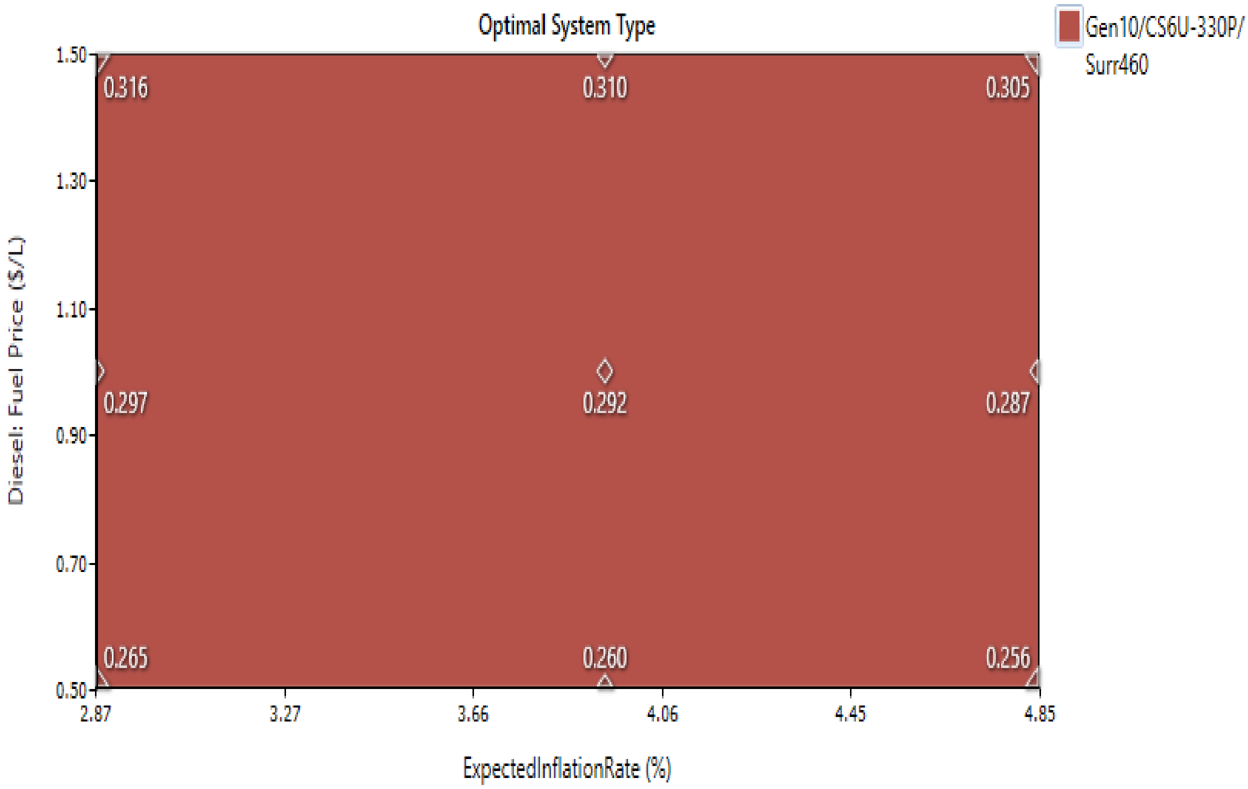


Figure 4.20: Impact of Varying Fuel Price and Inflation Rate on LCOE

4.6.2 Impact of Solar Irradiation and Annual Load on Optimal Solution

In this work, the variation of average solar irradiation is 5.15 kWh/m^2/day as recorded at Tororo weather station to 5.9 kWh/m^2/day obtained from NASA database in HOMER Pro. Its effect on the optimal solution was analyzed with NPC and COE. It can be observed from Figures 4.22 that by varying the solar irradiation scaled average from 5.15 – 5.15 kWh/m^2/day, the total NPC of the optimal system S1 is decreased from $27,426.650 to $26,278.960, and the COE is also reduced from $0.265 to $0.254. The effect of the variation of solar irradiation and load demand on optimal system's LCOE and NPC, are shown in Figures 4.22 and 4.23, respectively. The higher the solar radiation at a site, the lower the NPC value. This is because high irradiation will enable the PV system to supply the load for a longer period. With this, the use diesel generator with its associated cost will be reduced; this will bring about low NPC and will also lead to higher value of RF. The NPC increases from $27,426.650 to $29,742.910 with an increase in the electrical load demand. This is a result of the need for expansion of the system. However, the LCOE decreases from $0.265 to $0.261 at an average solar irradiation of 5.15kWh/m^2/day.

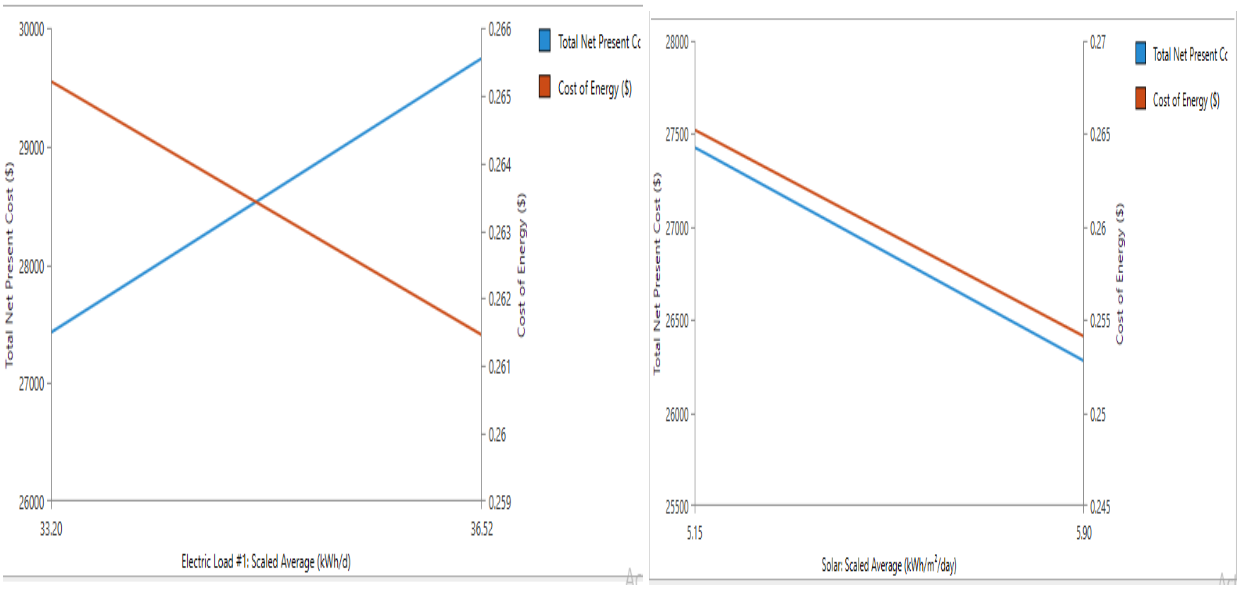


Figure 4.21: NPC and LCOE as a function of Average Solar irradiation and Average Load

