

**OPTIMAL SIZING AND ANALYSIS OF A SUSTAINABLE SOLAR PHOTO
VOLTAIC-BIOMASS HYBRID ENERGY SYSTEM FOR LEARNING
INSTITUTIONS**

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A Thesis submitted to Masinde Muliro University of Science and Technology, School of Engineering and built Environment, in partial fulfilment of the requirements for the award of Master of Science in Electrical Engineering degree

AUGUST 2025

DECLARATION

DECLARATION BY THE STUDENT

This Thesis entitled “**Optimal Sizing and Analysis of a Sustainable Solar PV-Biomass Hybrid Energy System for Learning Institutions**” is my original work, except where due acknowledgement is made in the text and to the best of my knowledge has not been previously submitted for the award of a degree in this or any other university.

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CERTIFICATION BY SUPERVISORS

This research Thesis has been submitted to Masinde Muliro University of Science and Technology (MMUST) with our approval as the supervisors.

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DEDICATION

I dedicate this research thesis to my beloved dad (Stephen Omondi) whose steadfast support and boundless love became the pillar of my academic journey. His encouragement and faith in my abilities gave me the strength to pursue a master's degree, and this achievement is as much his as it is mine.

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ABSTRACT

Access to quality energy is a necessity for the growing world. There is an increasing demand for clean and quality energy due to the ever-growing world population and development of new technologies. However, energy access is still a significant challenge globally and to learning institutions. Learning Institutions suffer from limited to no access to electricity due to unreliability of the grid extension that supply them with power. The main back up system for learning Institutions in Kenya is often diesel generators, which have high maintenance, and running costs in addition to emitting harmful gaseous emissions to the environment. To achieve environmental safety, sustainability and quality energy, renewable energy resources technologies need to be developed to help in the reduction of carbon footprints. The main objective of this research is to design and optimize a renewable energy system that can be used to power learning institutions which is also less sensitive to external conditions such as changes in solar irradiation levels and changing inflation costs. This research presents a sustainable, less sensitive, and optimal configuration of a hybrid renewable energy system (Solar PV-Biomass energy system) with storage needed to power Masinde Muliro University of science and Technology. It moreover, presents a techno-economic analysis for achieving the least cost configuration which is sustainable on using historical demand and supply data for the University. The results show that due to the high solar irradiance within the region ($5.9 \text{ kWh/m}^2 \text{ /day}$) and high levels of biomass due to high university population, a larger percent of energy shall be generated by the two energy resources. This energy mix was compared with other nine energy mix based on economical, technical and sustainability parameters. The results show that the integration of 360 kW of solar PV array, 540 kW of Biomass Generator, 142 kW converter and 576 strings of 1 kW lead-acid batteries storage bank is the best configuration that leads to an optimum configuration with the LCOE of 0.1026 \$/kWh in MMUST.

Key words: solar, biomass, analysis, optimization, sensitivity, sustainability

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LIST OF ABBREVIATIONS AND ACRONYMS

ANN	Artificial neural network
BESS	Battery Energy Storage System
BCHP	Building Combined Heat and Power
CO	Carbon (II) Oxide
CO ₂	Carbon (IV) Oxide
CCS	Carbon Capture and Storage
CC	Capital Cost
CRF	Capital Recovery Factor
COMPOSE	Compare Options for Sustainable Energy Systems
CORPAS	COmplex PRoportional Assessment
CAES	Compressed Air Energy Storage
CV	Constant Voltage
c-Si	Crystalline silicon
DG	Distributed Generation
EMCAS	Electricity Market Complex Adaptive System
FiT	Feed-in-Tariff
FDM	Fuzzy Decision Making
GTM _{ax}	Generation and Transmission Maximization Tool
GWh	Giga Watt-hour
GHGs	Green House Gases
GA	Genetic algorithm
H ₂ RES	Hybrid Renewable Energy System
HOMER	Hybrid Optimization of Multiple Energy Resources
HES	Hydrogen Energy Storage
kWhm ⁻²	Kilowatt hour per square meter
LCoE	Levelized Cost of Energy
LDR	Light-dependent resistor
MPPT	Maximum power point tracking
CH ₄	Methane
CH ₃ OH	Methanol
MFC	Microbial fuel cell
MABAC	Multi-Attributive Border Approximation Area Comparison
MSA	Multi Scenario Analysis
MMUST	Masinde Muliro University of Science and Technology
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PSO	Particle Swarm Optimization
PP	Payback Period
POA	Perturb and Observer Algorithm
PV	Photo Voltaic

PHES	Pumped Hydro Energy Storage
RES	Renewable Energy System
ROI	Rate of Return-on-Investment
SAW	Simple Additive Weighting
SET	Solar Energy Technology
SHS	Solar home systems
SSA	Sub-Saharan Africa
SOFC	Solid-oxide fuel cell
SCES	Supercapacitor Energy Storage
TLBO	Teaching Learning Based Optimization
TOPSIS	Technique for order preference by similarity to ideal solution
TOA	Trade-Off Analysis
WEC	World Energy Council

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CHAPTER ONE: INTRODUCTION TO THE STUDY

1.1 Background

The growing world population and industrialization have resulted in an increasing demand for clean and quality energy (Nowotny et al., 2018). Currently, over 75% of the total world's energy emanates from unsustainable fossil fuels (Al-Shahri et al., 2021; Elkadeem et al., 2019). The Kenyan economy had a growth rate of 5.4% in 2019 and thus the country experienced an annual increment in power demand of 3.7% (Energy and Petroleum Regulatory Authority, 2022). Despite Kenya's main electricity generation systems being renewable, there is still an energy crisis due to poor investment in modern power production techniques, over-reliance on hydro-power and monopolization of power distribution systems (Takase et al., 2021). Currently, power outages result in a financial loss average of \$ 52,940 per month to the Kenyan economy (Takase et al., 2021). To help achieve energy sustainability, there is a need to develop a decentralized energy system based on renewable technologies.

With the development of technology, researchers are working on improving the efficiency of renewable energy technologies as a means of powering institutions and rural areas due to the availability of renewable energy technologies (Panwar, Kaushik, and Kothari 2011). The Government of Kenya has prioritized renewable energy development for rural electrification to achieve Kenya's Vision 2030 and the United Nation's 7th goal of sustainable development (Ndiritu and Engola, 2020). Research on the potential of different Hybrid Power systems (HPS) have been carried out based on their techno-economic feasibilities such as stand-alone solar Photo-Voltaic (PV), Standalone Wind turbine, Solar PV-biomass (PV-B), Wind-Biomass (W-B), Diesel-Biomass-Battery (D-B-B), and Solar PV-Wind-Biomass (PV-W-B) (Bet Sarkis and Zare, 2018; Dhunny et al., 2019; Shahzad et al., 2017; Vendoti and Kiranmayi, 2020).

Most of these studies have recommended the Solar PV-Wind as the most suitable off-grid HPS (Al-Busaidi et al., 2016; Garg, 2022; Sawle, Gupta, and Bohre, 2017; Zhang, Xiao, and Razmjoooy, 2022), however, the availability of biomass in learning institutions creates opportunities for its exploration as a solution to the growing energy demand in a hybrid energy system that is decentralized with high applicability to learning institutions. HPS capitalizes on the existing energy infrastructure and adds components to help reduce costs (fuel inflexibilities), environmental impacts, transportation, and system disruptions. An overview of an HPS is shown in Figure 1.1.

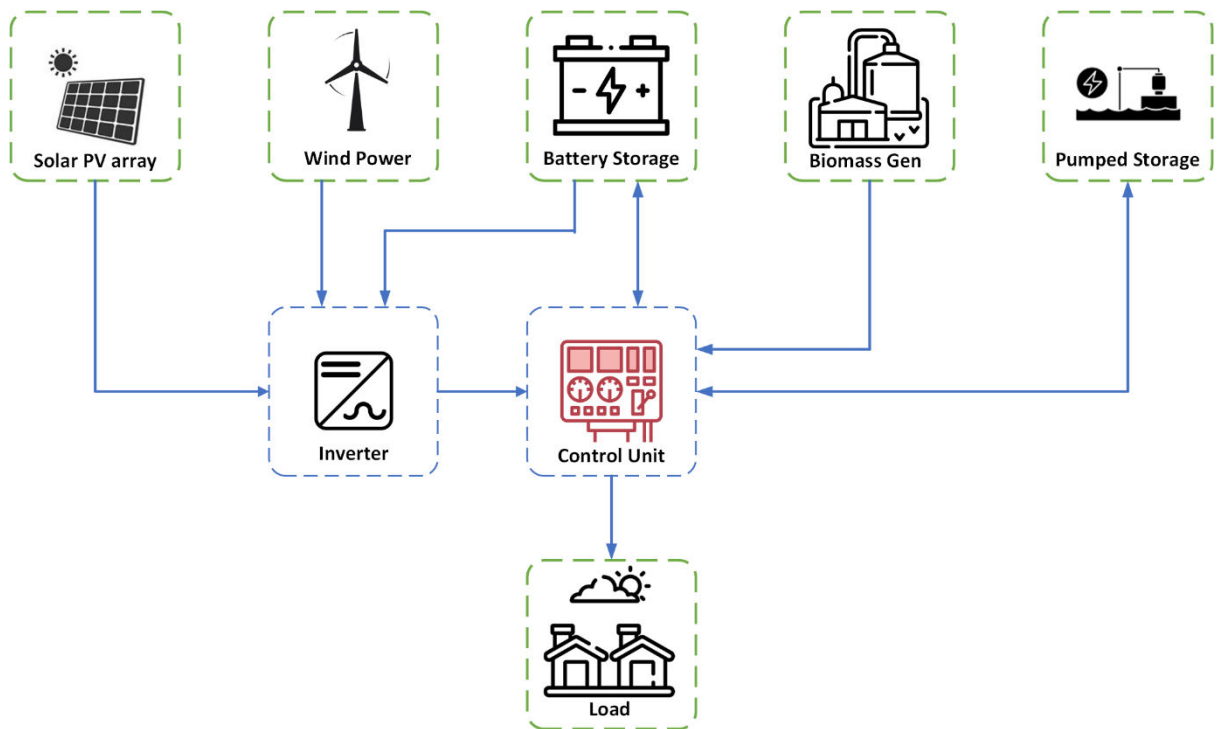


Figure 1.1: Basic renewable energy Hybrid Power System

The application of HPS helps to improve power reliability by switching between different renewable resources, reducing the cost of energy and making remote areas have access to power due to the decentralized nature of renewable energy systems (Kashif et al., 2020). However, HPS still faces challenges in implementation due to complex designs requiring specialized skills, high initial cost and storage complexities

due to the intermittent nature of these energy resources (Uwineza et al., 2021; Yaqoot et al., 2016). Despite these hindrances, several studies have been reported in literature on the development, improvement, and application of Solar PV-B HPS as a means of energy sustainability (Ahmed et al., 2015; Child et al., 2018; Chowdhury et al., 2019; Ghenai and Janajreh, 2016; Habib and Mahmood, 2017; Sawle et al., 2017). More emphasis has been on the optimization of the produced power, the sensitivity and sustainability of the PV-B system (Ahmed et al., 2015; Ji et al., 2021; Shahzad et al., 2017). Shahzad, (2017) Presented a report on the development of a PV-B system for rural Pakistan with a mix of 18 kW capable of serving a peak load of 17.08 kW at a Cost of Energy (COE) of \$ 0.066. Similarly, Suresh et al. (2020), presented an off-grid model of a PV-W, fuel cell and Battery for three villages in Kollegal block India with a combined peak load of 149.21 kW at a COE of \$ 0.163. Figure 1.2 presents an HPS for a Solar PV-Biomass Hybrid system.

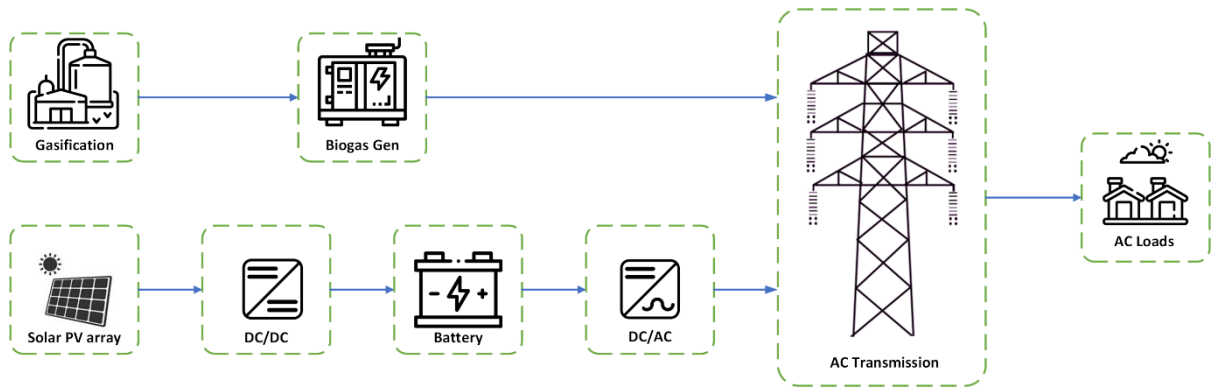


Figure 1.2: Hybrid Power System Conceptual Framework for Solar PV-Biomass Hybrid system

Despite several literatures on PV-B and the development of technology and with increased demand for reliable energy, there is still a limitation in the adoption of PV-B in the context of powering institutions as they are greatly affected by unreliability in

power supply mainly grid power which they rely on. Additionally, their power back-ups are often diesel generator (Elkadeem et al., 2019) whose running costs is directly dependent on the fuel costs and furthermore, they are not environmentally friendly (Sawle et al., 2017). Therefore, the main objective of this study is to design a feasible, sustainable, and efficient HPS based on solar PV and Biomass renewable energy resources. The design and analysis of the proposed PV-B system present an opportunity for a low cost of energy and improved power reliability to learning institutions.