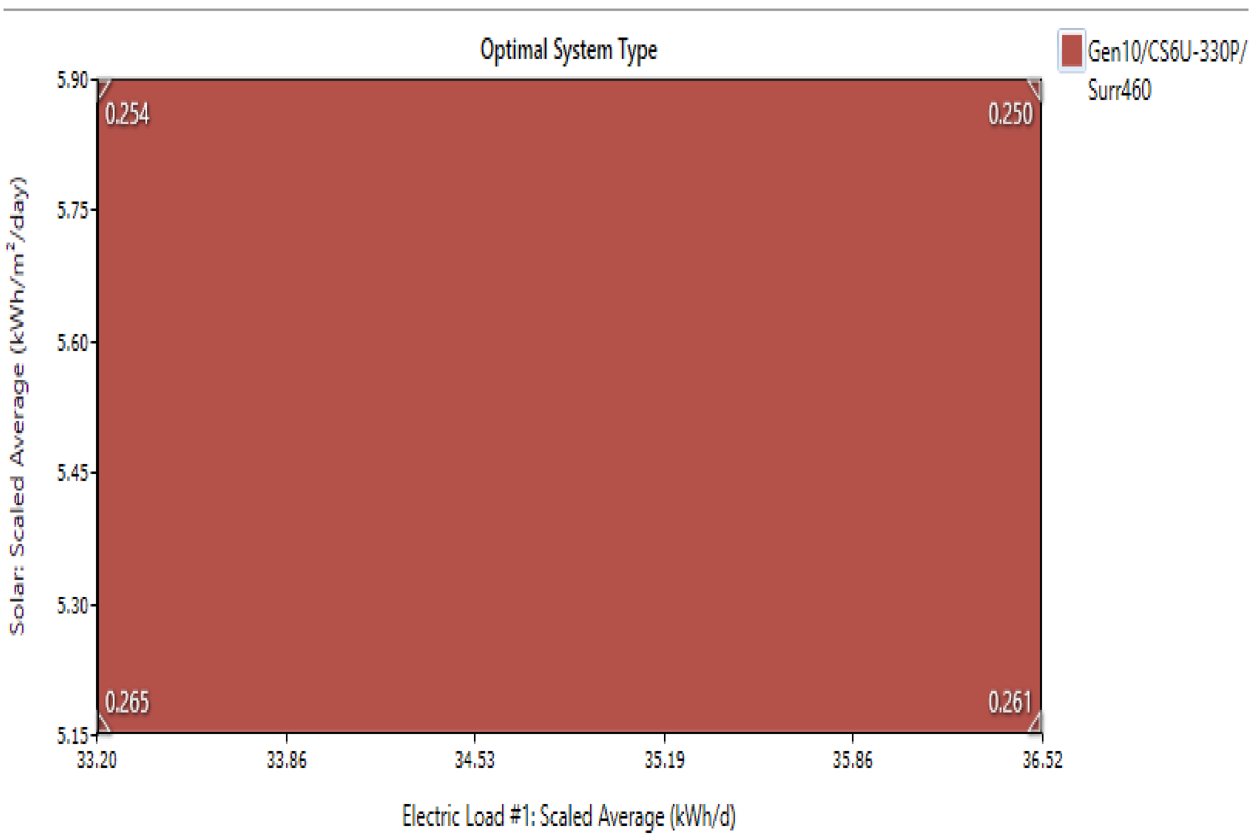


Figure 4.22: Sensitivity on Solar irradiation and Average load superimposed with LCOE

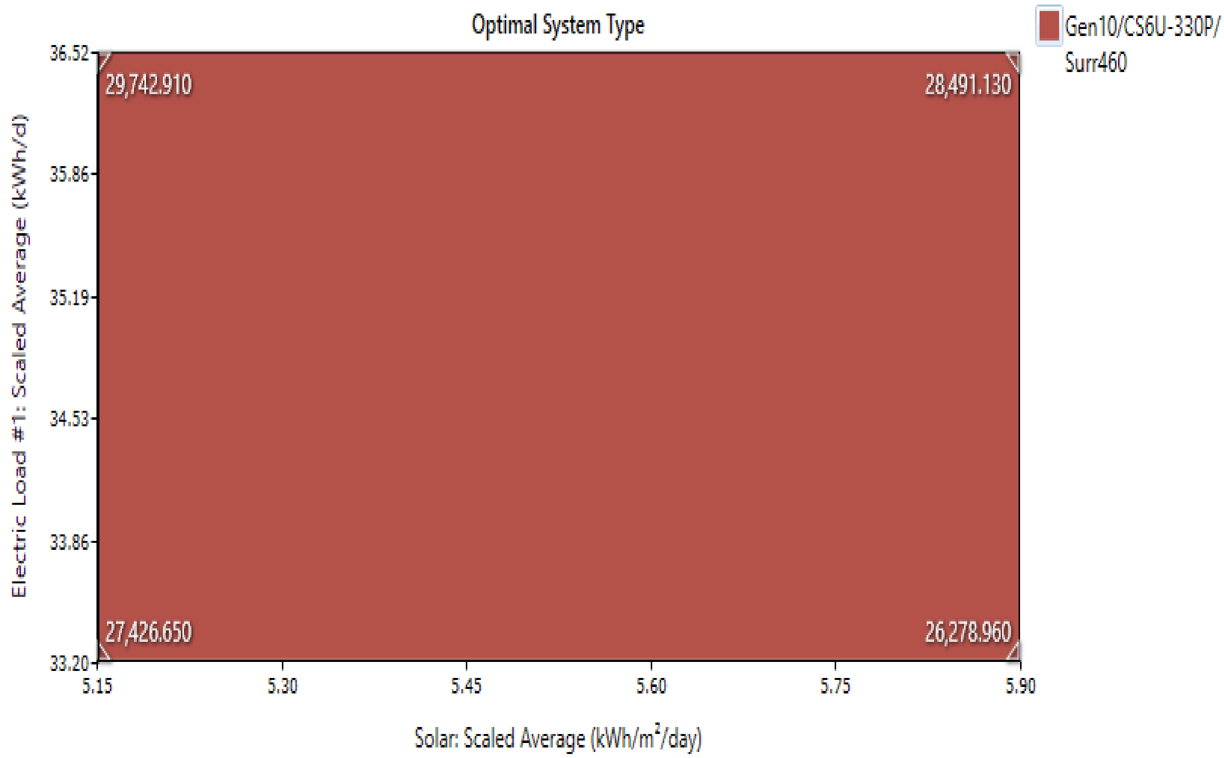


Figure 4.23: Sensitivity of Solar irradiation and scale average load superimposed with NPC

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The findings show that the wind energy potential of the study area is considerably lower. Although wind potential may not be sufficient for a large, independent wind system, the analysis has shown that if wind is integrated with other energy systems such as PV, diesel generator, and batteries etc., a viable solution can be obtained. Furthermore, with the available solar energy potential, the results show that there is that availability of utilizable potential of solar energy in the study area.

Several configurations are simulated within the specified capacity ranges for each of the system components in HOMER. Based on the results, configuration S1 consisting of solar PV and battery stood out as the most appropriate optimal system having a capacity of 15.78 kW of solar PV, and 9 batteries having 2.98 kWh nominal capacity each yielded the lowest NPC of 22,427 USD and LCOE of 0.265 USD/kWh. The LCOE is about 39% higher than the 2019 electricity tariff developed by UMEME.

Busitema Health Centre III has been relying on diesel generators and the unreliable national grid; hence, the PV/Diesel/Battery hybrid system will be of great importance in supplying quality electricity to the health Centre. The findings show that the optimal combination of the PV array, Genset and electric storage back-up system, is the most viable configuration despite its high investment cost. Current challenges such as grid instability that affects distribution networks, causing constant blackouts can be reduced if different sectors are allowed to produce their own electricity as back-up to the unreliable grid.