1.2 Statement of the Problem

Lack of quality power is a problem to most learning intuitions in Kenya. These institutions rely on grid extensions which are often unstable, unreliable, and costly. The main back up is often diesel generators, which have high maintenance and running costs, in addition to emitting harmful gaseous emissions to the environment.

With the ever-increasing student populations, there is an ever-increasing demand for electric power in learning institutions accompanied by unsustainable electric energy bills. The current grid connections have however failed to effectively meet this growing demand. There is therefore need for alternative solutions based on renewable energy technologies. However, there is still lack of adequate technical expertise and experience in renewable energy technologies (Ndiritu and Engola 2020). There is also a need for local communities to be sensitized on uptake, and more experts trained on these alternative energy solutions.

Non-renewable energy resources such as coal and nuclear have also led to environmental degradation, which has resulted in the current climate related crises. There is therefore a real problem faced by learning institutions in terms of energy costs,

energy security and sustainability. A significant proportion of scarce resources are usually diverted into paying energy bills. Frequent power outages often disrupt operations. To mitigate these problems, renewable energy resources need to be exploited to supplement non-renewable energy resources and enhance sustainability and availability of electrical power supply. Its on this background that Solar PV-Biomass hybrid energy systems become crucial in solving such problems.

1.3 Justification

This study proposes a renewable energy resource mix as an alternative to the grid extension, which is characterized by instability and unreliability. The equatorial region experiences high solar irradiation through-out the year. The proposed system will optimize power production during the entire year. Additionally, energy storage devices i.e., batteries were incorporated to store any excess energy which would be used during low irradiation periods and when required. This excess energy may also be back fed to the grid for peak shaving and any other grid stability issues as may be required.

Kenya has an annual growth rate of 2.3% (Nowotny et al., 2018) , which has consequently increased the energy demand. However, increment in student population resulted in an increased levels of waste biomass. This study proposed the utilization of this biomass to generate electrical energy that can be used within the learning institutions and to export any excess energy to the grid. The aim was to introduce an optimized energy mix in learning institutions which would open new research areas on how to improve the performance of these renewable technologies. Concurrently, this would increase more technical knowledge and information on renewable energy resource technologies to both students and the community.

The main solution to the current world energy problem is green energy which is considered as clean, infinite, available and reliable. Non-renewable energy resources such as diesel power plants have resulted into extreme environmental pollutions. This study proposes a green energy resource with negligible emissions that would result to diverse environmental effects therefore reducing the carbon footprints.

1.4 Objectives

1.4.1 Main Objective

To develop an optimized, sustainable, and efficient hybrid energy system based on solar PV and locally available Biomass energy resources for powering learning institutions.

1.4.2 Specific Objectives

1. To determine the optimal energy mix of locally available alternative energy resources.
2. To evaluate the sensitivity of the optimal energy mix based on variation of solar irradiation levels and inflation rate.
3. To evaluate the sustainability of the alternative energy mix based on technical, economic, and environmental parameters.

1.5 Scope and Delimitation of the Study

This study focuses on the design of a solar PV-biomass hybrid energy. The sources of biomass from this research were plants and animals waste as well treated sewer wastes. This study aimed at carrying out comprehensive techno-economic analysis based on optimization, sensitivity analysis and sustainability analysis focusing on emissions from the biomass unit and the ecological impact of large-scale solar PV installations.

This study was carried out in Masinde Muliro University of Science and Technology, Main campus. The study did not explore other renewable energy resources such as wind and hydro due to presence of forest surrounding the university which limits the speeds of wind and due to lack of water bodies around the University.

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter explores the literature that is relevant to the Design and optimization of solar PV-Biomass hybrid renewable energy system for learning institutions. It gives an introductory part to the entry point of this research work.

2.1 Global energy situation

There is an increasing demand for energy globally occasioned by increased industrialization and rapid population growth-rate. This high demand for electricity and energy has occasioned a price increment (Nowotny et al., 2018). The global world relies on fossil fuels to power their economy. However, over-reliance on the fossil fuel is linked with high environmental pollution and the ever-rising cases of global warming. Due to such, counter measures are needed to preserve the environment from such pollution effects and risks of global warming. The use of renewable energy has been advocated for to help reduce the global carbon footprints (Al-Shahri et al., 2021).

The leading global source of energy has been oil and its global demand has increased over the last 25 years from 7.2 billion Tonnes of oil Equivalent to 11.2 billion (Styrikovich, 1980). The demand for energy is predicted to increase rapidly as economies of different countries grows and more manufacturing industries are opened. The high demand for oil is also leading to rapid depletion of oil reserves and International Energy Agency (IEA) estimates the world's oil reserves depletion rate at 7.5 percent annually.

High population and the use of the latest technologies that consumes a lot of energy occasioned the high demand for energy. Transportation sector accounts for the highest consumption of energy followed by other manufacturing activities. The engine types

used in jets and some locomotives only use oil with no alternative. Such situation brings into question the redesigning of the engines to accommodate other forms of energy sources to power them.

The world Energy Council (WEC) described the global energy situation in three different pathways and scenarios for the possible energy transition over a period till 2060. Modern Jazz scenario (World Energy Council (WEC) and Institute 2019) advocates for a more clean energy access on both global and local scales. This scenario also advocates for integration of new systems into the grid and at the same time protecting automated power system from cyber-attacks (World Energy Council (WEC) and Institute, 2019).

The unfinished symphony scenario advocates for energy system addressing the atmospheric carbonization level (World Energy Council (WEC) and Institute, 2019). It addresses global commitment towards mitigating the climate change governed by world policies. Hard rock scenario investigates the ramifications of inward looking national policies on weaker and unsustainable global economic growth (World Energy Council (WEC) and Institute, 2019).

In Kenya, the power demand has been on the rise. Over a ten-year period from 2004 to 2013, Kenya's electricity grew by 20% annually. The available power which majorly comes from hydro and geothermal are not able to keep up with this growing demand (Mokveld and Eije, 2018). The ever-rising population and industrialization in Kenya have led to a rise in the costs of power within the country. This high cost of power is an impediment to the expansion of economic activities in Kenya. The unreliability associated of the Kenyan electricity system is also high.

To achieve the Kenya’s big four agenda and full realization of vision 2030, there is a need for sufficient and reliable clean energy. The four pillars of vision 2030 are energy driven. The current production activities in Kenya are driven by energy generated from fossil fuels. Such type of energy has high levels of carbon (iv) oxide emission into the atmosphere. Fossil fuels and energy sector accounts for at least 70 % of carbon emissions and such is having a direct impact on climate change (Suswatch, 2020). A need to shift and have alternative forms of energy based on renewable technologies to drive the country forward is of noble call.

According to the 2020 Kenya’s energy report, biomass dominates the Kenya’s energy sector at 68 % followed by electricity at 9% while imported oil accounts to 21% of total energy usage in Kenya. The demand of energy is high in Kenya and the available generation station of hydropower, geothermal and other renewables has never fully met this demand and importation has to be done to meet this demand (Suswatch, 2020). Table 2.1 depicts Kenya’s power demand and usage in 2017 (Suswatch, 2020).

Table 2.1: Kenya’s energy demand across different sectors in 2017

Sectors	Energy Consumption
Residential	77% of final consumption
Transport	14%
Industry	7%
Commercial and Public	1%
Agricultural and Forestry	Less than 1%

2.2 Renewable Energy Technologies as Alternative Sources of Energy

The government of Kenya is exploring all means possible to have a stable power supply across its sectors. Energy security is a key goal and a strong indicator for a country’s economic growth. Due to such, renewable energy resources are being adopted as alternative energy sources owing to their nature in conserving the

environment as well reducing reliance on non-renewable energy sources (Nematollahi et al., 2016). With the current rapid depletion of fossil fuels, countries should therefore make use of the remaining developed fossil fuel infrastructure to transition to renewable energy (Nematollahi et al., 2016).

The current installed capacity of renewable energy systems is over 70% of the total installed capacity in Kenya (Suswatch, 2020). The Kenyan government has sensitized on the usage of renewable energy technologies i.e., installation of solar PV panels on hospitals, public and learning institutions. Through the Feed-in-Tariff (FiT), Kenya has seen an increment in the uptake of renewable technologies with over 278 renewable energy projects completed and contributes to over 4.7 GW of electrical energy in Kenya. The commissioning of 310 MW , 100 MW and 51 MW Garissa solar plants have immensely contributed to the total installed capacity of renewable energies in Kenya (Suswatch, 2020).

In-terms of renewable energy technology, Kenya is well-endowed with different types of renewables, which are potential to running the economy to greater heights with Biogas having the potential to generate 1045 GWh of energy (Suswatch, 2020). As a domestic energy biogas can fully replace other means of energy like firewood and charcoal.

The wind exploration in Kenya is still ongoing with Lake Turkana Wind Power Project (LTWP) and the Ngong' Hills Wind Power Project leading in Kenya as fully installed projects. LTWP is having a capacity of 310 MW while Ngong' is having an installed capacity of 25.5 MW (Suswatch, 2020). The Kipeto wind project in Kajiado upon completion will be the second largest in Kenya.

Kenya being an equatorial country, it has a huge potential for solar energy with insolation range 4-6 kWhm⁻². The application of solar as an alternative energy is on the rise due to its availability. Currently solar is used for lighting, and heating of water. Other renewable sources of hydroelectric and geothermal account for the highest energy consumed at 80% of total energy in Kenya.

2.3 Solar PV and Biomass Renewable Energy Resources

East African countries have a huge potential for RES with Kenya having an access rate of 85% of the installed RESs (Mugisha et al., 2021). Biogas has the potential to generate 1045 GWh and as domestic energy, biogas can fully replace other conventional means of energy like firewood and charcoal (Mao et al., 2018; Suswatch 2020). Additionally, the solar insolation is between 4 – 6 kWhm⁻² within the equatorial region (Suswatch, 2020). Despite the huge potential of these RESs, only a small proportion is being utilized for energy generation. This section will present a review of the available solar PV and Biomass resources and their availability in Kenya. The Kenyan government and stakeholders are currently sensitizing on the usage of renewable energy technologies through systems such as outreach and Feed-in-Tariff (FiT) (Suswatch, 2020). Additionally, the number of renewable energy projects (310 MW, 100 MW, and 51 MW Garissa Solar plants) has increased drastically to over 4.7 GW of electrical energy in Kenya (Suswatch, 2020). Moreover, Strathmore University in Kenya fully implemented a 600kW power of grid connected Solar PV to run its operations and surplus sold.

2.4 Biomass Resource

Biomass as a renewable energy source can only be made useful when it is converted into heat through combustion or a clean useable form of energy such as biofuel or bio-syngas or biogas through biological, chemical, and thermochemical biomass

conversion processes (pyrolysis, gasification, and liquefaction) which eventually can be converted to electrical energy (Ahmed et al., 2015). Table 2.2 presents the categories of biomass resources in Kenya.

Biogas is produced by alcoholic fermentation and aerobic digestion. Biogas is a methane (CH_4) gas which is a high-heat gas that is easily converted to methanol (CH_3OH) and is used in engine combustion for electricity generation (Ahmed et al., 2015). According to Takase et al. (2021), there are about 1932 biogas plants in Kenya with a daily generation capacity of 1.2 m^3 each. This low generation capacity can be attributed to insufficient technology, inadequate awareness of the production of biogas, and lack of awareness of the potential benefits of biogas (Benti et al. 2021; Takase et al., 2021). Another form of biomass is biofuel which is generated by the pyrolysis process (first generation), thermochemical process (second generation), and microbiological process (third generation) (Benti et al., 2021; Renzaho et al., 2017). The main biofuels produced from biomass are mainly butane, biodiesel, and bioethanol (Renzaho et al., 2017). Biomass can also be converted to bio-oil (biochar) via pyrolysis and later to bio-syngas through the gasification process (Bermudez and Fidalgo, 2016).