The study also revealed that the choice of components is vital in setting the NPC of a project. For instance, investing in higher capital cost for a good battery with a longer life span can go further into reducing the LCOE of the project. The chosen batteries have a longer life, which if properly managed, can make the electrical systems cheaper. The replacement costs through the lifetime of the project dwindled thereby reducing further the LCOE of the electric system. The overall results indicate that not only does the hybrid system configurations perform better than base case simulation with regards to the NPC for all 10 simulations; the results also displayed better performance in the categories such as electrical, fuel consumption and CO_2 reduction.

Finally, the results of the findings from the sensitivity analysis, as well as information gained from the entire study can be applied in the design, execution, or development of HRES for any applications in other locations across the country having similar geographical coordinate as the site considered in this study.

5.2 Recommendations

The following are recommendations of this research work, that may be useful to researchers and decision makers. The price of energy systems' equipment keeps changing and are affected by the discount rate and inflation rate of the country. Favorable rates enable developers of energy system to secure financing for the establishment of mini-grids that will have an impact on the cost of energy in the long run. However, the effect of the discount rate and cost of different equipment was not discussed during the sensitivity analysis. An in-depth study is therefore recommended for the impact of changes in the inflation rate, discount rate and equipment costs on the economics of the optimal system.

The Implementation for this hybrid system in the rural health Centre can serve as a pilot project for the whole country. This will serve as an impetus for more research, study, and analysis. Concerning environmental aspects, this kind of hybrid energy system has to be widespread in order to support the renewable energy policy of the government of Uganda as a way of curbing deforestation and reduction of greenhouse gas emission.

This study is conducted on one health Centre in Eastern Uganda that is randomly selected. It does not cover all health Centers in the Region. Future researches should consider extending such work to other potential sites, so that all the rural health facilities will benefit from the abundant and free renewable energy resource. The COE for the hybrid system is very high, hence the need to provide subsidy by the government to minimize the initial cost of the system.

6. REFERENCES

[1] AGECC, "Energy for a Sustainable Future," 2010.

[2] OECD/IEA, "Africa Energy Outlook, A FOCUS ON ENERGY PROSPECTS IN SUB-SAHARAN AFRICA.," 2014.

[3] I. E. A. IEA, "Africa energy outlook," 2014.

[4] steven von E. Mokveld, Kees, "Final Energy Report Uganda," Final energy Rep. uganda, p. 30, 2018.

[5] PWC, "Industrialisation for job creation and shared prosperity: Uganda's 2018/19 National Budget," 2018.

[6] A. Agenda, "UGANDA ' S SUSTAINABLE ENERGY FOR ALL INITIATIVE –," no. June, 2015.

[7] Daniel K, "Uganda to extend Bujagali tax breaks beyond mid-2017 over high power tariffs - The East African," The East African, Nairobi, Oct-2016.

[8] M. Gustavsson, O. Broad, and M. Hankins, "a 100% Renewable Energy Future By 2050 Energy Report for Uganda," no. October, 2015.

[9] S. Report, "HEALTH FACILITY ENERGY NEEDS ASSESSMENT," no. August, pp. 1–51, 2015.

[10] UBOS, "Uganda bureau of statistics 2019 statistical abstract," Kampala, 2019.

[11] NEMA, "The Republic of Uganda State of the Environment Report.," pp. 1–205, 2010.

[12] K. K. Mathew Woods, Timothy Cowman, "Uganda: Captive Power Developer Guide GET.INVEST MARKET INSIGHTS," 2019.

[13] UNDP, "Human Development Report 2019: Inequalities in Human Development in the 21st Century Jordan," pp. 1–10, 2019.

[14] UBOS, "The National Population and Housing Census 2014 – Main Report," Kampala, Uganda, 2016.

[15] MEMD, "Ministry of Energy and Mineral Development Draft National Energy Policy October 2019," 2019.

[16] R. Tumwesigye, P. Twebaze, N. Makuregye, and E. Muyambi, Key issues in Uganda ' s energy sector. London, 2011.

[17] T. H. E. Republic, "THE REPUBLIC OF UGANDA Ministry of Energy and Mineral Development Energy and Mineral Development Sector Sector Development Plan," no. June

2015, 2015.

[18] REA, “ENVIRONMENTAL AND SOCIAL IMPACT ASSESEMNT FOR THE PROPOSED 33KV DISTRIBUTION LINES IN THE DISTRICTS OF MASAKA , GOMBA , BUTAMBALA , MUKONO AND LUWERO DEVELOPER RURAL ELECTRIFICATION AGENCY (REA),” no. Ert Iii, 2018.

[19] MEMD, “Strategy and Plan Rural Electrification Strategy and Plan,” 2013.

[20] ERA, “Uganda Renewable Energy Feed-in Tariff (REFIT) Phase 3 Guidelines Revised July 2016,” no. July, 2016.

[21] GOU, “Government of Uganda: Second National Development Plan,” Natl. Plan. Auth. Uganda, vol. 1, no. 2, pp. 65–70, 2015.

[22] WBG, “World Bank Group Climate Change Action plan 2016-2020,” World Bank Gr., p. 74, 2016.

[23] O. Broad and M. Hankins, “Energy Report for Uganda a 100 % Renewable,” 2015.

[24] T. H. E. Republic, “THE OIL AND GAS SECTOR IN UGANDA : FREQUENTLY ASKED QUESTIONS,” no. January, pp. 1–30, 2017.

[25] O. William, K. Avellino, F. Mwarania, A. A. Wahab, and K. T. Aime, “Uganda Solar Energy Utilization : Current Status and Future Trends,” vol. 8, no. 3, pp. 317–327, 2018.

[26] Solargis, “Solar resource maps and GIS data for 200+ countries,” Solargis.com. 2017.

[27] G. Kamese, “Renewable Energy Technologies in Uganda : The potential for Geothermal Energy Development,” 2004.

[28] A. Fashina, M. Mundu, O. Akiyode, L. Abdullah, D. Sanni, and L. Ounyesiga, “The Drivers and Barriers of Renewable Energy Applications and Development in Uganda: A Review,” Clean Technol., vol. 1, no. 1, pp. 9–39, 2018.

[29] M. Gustavsson, O. Broad, M. Hankins, and K. Sosis, “Energy Report for Uganda – A 100% Renewable Energy Future by 2050.,” no. October, p. 92, 2015.

[30] C. Report, Competitiveness Report 2015. 2015.

[31] E. Consumption and E. Resources, “Uganda,” no. Table 1, pp. 2013–2016, 2015.

[32] BMAU, “Biomass Technology in Uganda:The Unexploited Energy Potential OVERVIEW.” p. 4, 2015.

[33] IRENA, “Solar Photovoltaics Technology Brief,” Int. Renew. Energy Agency, no. January, pp. 1–28, 2013.

[34] SNV, “Solar PV Training & Referral Manual.”

[35] IRENA, International Renewable Energy Agency. Renewable Power Generation Costs in 2017. 2018.

[36] A. F. Čotar, Andrej, “Photovolataic Systems,” Darko Jardas, dipl. ing. REA Kvarner Ltd, p. 1, 2012.

[37] S. T. Bahta, “Design and Analyzing of an Off-Grid Hybrid Renewable Energy System to Supply Electricity for Rural Areas,” Master Sci. Thesis KTH Sch. Ind. Eng. Manag., p. 95, 2013.

[38] US National Renewable Energy Laboratory, “Best Research-Cell Efficiencies,” Nrel. p. 1, 2019.

[39] Alasdair Miller and Ben Lumby, “Utility Scale Solar Power Plants. A Guide for developers and investors,” World Bank Gr., pp. 24–48, 2012.