Biofuels can also be generated from energy crops such as cassava, millet, maize, papyrus plants, sugar cane, rice feedstocks castor seeds, and sunflower (Banunle et al. 2021; Njogu et al., 2015). Cassava, maize, and millet can be used to generate ethanol while castor seeds and sunflower seeds are processed and used to generate biodiesel (Njogu et al., 2015). According to Jones et al. (2018), papyrus grass plant represents low-input, high-diversity grasslands that have the potential to be a sustainable biofuel option because they can be targeted at marginal agricultural land and represent a carbon-neutral, where CO_2 assimilation and sequestration during the growth cycle exceeds the released CO_2 during combustion. Thus, there is reduced competition for

land for food production and biodiversity loss due to habitat degradation. However, it is necessary to transform papyrus into a form that is properly flammable before using it as a biofuel for heating and cooking (Banunle et al., 2021; Jones et al., 2018). Papyrus culms can either be made into charcoal or their density is increased because they are not dense enough to burn directly in stoves (Jones et al., 2018). The potential use of papyrus as a fuel will, however, be contingent on assurances that these ecosystems can produce a consistent supply of biomass that does not ultimately result in the extinction of these wetlands and that exploitation of this type does not jeopardize the other crucial ecosystem services that these wetlands provide (Banunle et al., 2021). The potential of sugarcane for energy generation has also been successfully implemented within the country by sugar-producing regions of the country such as Mumias sugar-producing company (Konneh et al., 2019). The use of bagasse for energy generation has expanded other industries, such as pulp and paper production industries and cogeneration facilities that produce electricity for the grid. The high energy content of bagasse makes it an attractive fuel source, as its combustion in a boiler is used to produce steam that can then be used to generate electricity through a turbine (Konneh et al., 2019; Solomon, 2016). The use of bagasse provides an environmentally friendly energy source (Solomon, 2016). Additionally, a big human population has resulted in huge municipal and human waste that can be processed to produce CH₄ (Renzaho et al., 2017).

A huge population of the SSA still depends on biomass combustion as a source of energy, out of the total energy demand, biomass energy demand account for 69% (Okoko et al., 2017). According to Okoko et al. (2017), 94 % of the rural population heavily depends on wood-based fuels (firewood) while 74% of the urban population depends on charcoal as a source of domestic energy. The increase in population has

resulted in increased biomass energy demand which consequently has resulted in land degradation (a climate change problem). Currently, in Kenya, there is an evolution in the application of biogas as domestic energy. Efficient cook stoves are replacing conventional and inefficient cook stoves as well as open-fire cooking. From the World Health Organization (WHO) report, household air pollution results in 15,600 annual fatalities and negatively affects the health of almost 15 million people (Carvalho et al., 2019). Traditional cooking accounts for over 77% of harmful exposure to environmental contaminants. According to Carvalho et al. (2019) transiting to clean cooking technology involving the use of efficient cook stoves is a relevant way of addressing the 2030 agenda of sustainable development in the country. Going green is the way for Kenya due to its strategic policy of ensuring reduced greenhouse emissions by 30%. Over 46% of the electricity produced globally comes from coal, which has long been the major source of electricity internationally (Roni et al., 2017). However, coal has been the largest source of environmental pollutants and the largest source of CO₂ into the atmosphere even though there is an urgent need to reduce GHGs. However, according to Roni et al. (2017), co-firing coal plants with other biomass fuel sources (such as woody biomass which has zero Sulphur) is an effective way of reducing the level of GHGs emissions from the plants. In comparison to other alternative applications of biomass, co-firing is a low-risk option to produce renewable energy due to the substantially lower hazards associated with large capital investments and raw material sources. Direct co-firing is also one of the most innovative and successful ways to lower GHG emissions from coal-fired power stations (Roni et al., 2017).

Table 2.2: Categories of biomass resources

Biomass Group	Varieties	Reference
Municipal wastes	Household wastes Market solid wastes	Tursi (2019), Jouhara et al. (2017)
Industrial wastes	Fruit peelings and vegetable scraps, pulp, and fiber from processing firms e.g sugar companies, coffee grounds, Liquid wastes which contain sugars and dissolved organic matter Pulp and paper industry wastes Wood-wastes from wood Industries Textile company wastes	Kwon et al., (2020), Premaratne et al. (2021)
Agricultural wastes	Animal and human wastes (manures and bones), Wood and woody biomass, Herbaceous biomass	Verma and Suthar (2015), Saini, Saini, and Tewari (2015)
Energy crops	Cassava, millet, maize, papyrus plants, sugar cane, rice feedstocks caster seeds and sunflower, Duckweed	Njogu et al. (2015), Banunle et al. (2021)

Biomass briquettes, which are solid wastes made from carbonized biomass are also presenting a huge opportunity for biomass usage and adoption in Kenya (Mwampamba, Owen, and Pigaht, 2013). Over 80% of both urban and rural populations still rely on the use of non-sustainable charcoal for heating and cooking. This provides an opportunity for briquette manufacturers, as there is a rising demand for charcoal, which briquettes may substitute. According to Mwampamba et al. (2013), it is acknowledged that even if the region's electrification rates increase, the demand for satisfying cooking energy requirements will not be much reduced. Kerosene, ethanol-based fuels, and LPG are also expensive for most institutions and households to utilize as cooking fuels. Briquette adoption acknowledges the environmental and sustainability qualities sought after in contemporary energy since it is also renewable for sustainable energy security. Briquettes are marketed as a more affordable

alternative to LPG or kerosene because they don't involve the purchase of a new stove, making them more alluring to charcoal users who want to switch fuels with the least amount of expense (Mwampamba et al., 2013). Regardless of the apparent opportunities offered by briquettes, the capital investment for a briquette-making facility are often unaffordable to potential consumers. Moreover, full potential for biomass briquettes has not been explored fully in the region because, at the policy level, biomass has been perceived as a traditional fuel (Mwampamba et al., 2013). Moreover, the insufficient briquette densification technology for the manufacture of briquettes poses a significant challenge for the briquette industry in the country. Despite renewable energy having a huge contribution towards the reduction of GHGs, its uptake is still low due to the economic challenges associated with-its first-time installation costs.

Additionally, the rise of energy crops has created a huge opportunity for the growth of biomass usage in the country. The use of energy crops has risen widely as a result of their potential usage as a carbon-free, eco-friendly, and clean source of renewable energy that could aid in meeting the world's energy needs (Pandey, Bajpai, and Singh, 2016). With the identification of more energy crops in the country, their adoption is set to rise.

Kenya's economy is dominated by agriculture, which generates up to 65 % of export revenue and up to 30 % of the country's annual GDP (Welfle, Chingaira, and Kassenov, 2020). The main commercial crop is tea, which makes Kenya the third-largest tea grower and a significant global exporter. This provides a huge opportunity for biomass exploration and usage. The Kenya Vision 2030 plan places a strong emphasis on agricultural growth as a result, with one of its main objectives being to ensure that future development is based on renewable energy technologies. The plan

recognizes the connections between the agriculture and energy sectors and identifies a chance to industrialize the agriculture sector while also diversifying Kenya's energy mix through increased use of energy crops that have been grown as well as agricultural waste and residues for bioenergy (Welfle et al., 2020).

2.5 Biomass Energy Conversion Technologies

There are several biomass energy conversion technologies which are directed toward the efficient conversion of biomass to other useful clean fuels (Tursi, 2019). Biomass conversion technology is dependent on the production process, quantity and quality of the end product (fuel), cost of the conversion process, and required end product (Tursi, 2019). The main conversion technologies of biomass to intermediate products for electricity generation include; thermo-chemical conversion technologies, physicochemical conversion technologies, and bio-chemical conversion technologies (Tursi, 2019).

Thermo-chemical conversion technologies involve processes such as combustion, pyrolysis, gasification, and liquefaction (Tursi, 2019). Over 90% of biomass energy in use is by combustion whereby biomass is mixed with

oxygen at a high temperature to produce heat (Tursi, 2019). Micro-gas turbine has been effectively used for biomass combustion as it produces low levels of GHGs (A. Liu et al., 2020). Despite biomass combustion being effective, it however still emits some levels of GHGs (A. Liu et al., 2020). However, studies have reported that GHG levels can be reduced by the pyrolysis process (Tursi, 2019). The pyrolysis process converts biomass into more valuable combustion forms such as the syngas used in gas turbines, biochar, and bio-oil (Abou Rjeily et al., 2021; Uddin et al., 2018). The gasification conversion process (carried out in a gasification reactor) leads to the

formation of synthesis gas which is used for the production of biofuels such as methanol, ethanol, gasoline, and diesel (Molino et al., 2018; Perkins et al. 2019).

Biomass conversion to electricity has attracted more interest due to the numerous application of electrical power (W. Liu et al. 2020). Therefore, more technologies have been introduced to convert biomass energy to electrical energy i.e., steam turbine generators, high-temperature biomass fuel cells, and microbial fuel cells (W. Liu et al., 2020). Turbine-based steam generators have predominantly been used for biomass to electricity conversion due to their initial use in the conversion of coal to electricity (W. Liu et al., 2020). Gasification, pyrolysis, and liquefaction processes are the intermediate processes used to provide the primary substrate used by turbine-based steam generators. The biomass-operated steam turbines are big (in size) as a huge amount of biomass is needed to sustain their operation (W. Liu et al., 2020).

Studies have shown that biomass gasification provides the easiest conversion process to electricity (Asadullah, 2014). The conversion processes involved are biomass pre-treatment, biomass gasification, gas cleaning and finally feeding the end product (combustible gas) to a gas turbine or engine for electrical power generation or a boiler to a steam turbine for electrical power generation (Asadullah, 2014). For optimal power generation, the gas used must have a high heating value to increase its efficiency in power generation. Figure 2.1 illustrates the electric power generation from biomass by gasification process.

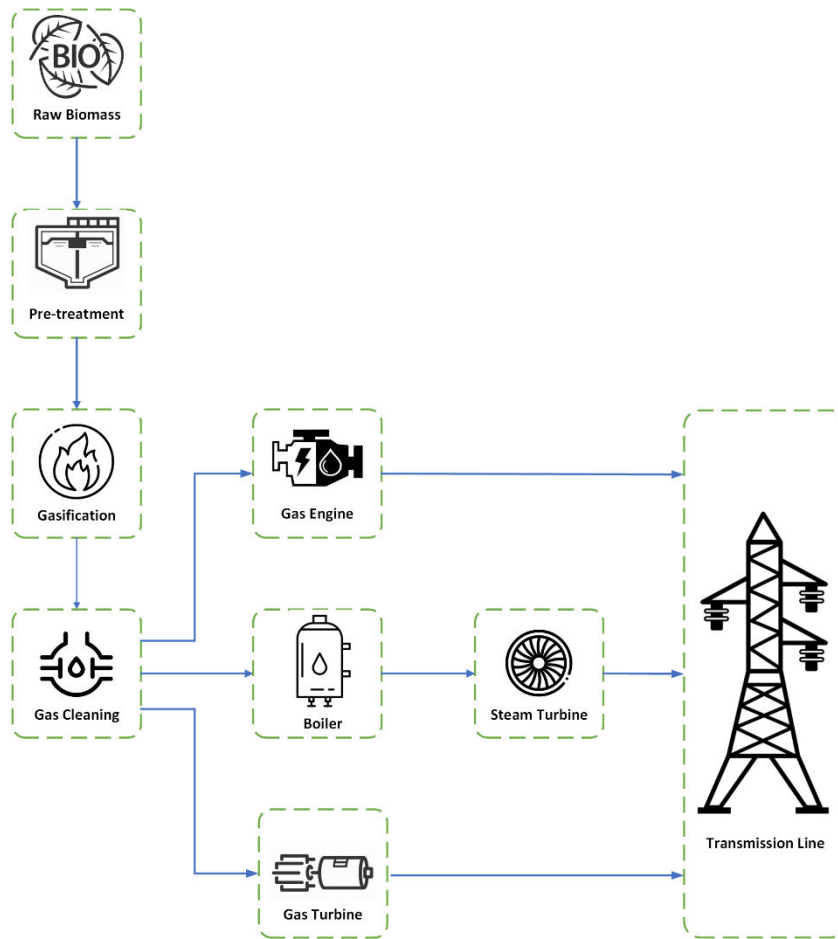


Figure 2.1: Biomass gasification power generation stages

An alternative to turbine-based biomass conversion to electricity is the high-temperature biomass fuel cell. The biomass fuel cell converts chemical energy in biomass into electrical energy and gives out water (H_2O) and CO_2 as their by-products (W. Liu et al., 2020). The most vital technology for biomass fuel-cell technology is the solid-oxide fuel cell (SOFC) which uses thermodynamics to generate electricity at high efficiency (Pongratz et al., 2021). SOFC is a high-temperature operated system whose main biomass inputs are gasification end products such as biogas, syngas, and methanol (W. Liu et al., 2020; Pongratz et al., 2021).

Microbial fuel cell (MFC) is an additional technology for converting organic biomass to electricity. The MFC is a special type of reactor that converts biomass to electricity through microorganism action at a low temperature. MFC is made up of two electrode-

equipped electrolytic chambers that are connected by an external electrical circuit and separated by a semi-permeable membrane (Kabutey et al., 2019; W. Liu et al., 2020). The fuel in the anodic chamber is oxidized by the microorganisms acting directly on the feed substrates, which normally results in the production of CO₂, protons, and electrons. The formed electrons are attracted towards the anode and are captured and later on passed to the cathode for electrical current generation via the external electrical circuit. However, the formed protons found at the anode are pushed to the cathodic terminal to form water and electrons (Li et al., 2018). During the fuel oxidation process, the microorganisms in the MFC gain energy by transferring the electrons generated during the process. The potential difference existing between the anode and the cathode generates electrical power (W. Liu et al., 2020).