[40] M. H. Ahmadi, M. Ghazvini, M. Sadeghzadeh, and A. Puia, “Solar power technology for electricity generation : A critical review,” no. September, 2018.

[41] H. Islam et al., “Performance evaluation of maximum power point tracking approaches and photovoltaic systems,” Energies, vol. 11, no. 2, pp. 7–9, 2018.

[42] S. Davis, “Solar System Efficiency_ Maximum Power Point Tracking is Key _ Power Electronics,” 2015. .

[43] M. N. Islam, M. Z. Rahman, and S. M. Mominuzzaman, “The effect of Irradiation on different parameters of monocrystalline photovoltaic solar cell,” Proc. 2014 3rd Int. Conf. Dev. Renew. Energy Technol. ICDRET 2014, 2014.

[44] A. R. Amelia, Y. M. Irwan, W. Z. Leow, M. Irwanto, I. Safwati, and M. Zhafarina, “Investigation of the effect temperature on photovoltaic (PV) panel output performance,” Int. J. Adv. Sci. Eng. Inf. Technol., vol. 6, no. 5, pp. 682–688, 2016.

[45] C. D. Ahrens, “An introduction to weather, climate, and the environment,” Meteorol. today, 2003.

[46] H. A. Kazem et al., “Effect of humidity on the PV performance in Oman,” Asian Trans. Eng., vol. 2, no. 4, pp. 29–32, 2014.

[47] U. O. G. E. M. A. (UOMA), “Mapping the Ugandan off-grid energy market,” 2018.

[48] M. Bošnjaković, “Wind energy technology trends,” no. November, 2016.

[49] L. Y. Pao and K. E. Johnson, “Control of Wind Turbines: Approaches, challenges, and

recent developments," IEEE Control Syst., vol. 31, no. 2, pp. 44–62, 2011.
[50] M. K. Bourdoulis and A. T. Alexandridis, "Direct power control of DFIG wind systems based on nonlinear modeling and analysis," IEEE J. Emerg. Sel. Top. Power Electron., vol. 2, no. 4, pp. 764–775, 2014.
[51] M. Ó. Óskarsdóttir, "A General Description and Comparison of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines," 2014.
[52] M. Kebbati, "Master Dissertation," 2018.
[53] D. Kajela and M. S. Manshahia, "Optimization of Renewable Energy Systems : A Review," no. December, 2017.
[54] A. K. S. David Tan, "Handbook for Solar Photovoltaic Systems," Energy Mark. Authority, Singapore Publ., pp. 4–9, 2011.
[55] S. Pei and Y. Li, "applied sciences Wind Turbine Power Curve Modeling with a Hybrid Machine Learning Technique," 2019.
[56] O. Uluyol, G. Parthasarathy, W. Foslien, and K. Kim, "Power curve analytic for wind turbine performance monitoring and prognostics," Proc. Annu. Conf. Progn. Heal. Manag. Soc. 2011, PHM 2011, no. January 2015, p. 9, 2015.
[57] Y. Wang, Q. Hu, L. Li, A. M. Foley, and D. Srinivasan, "Approaches to wind power curve modeling: A review and discussion," Renew. Sustain. Energy Rev., vol. 116, no. October, p. 109422, 2019.
[58] A. Oberhofer, "Energy Storage Technology & Their Role in Reneable Integration," 2012.
[59] A. L. LILY, ODARNO, ESTOMIH, SAWE, MARY, SWAI, MANENJO J.J, "Accelerating Mini- Grid Deployment in Sub-Saharan Africa," 2017.
[60] EEP-Africa, "Opportunities And Challenges In The Mini-Grid Sector In Africa," Hatfield, 2018.
[61] Mike Rycroft, "The development of renewable energy based mini-, micro- and nano-grids - EE Publishers," EE Publishers, 2016. .
[62] USAID, "KEY STEPS IN MINI-GRID Part of the Technical Design module of," 2020.
[63] PwC, "Electricity beyond the grid: Accelerating access to sustainable power for all," PwC Glob. power Util., pp. 1–24, 2016.
[64] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," Renew. Sustain. Energy Rev., vol. 90, no. March, pp. 402–411,

2018.

[65] P. Kumar, R. Pukale, N. Kumabhar, and U. Patil, “Optimal Design Configuration Using HOMER,” Procedia Technol., vol. 24, no. October, pp. 499–504, 2016.

[66] S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” vol. 32, pp. 192–205, 2014.

[67] O. Krishan and S. Suhag, “Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community,” J. Energy Storage, vol. 23, no. March, pp. 305–319, 2019.

[68] M. A. M. Ramli, A. Hiendro, and Y. A. Al-turki, “Techno-economic energy analysis of wind / solar hybrid system : Case study for western coastal area of Saudi Arabia,” Renew. Energy, vol. 91, pp. 374–385, 2016.

[69] RETScreen, Clean Energy Project Analysis: RETScreen® Engineering & Cases Textbook, Third Edit., no. Third Edition. 2005.

[70] R. E. Ganoe, P. W. Stackhouse, and R. J. Deyoung, RETScreen ® Plus Software Tutorial, no. November. 2014.

[71] T. Lambert, P. Gilman, and P. Lilienthal, “Micropower System Modeling with Homer,” Integr. Altern. Sources Energy, pp. 379–418, 2006.

[72] A. G. Sourabh Namdev, “FEASIBILITY ANALYSIS OF PV SYSTEM WITH DUAL AXIS MODE,” vol. 4, no. 9, pp. 1544–1547, 2017.

[73] T. Andrews and H. Elzarka, “Effective Selection of Renewable Energy Projects in Constructed Facilities,” 2013.

[74] S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” Renew. Sustain. Energy Rev., vol. 32, pp. 192–205, 2014.

[75] H. Ibrahim, J. Lefebvre, J. F. Methot, and J. S. Deschenes, “Numerical Modeling Wind-Diesel Hybrid System : Overview of the Requirements , Models and Software Tools,” pp. 23–28, 2011.

[76] S. Singh, M. Singh, and S. C. Kaushik, “A review on optimization techniques for sizing of solar-wind hybrid energy systems,” Int. J. Green Energy, vol. 13, no. 15, pp. 1564–1578, 2016.

[77] R. Siddaiah and R. P. Saini, “A review on planning , con fi gurations , modeling and optimization techniques of hybrid renewable energy systems for off grid applications,” vol.

58, pp. 376–396, 2016.

[78] K. Anoune, M. Bouya, A. Astito, and A. Ben, “Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system : A review,” vol. 93, no. May, pp. 652–673, 2018.

[79] P. Bajpai and M. Kumar, “Genetic algorithm–an approach to solve global optimization problems,” Indian J. Comput. Sci. Eng., vol. 1, no. 3, pp. 199–206, 2010.

[80] H. Yang, Z. Wei, and L. Chengzhi, “Optimal design and techno-economic analysis of a hybrid solar-wind power generation system,” Appl. Energy, vol. 86, no. 2, pp. 163–169, 2009.

[81] G. Merei, C. Berger, and D. U. Sauer, “Optimization of an off-grid hybrid PV-Wind-Diesel system with different battery technologies using genetic algorithm,” Sol. Energy, vol. 97, pp. 460–473, 2013.

[82] C. Mekontso, A. Abubakar, S. Madugu, O. Ibrahim, and Y. A. Adediran, “Review of Optimization Techniques for Sizing Renewable Energy Systems,” Comput. Eng. Appl. J., vol. 8, no. 1, pp. 13–30, 2019.

[83] T. B. Riccardo Poli, James Kennedy, “Particle swarm optimization An overview,” pp. 33–57, 2007.