2.6 Solar Energy Resource

Kenya has a high potential in solar energy generation due to its relative position in the equatorial region (Rose et al., 2016). The region experiences an annual average temperature of about 22°C with high insolation of 4 – 6 kWhm⁻² (Kiplagat et al., 2011; Suswatch, 2020). Currently, there is a rise in Solar Energy Technology (SET) development and utilization due to increased load and unreliability in grid extension. Despite Solar PV systems having a high initial cost, they are reliable and have a short installation period (Rose et al., 2016). Additionally, Solar PV can be installed close to load centers, therefore eliminating the transmission infrastructure thus Solar PV can both substitute and complement the conventional power generating system at an overall lower cost (Rose et al., 2016).

Solar PV microgrid generation system often requires vast land for installation. However, most regions in Kenya are arid and semi-arid characterized by a sparse population, therefore, giving opportunity for large capacity installation within the

country (Lei et al., 2019). Additionally, distributed Solar PV power systems offer a cost-effective supply of electricity in off-grid inaccessible areas (high cost in grid extension) (Lei et al., 2019). According to Kiprop et al. (2019), about 1.2% of Kenyans have Solar Home Systems (SHS). However, studies have projected an increase in the utilization of SHS due to the current sensitization campaigns and the introduction of mini and micro SHS (IREK 2015; Kiprop et al., 2019). The solar energy market can be subdivided into three main segments. Firstly, domestic SHS and small-scale commercial Solar PV systems characterized by less than 100W peak power with typically 14–20 WP (Ondraczek, 2013). Energy centers, which are centralized power production with no distribution systems i.e., renting of Solar lanterns and battery banks are also considered in this segment. (Roche and Blanchard, 2018). This segment accounts for about 75% of the total installed capacity in Kenya (Ondraczek, 2013). The second segment is the off-grid systems, which provide a power of more than 100 W, and they are normally found in institutions (schools, health centers, and social organizations). As aforementioned, a large population occurs in rural areas in the SSA region with limited access to electricity, therefore off-grid solutions will contribute to the transformation of these regions with reference to social, economical, and technical development through improved ICT, education, growth of microenterprises (business and agriculture), and health care (Mugisha et al., 2021). The last segment is Solar Energy Systems used in powering telecommunications systems such as the base transmitter station (BTS) and main switching stations (MSC) (Ondraczek, 2013) and is characterized by being standalone systems with high power production (over 1kW). The feasibility of SHS depends on load capacity and population density. With a high load (over 100 households), a micro-grid system is more feasible compared to a low

load in sparsely populated regions (50-100 households) where SHS would be preferred (Roche and Blanchard, 2018).

2.6.1 Solar PV Energy Technologies

With the current global efforts on mitigation of climate change and the low-cost nature of implementing solar technology, a lot of research has been directed toward sustainable RES (Luan et al., 2021). Additionally, the rapid depletion of oil reserves is a major influencing factor for the development of Solar energy technologies as a feasible option to fossil fuels as well as the global push for clean and affordable RES (Almosni et al., 2018). Studies have been directed toward improved efficiency of Solar PV systems (commercial thin film, wafer-based cells, and new film technologies) (Kabir et al., 2018).

The first solar cell based on Selenium was introduced by Charles Fritts in 1883 (Almosni et al., 2018). However, its efficiency was below 1%. In 1954, the first practical silicon solar cell was developed by Bell Laboratories with an efficiency of 6% . Significant development in solar cell technology was first made by Russell Shoemaker based on the p – n junction technology in 1940 (Almosni et al., 2018). The development of terrestrial solar PV started in 1970 due to the high costs of crystalline silicon solar cells. The emergence of other breakthrough technologies i.e., the thin film led to crystalline silicon being used majorly for space applications (Swanson, 2007). The process stages of manufacturing crystalline silicon solar cells from silicon involved silicon purification, growth of single crystals ingot, wafer sawing, making of solar cells from the wafer, and finally stringing them together (Swanson, 2007). This technology could only generate not more than 0.5 W with a high generation cost of \$70 per W (Almosni et al., 2018). In 1978, the use of evaporated metal grids for solar

energy conversion became dominant as they were cheap and more efficient than crystalline silicon solar cells (Almosni et al., 2018). In 1990, wire saws became vital as they could be used to fabricate thinner wafers with high efficiency. Solar PV technologies are broadly categorized into three main evolutionary stages, i.e., Silicon-based solar cells, second-generation, and third-generation (Almosni et al., 2018; Swanson, 2007). Silicon-based solar cells constitute polycrystalline and monocrystalline silicon was the first technology in Solar PV. The second generation of solar cell technology was based on amorphous silicon. Despite this technology having low efficiency it had better mechanical strength (Almosni et al., 2018; Swanson, 2007). Lastly, the third generation of solar cell technologies also termed emerging technologies offers high efficiency with a diverse range of Solar PV applications (Almosni et al., 2018).

The recent development in SET has led to the superiority of Solar PV over other renewable sources due to their cost effectiveness, accessibility, and capacity (Bae et al., 2016; Gul et al., 2016; Lupangu and Bansal, 2017). According to Kabir et al. (2018), researchers in Hong Kong developed perovskite-silicon solar cells with a high thermal conversion rate of 25.5% up from the 8%. Perovskite solar cells have a fast growth rate due to their high carrier mobility and raw materials for their fabrication are readily available (Zuo et al., 2018). According to Almosni et al. (2018), thin film technology is preferred to silicon-based technology with reference to fabrication cost, efficiency, and long lifetime (25-40 years) (Almosni et al., 2018; Gul et al., 2016)

Studies on techno-economic analysis of solar technologies have identified demand as a key factor driving SETs innovations (Luan et al., 2021). The technological classification of solar energy technologies includes both active and passive technologies. Passive SET involves the collection and transformation of solar energy

into light energy or thermal energy without any kind of transformation (Kabir et al. 2018). However, the use of active SET involves collecting solar energy and using electrical or mechanical equipment to convert it to electrical power and heat (Kabir et al., 2018). Active Solar energy is further categorized into Solar PV technology and thermal cells technology. Solar thermal technology is used for heating, cooling, and drying (Huang et al., 2019). However, Solar PV system performance strongly depends on cell temperature, irradiance level, and load profile (Karami et al., 2017). As already mentioned the main drawback of Solar PV is the intermittent nature of the RES, this has led to the application of solar energy storage technology (Cavallo, 2001; Sánchez et al., 2022). The available solar energy storage technologies include Flywheel Energy Storage (FES), Hydrogen Energy Storage (HES), Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), Supercapacitor Energy Storage (SCES) and Battery Energy Storage (BES) (Carvalho et al., 2019; Liu et al., 2019)

CAES and PHES have been widely used at the commercial level. However, PHES requires special geographical consideration (potential head) as a key factor for its success. Currently, the application of hydrogen-based storage and batteries-based storage has increased due to their low cost and ease of storing low-cost energy (Sánchez et al., 2022). Additionally, studies have reported that with the increasingly improved storage technologies, future Solar PV systems will always be integrated with batteries to optimize their value of being fully stand-alone systems (O'Shaughnessy et al., 2018). However, the application of batteries has been constrained by battery life and long payback period (Kabir et al. 2018; Lupangu and Bansal, 2017).