[84] O. Erdinc and M. Uzunoglu, “Optimum design of hybrid renewable energy systems : Overview of different approaches,” vol. 16, pp. 1412–1425, 2012.

[85] A. Maleki, M. Ameri, and F. Pourfayaz, “TECHNO-ECONOMIC ANALYSIS AND OPTIMAL DESIGN OF AN OFF-GRID HYBRID PV/WIND/DIESEL SYSTEM WITH BATTERY STORAGE Akbar Maleki,” vol. 6, no. 4, pp. 23–39, 2014.

[86] S. A. Nowdeh, M. B. Nasrollahnezhad, and S. Khanabdal, “Optimal Sizing of a Stand-alone PV / FC / Wind Hybrid System Using PSO Modified Algorithm,” vol. 3, no. 3, 2013.

[87] K. Sasidhar and B. J. Kumar, “Optimal sizing of PV-Wind Hybrid energy system using Genetic Algorithm (GA) and Particle swarm optimization (PSO),” Int. J. Sci. Eng. Technol. Res., vol. 4, no. 2, pp. 354–358, 2015.

[88] P. Paliwal, N. P. Patidar, and R. K. Nema, “Determination of reliability constrained optimal resource mix for an autonomous hybrid power system using Particle Swarm Optimization,” Renew. Energy, vol. 63, pp. 194–204, 2014.

[89] M. Majumder, “Artificial Neural Network,” vol. 6, no. 4, pp. 49–54, 2015.

[90] K. Murugaperumal and P. Ajay D Vimal Raj, “Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification,” Sol. Energy, vol. 188, no. June, pp. 1068–1083, 2019.

[91] P. Nagapurkar and J. D. Smith, “Techno-economic optimization and social costs assessment of microgrid-conventional grid integration using genetic algorithm and Artificial Neural Networks: A case study for two US cities,” J. Clean. Prod., vol. 229, pp. 552–569, 2019.

[92] J. S. R. Jang, “ANFIS: Adaptive-Network-Based Fuzzy Inference System,” IEEE Trans. Syst. Man Cybern., vol. 23, no. 3, pp. 665–685, 1993.

[93] R. K. Rajkumar, V. K. Ramachandaramurthy, B. L. Yong, and D. B. Chia, “Techno-economical optimization of hybrid pv/wind/battery system using Neuro-Fuzzy,” Energy, vol. 36, no. 8, pp. 5148–5153, 2011.

[94] M. Adel, “An ANFIS-based Modeling for a Photovoltaic Power Supply (PVPS) System An ANFIS-based Modeling for a Photovoltaic Power Supply (PVPS) System,” no. January, 2006.

[95] N. Varghese, “Energy storage management of hybrid solar / wind standalone system using adaptive neuro - fuzzy inference system,” no. January, pp. 1–20, 2019.

[96] P. García, C. A. García, L. M. Fernández, F. Llorens, F. Jurado, and S. Member, “ANFIS-Based Control of a Grid-Connected Hybrid System Integrating Renewable Energies , Hydrogen and Batteries,” vol. 10, no. 2, pp. 1107–1117, 2014.

[97] L. Suganthi, S. Iniyan, and A. A. Samuel, “Applications of fuzzy logic in renewable energy systems - A review,” Renew. Sustain. Energy Rev., vol. 48, pp. 585–607, 2015.

[98] A. H. Fathima and K. Palanisamy, “Optimization in microgrids with hybrid energy systems – A review,” vol. 45, pp. 431–446, 2015.

[99] W. Dong, Y. Li, and J. Xiang, “Optimal sizing of a stand-alone hybrid power system based on battery/hydrogen with an improved ant colony optimization,” Energies, vol. 9, no. 10, 2016.

[100] S. K. C. D. G. M. P. Vecchi, “Optimization by Simulated Annealing,” Am. Assoc. Adv. Sci., vol. 220, no. 9, pp. 671–680, 1983.

[101] B. Chopard and M. Tomassini, “Simulated annealing,” Nat. Comput. Ser., no. February 2011, pp. 59–79, 2018.

[102] O. Ekren and B. Y. Ekren, “Size optimization of a PV / wind hybrid energy conversion

system with battery storage using simulated annealing," Appl. Energy, vol. 87, no. 2, pp. 592–598, 2010.

[103] W. Zhang, A. Maleki, M. A. Rosen, and J. Liu, "Optimization with a simulated annealing algorithm of a hybrid system for renewable energy including battery and hydrogen storage," Energy, vol. 163, pp. 191–207, 2018.

[104] S. Das, A. Mukhopadhyay, A. Roy, A. Abraham, and B. K. Panigrahi, "Exploratory power of the harmony search algorithm: Analysis and improvements for global numerical optimization," IEEE Trans. Syst. Man, Cybern. Part B Cybern., vol. 41, no. 1, pp. 89–106, 2011.

[105] Z. W. Geem and Y. Yoon, "Harmony search optimization of renewable energy charging with energy storage system," Int. J. Electr. Power Energy Syst., vol. 86, pp. 120–126, 2017.

[106] A. Maleki, M. A. Nazari, and F. Pourfayaz, "Harmony search optimization for optimum sizing of hybrid solar schemes based on battery storage unit," Energy Reports, no. xxxx, 2020.

[107] M. A. Munoz, S. K. Halgamuge, W. Alfonso, and E. F. Caicedo, "Simplifying the Bacteria Foraging Optimization Algorithm Simplifying the Bacteria Foraging Optimization Algorithm," no. July, 2010.

[108] K. M. Passino, "Biomimicry of Bacterial Foraging," Small, no. June, pp. 52–67, 2002.

[109] N. H. Saad, A. A. El-Sattar, and M. E. Marei, "Improved bacterial foraging optimization for grid connected wind energy conversion system based PMSG with matrix converter," Ain Shams Eng. J., vol. 9, no. 4, pp. 2183–2193, 2018.

[110] A. F. Mohamed, M. M. Elarini, and A. M. Othman, "A new technique based on Artificial Bee Colony Algorithm for optimal sizing of stand-alone photovoltaic system," J. Adv. Res., vol. 5, no. 3, pp. 397–408, 2014.

[111] N. K. Paliwal, A. K. Singh, N. K. Singh, and P. Kumar, "Optimal sizing and operation of battery storage for economic operation of hybrid power system using artificial bee colony algorithm," Int. Trans. Electr. Energy Syst., vol. 29, no. 1, pp. 1–23, 2019.

[112] D. K. Geleta and M. S. Manshahia, "Artificial Bee Colony-Based Optimization of Hybrid Wind and Solar Renewable Energy System," no. June, pp. 429–453, 2019.

[113] X. S. Yang and S. Deb, "Cuckoo search via Lévy flights," 2009 World Congr. Nat. Biol. Inspired Comput. NABIC 2009 - Proc., no. January, pp. 210–214, 2009.

[114] S. S. Singh and E. Fernandez, Modeling, size optimization and sensitivity analysis of a remote hybrid renewable energy system. Elsevier Ltd, 2017.

[115] S. Berrazouane and K. Mohammedi, “Parameter optimization via cuckoo optimization algorithm of fuzzy controller for energy management of a hybrid power system,” Energy Convers. Manag., vol. 78, pp. 652–660, 2014.

[116] E. Science, “Optimal Energy Scheduling of Renewable Energy Sources in Smart Grid using Cuckoo Optimization Algorithm with Enhanced Local Search Optimal Energy Scheduling of Renewable Energy Sources in Smart Grid using Cuckoo Optimization Algorithm with Enhanced Local ,” 2019.

[117] O. Nadjemi, T. Nacer, A. Hamidat, and H. Salhi, “Optimal hybrid PV / wind energy system sizing : Application of cuckoo search algorithm for Algerian dairy farms,” Renew. Sustain. Energy Rev., vol. 70, no. November 2016, pp. 1352–1365, 2017.

[118] S. F. Mekhamer, A. Y. Abdelaziz, and M. A. L. Badr, “Optimal Multi-Criteria Design of Hybrid Power Generation Systems Using Cuckoo Search and Firefly Algorithms,” 2015.

[119] A. Salmani, S. Sadeghzadeh, and M. R.Naseh, “Optimization and Sensitivity Analysis of a Hybrid System in Kish_Iran,” Int. J. Enrging Technol. Adv. Eng., vol. 4, no. 1, pp. 349–355, 2014.

[120] E. Options, F. O. R. Rural, and H. Centers, “Powering health.”

[121] J. A. D. Deceased and W. A. Beckman, of Thermal Processes Solar Engineering. .

[122] D. Okello, J. Mubiru, and E. J. K. Banda, “AVAILABILITY OF DIRECT SOLAR RADIATION IN UGANDA.”

[123] P. Blanc et al., “Direct normal irradiance related definitions and applications: The circumsolar issue,” Sol. Energy, vol. 110, no. October, pp. 561–577, 2014.

[124] H. A. N. Hejase and A. H. Assi, “Estimation of Global and Diffuse Horizontal Irradiance in Abu Dhabi, United Arab Emirates,” Renew. Energy Serv. Mank. Vol II, no. August, pp. 3–14, 2016.

[125] BinWu and Y. L. N. Z. S. Kouro, POWER CONVERSION AND CONTROL OF WIND ENERGY SYSTEMS, no. 1. John Wiley & Sons, Inc., Hoboken, New Jersey, 2003.

[126] A. M. A. Haidar, P. N. John, and M. Shawal, “Optimal con fi guration assessment of renewable energy in Malaysia,” Renew. Energy, vol. 36, no. 2, pp. 881–888, 2011.

[127] L. Oatomiwa, S. Mekhilef, A. S. N. Huda, and O. S. Ohunakin, “Renewable Energy (

Published 2015) Economic evaluation of hybrid energy systems for rural electri fi cation in six geo-political zones of Nigeria," Renew. Energy, vol. 83, no. June, pp. 435–446, 2015.

7. APPENDIX

Busia _Wind Speed, Temperature_ and Solar Radiation - Excel

	A	B	D	E	I	K
1	Date and Hour	Direct irradiance in kW/m²	Diffuse irradiance_in kW/m²	Global irradiance in kW/m²	Temperature Mean (0C)	wind_speed Vector mean (m/s)
2	1/1/2019 3:00	0	0	0	18.548	4.666
3	1/1/2019 4:00	0	0	0	17.988	4.867
4	1/1/2019 5:00	0	0	0	17.581	4.963
5	1/1/2019 6:00	0.003	0.003	0.006	17.3	4.983
6	1/1/2019 7:00	0.212	0.05	0.262	18.528	5.151
7	1/1/2019 8:00	0.466	0.071	0.537	20.698	5.244
8	1/1/2019 9:00	0.68	0.083	0.763	23.441	5.533
9	1/1/2019 10:00	0.845	0.093	0.938	25.536	4.701
10	1/1/2019 11:00	0.953	0.101	1.054	26.946	3.586
11	1/1/2019 12:00	0.996	0.105	1.101	27.873	2.615
12	1/1/2019 13:00	0.976	0.105	1.081	28.405	1.865
13	1/1/2019 14:00	0.89	0.101	0.991	28.616	1.457
14	1/1/2019 15:00	0.736	0.095	0.831	28.535	1.299
15	1/1/2019 16:00	0.541	0.085	0.626	28.195	1.186
16	1/1/2019 17:00	0.287	0.071	0.358	27.884	1.091
17	1/1/2019 18:00	0.059	0.021	0.08	26.217	1.009
18	1/1/2019 19:00	0	0	0	25.032	1.312
19	1/1/2019 20:00	0	0	0	24.037	1.669
20	1/1/2019 21:00	0	0	0	23.014	2.023
21	1/1/2019 22:00	0	0	0	22.511	2.124
22	1/1/2019 23:00	0	0	0	22.071	1.901

sheet 1

Figure 7.1: Meteorological data for Busia

HOMER Pro

System Simulation Report

File:

Author: Onesmas GUMISIRIZA

Location: Unnamed Road, Busia Uganda, Uganda (0°28.2'N, 34°5.5'E)

Total Net Present Cost: $27,426.65

Levelized Cost of Energy ($/kWh): $0.265

Notes: This project aims at optimally designing a stand alone Photovoltaic-Wind Hybrid power system with a battery. The meteorological data used are collected from Tororo Automatic Weather Station in Eastern Uganda. The load data used was obtained by doing the load assessment of the Health Centre.

Sensitivity variable values for this simulation

Variable	Value	Unit
Diesel Fuel Price	0.500	$/L
Electric Load #1 Scaled Average	33.2	kWh/d
ExpectedInflationRate	2.87	%
Solar Scaled Average	5.15	kWh/m²/day

Figure 7.2: System Simulation Report

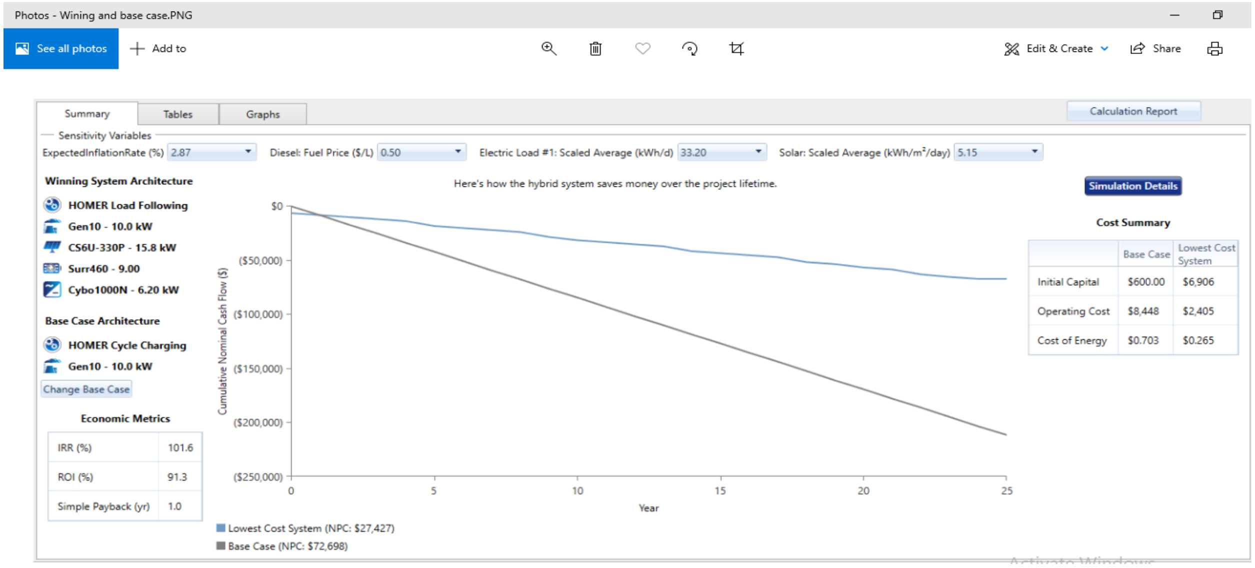
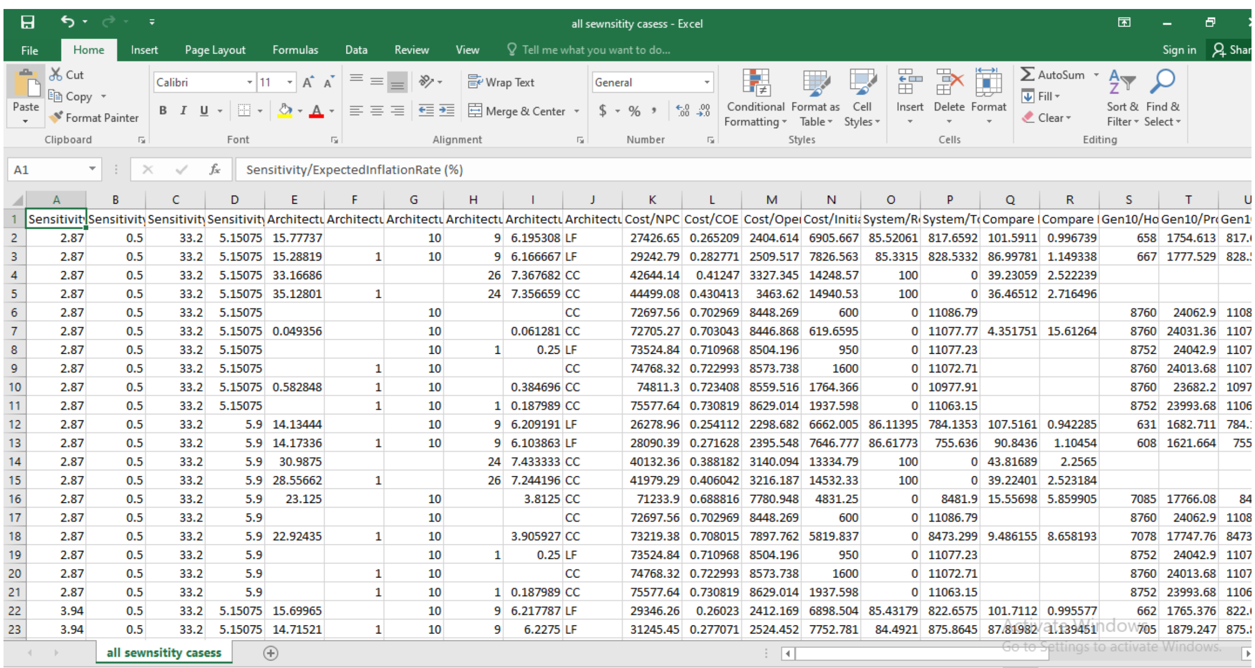


Figure 7.3: Optimal system and a Base Case



	A	B	C	D	E	F	G	H	I	J
1	Sensitivit	Sensitivity	Sensitivity	Sensitivity	Architectu	Architectu	Architectu	Architectu	Architectu	Architectu
2	2.87	0.5	33.2	5.15075	15.77737		10	9	6.195308	LF
3	2.87	0.5	33.2	5.15075	15.28819	1	10	9	6.166667	LF
4	2.87	0.5	33.2	5.15075	33.16686			26	7.367682	CC
5	2.87	0.5	33.2	5.15075	35.12801	1		24	7.356659	CC
6	2.87	0.5	33.2	5.15075			10			CC
7	2.87	0.5	33.2	5.15075	0.049356		10		0.061281	CC
8	2.87	0.5	33.2	5.15075			10	1	0.25	LF
9	2.87	0.5	33.2	5.15075		1	10			CC
10	2.87	0.5	33.2	5.15075	0.582848	1	10		0.384696	CC
11	2.87	0.5	33.2	5.15075		1	10	1	0.187989	CC
12	2.87	0.5	33.2	5.9	14.13444		10	9	6.209191	LF
13	2.87	0.5	33.2	5.9	14.17336	1	10	9	6.103863	LF
14	2.87	0.5	33.2	5.9	30.9875			24	7.433333	CC
15	2.87	0.5	33.2	5.9	28.55662	1		26	7.244196	CC
16	2.87	0.5	33.2	5.9	23.125		10		3.8125	CC
17	2.87	0.5	33.2	5.9			10			CC
18	2.87	0.5	33.2	5.9	22.92435	1	10		3.905927	CC
19	2.87	0.5	33.2	5.9			10	1	0.25	LF
20	2.87	0.5	33.2	5.9		1	10			CC
21	2.87	0.5	33.2	5.9		1	10	1	0.187989	CC
22	3.94	0.5	33.2	5.15075	15.69965		10	9	6.217787	LF
23	3.94	0.5	33.2	5.15075	14.71521	1	10	9	6.2275	LF

	K	L	M	N	O	P	Q	R	S	T	U
1	Cost/NPC	Cost/COE	Cost/Ope	Cost/Initi	System/R	System/T	Compare	Compare	Gen10/Ho	Gen10/Pr	Gen1
2	27426.65	0.265209	2404.614	6905.667	85.52061	817.6592	101.5911	0.996739	658	1754.613	817.
3	29242.79	0.282771	2509.517	7826.563	85.3315	828.5332	86.99781	1.149338	667	1777.529	828.
4	42644.14	0.41247	3327.345	14248.57	100	0	39.23059	2.522239			
5	44499.08	0.430413	3463.62	14940.53	100	0	36.46512	2.716496			
6	72697.56	0.702969	8448.269	600	0	11086.79			8760	24062.9	1108
7	72705.27	0.703043	8446.868	619.6595	0	11077.77	4.351751	15.61264	8760	24031.36	1107
8	73524.84	0.710968	8504.196	950	0	11077.23			8752	24042.9	1107
9	74768.32	0.722993	8573.738	1600	0	11072.71			8760	24013.68	1107
10	74811.3	0.723408	8559.516	1764.366	0	10977.91			8760	23682.2	1097
11	75577.64	0.730819	8629.014	1937.598	0	11063.15			8752	23993.68	1106
12	26278.96	0.254112	2298.682	6662.005	86.11395	784.1353	107.5161	0.942285	631	1682.711	784.
13	28090.39	0.271628	2395.548	7646.777	86.61773	755.636	90.8436	1.10454	608	1621.664	755
14	40132.36	0.388182	3140.094	13334.79	100	0	43.81689	2.2565			
15	41979.29	0.406042	3216.187	14532.33	100	0	39.22401	2.523184			
16	71233.9	0.688816	7780.948	4831.25	0	8481.9	15.55698	5.859905	7085	17766.08	84
17	72697.56	0.702969	8448.269	600	0	11086.79			8760	24062.9	1108
18	73219.38	0.708015	7897.762	5819.837	0	8473.299	9.486155	8.658193	7078	17747.76	8473
19	73524.84	0.710968	8504.196	950	0	11077.23			8752	24042.9	1107
20	74768.32	0.722993	8573.738	1600	0	11072.71			8760	24013.68	1107
21	75577.64	0.730819	8629.014	1937.598	0	11063.15			8752	23993.68	1106
22	29346.26	0.26023	2412.169	6898.504	85.43179	822.6575	101.7112	0.995577	662	1765.376	822.
23	31245.45	0.277071	2524.452	7752.781	84.4921	875.8645	87.81982	1.139451	705	1879.247	875.

Figure 7.4: Extract of all the Sensitivity Cases

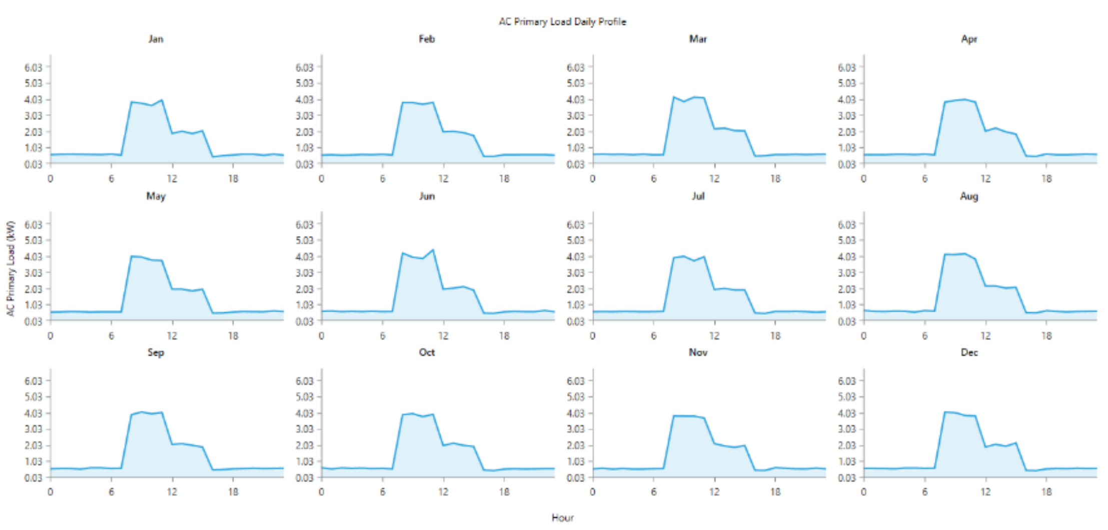


Figure 7.5: AC Primary Load Daily Profile

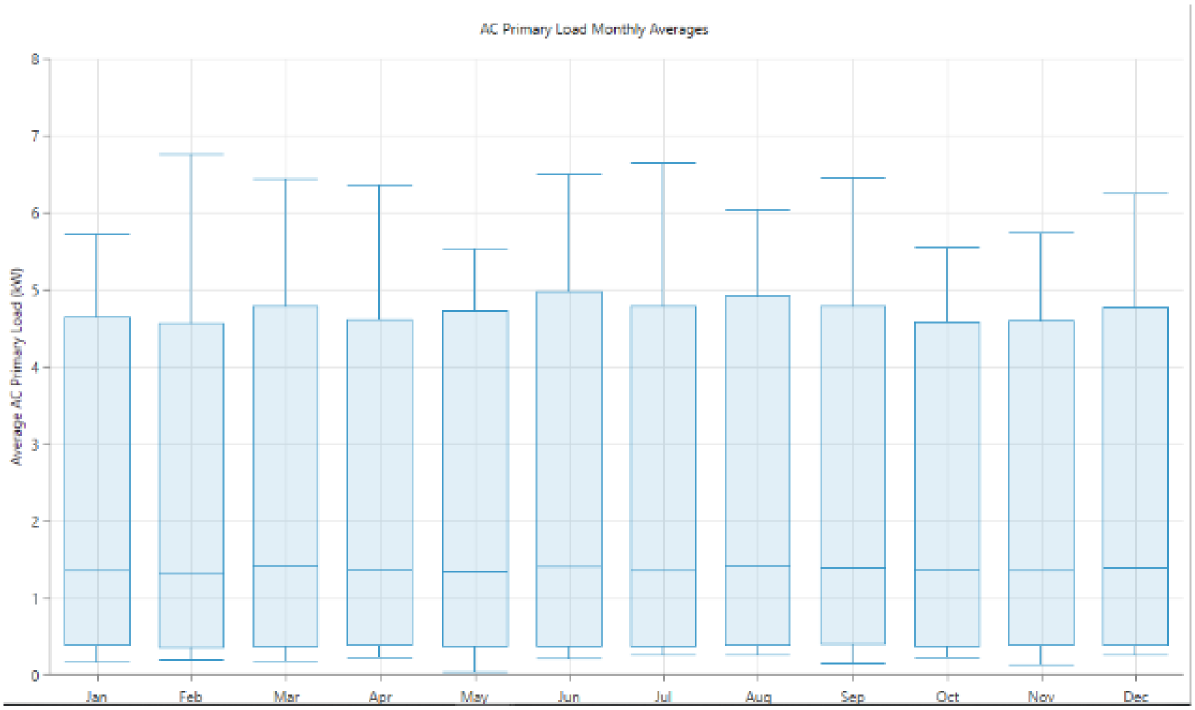


Figure 7.6: AC Primary Load Monthly Averages

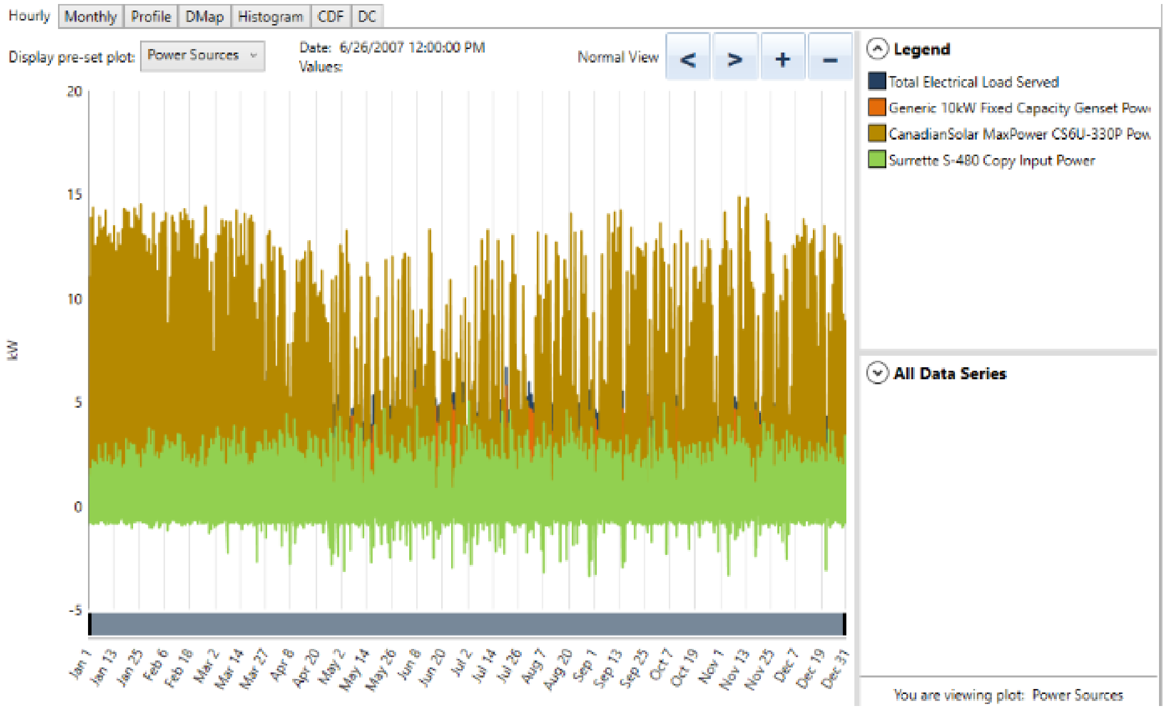


Figure 7.7: Power Sources for an Optimal System and Total Electric Load Served