The uptake of solar technology is predicted to rise due to efficient Solar PV sizing technology, skilled manpower, and good energy policy (Lai and McCulloch, 2017). Solar PV sizing technology is a key aspect of Solar design parameters regarding the

desired supplied load, this necessitates simulation of each stage of the Solar PV system (Lai and McCulloch, 2017; Manoj, 2017). Thus, sizing technology takes into account three main stages of solar PV design i.e., the pre-feasibility stage, sizing stage, and simulation stage (Cai et al., 2020; Jedou et al., 2021). Some of the presented solar PV simulation technology include Building Combined Heat and Power (BCHP) Screening Tool, Compare Options for Sustainable Energy System (COMPOSE), and Electricity Market Complex Adaptive System (EMCAS). Additionally, EMINENT™, EnergyPRO™, Generation and Transmission Maximization Tool (GTMax™), AEOLIUS™, Hybrid Renewable Energy System (H₂RES), PV Online, PV*SOL™, PVGIS™, PV Watts, Hybrid Optimization of Multiple Energy Resources (HOMER) have been intensively used for the optimization of HESs (Connolly et al., 2010). The choice of an effective tool for the analysis of a particular HES depends on its functional capability in preference to another analysis tool and the type of investigation to be performed. Through the application of simulation tools, the technical sizing analysis, pre-feasibility analysis of the stand-alone solar system, long-term system performance with parameter changes (Eteiba et al., 2018; Jedou et al., 2021; Lai and McCulloch, 2017), financial benefits of the installed system, as well as GHG emission potential, can be analyzed (Cai et al., 2020; Manoj, 2017). To improve the efficiency of Solar PV energy systems there is a need to identify the most optimal point for maximum solar power extraction. This can mainly be achieved by maximum power point tracking (MPPT) and solar tracking technologies (Ram et al., 2017). Table 2.3 illustrates different types of Solar PV simulation softwares and their functionalities.

Table 2.3: Solar PV simulation software and their functionalities

Simulation software	Functionality and usage	Operating Environment	Reference (usage)
HOMER	Hybrid energy system analysis based on technical and optimization analysis. Design of renewable hybrid energy system Hybrid energy system simulation Sensitivity analysis and economic analysis.	Windows OS Linux OS Unix OS Mac OS	Khare et al. (2017), Ramli et al.(2017), Ribó-Pérez et al. (2021), Uwineza et al. (2021), Zhang et al. (2022), Dawoud (2021)
RET Screen	Hybrid energy system analysis based on technical and optimization analysis. Hybrid energy system simulation Sensitivity analysis and economic analysis.	Windows OS	Pan et al. (2017), Zandi et al.(2017), Yimen & Dagbasi (2019), Owolabi et al. (2020), Bhutto et al. (2018)
H ₂ RES	Modeling of hybrid renewable energy system Optimization and economic analysis Sustainability analysis	Windows OS	Herc et al. (2021), Pfeifer et al.(2018), Y. Liu et al. (2018), Ma et al. (2018),
PV*SOL	PV system modelling and modelling	Windows OS	Silva et al. (2020), Sharma & Gidwani (2017), Petreuş et al. (2019)
PVGIS	Sizing of photovoltaic systems. Performance analysis of solar radiation data, off-grid solar system, and grid-connected PV system.	Windows OS MAC OS LINUX OS	Haffaf et al. (2021), Manoj Kumar et al. (2019), Dondariya et al. (2018), Kassem et al.(2019)

PV Online	Performance analysis tool for analysis of roof grid solar PV	Windows OS MAC OS LINUX OS	Dondariya et al. (2018), Manoj, (2017)
PV Watts	To get data about a geographical area to allow users to know areas for PV plotting	Windows OS MAC OS LINUX OS	Thotakura et al. (2020), Khandelwal & Shrivastava (2018)
PVsyst	Advanced modeling of PV system Optimization of solar system parameters Financial modeling GHG Emission analysis	Windows OS MAC OS LINUX OS	Belmahdi & El Bouardi (2020), Siregar et al. (2020), Chauhan et al. (2020), Spea & Khattab (2019), Satish et al. (2020)

2.6.2 MPPT Techniques and Solar Tracking Systems

Solar Maximum Power Point Tracking (MPPT) technique is a maximization technique for solar panel output by continuously adjusting the operating voltage and current to match the panel's maximum power point (Ram et al., 2017; Verma et al., 2016). Solar tracking involves physical adjustment of the solar panel position to follow the movement of the sun to maximize the reception of the intensity of sunlight to increase the solar panel output (Racharla and Rajan, 2017). Both MPPT and solar tracking increase the efficiency of solar power systems by lowering solar energy production costs.

2.6.2.1 Solar MPPT Techniques

MPPT optimization techniques (optimization algorithms) are designed and implemented in a converter. The operation of MPPT is based on varying the operating PV current and voltage to achieve the maximum and optimal power from a given PV module by switching a converter to sweep through the PV power. The selection of any given MPPT technique involves the ease of implementation of a particular technique and the required number of sensors for the full implementation of any MPPT algorithm (Karami et al., 2017).

System Optimization aims at ensuring proper economic returns on a given investment. The design of HES, therefore, involves solving optimization equations involving system sizing for cost minimization, different renewable source alternatives, energy demands model, and management of the system to eliminate uncertainties. According to Tezer et al. (2017), optimization modeling helps to model HES into their equivalent mathematical modeling for easy analysis. Due to the availability of different RESs efficient use of optimization technology would help inform the best hybrid system to develop (Sawle et

al., 2018). Depending on the optimal output to be achieved, several optimization techniques would help achieve the desired optimal output such as Genetic algorithm (GA) (Bhandari et al., 2015), Particle Swarm Optimization(PSO) (Jyoti et al., 2018), Teaching Learning Based Optimization (TLBO) (Jyoti Saharia et al., 2018), Fuzzy Decision Making (FDM) (Jyoti Saharia et al., 2018), Perturb and Observer Algorithm (POA) (Gopal et al., 2017) , Trade-Off Analysis (TOA), Matlab functions, Model predictive control (Jyoti Saharia et al., 2018), Multi Scenario Analysis (MSA) (Jyoti et al., 2018).

Genetic Algorithm: GA is a dynamic computational search technique for optimal solutions of systems based on optimization problems (Bhandari et al., 2015; Suresh et al. 2020). The GA approach is inspired by evolutionary biology i.e., inheritance, mutation, selection, and recombination to find the optimal solution to an objective function (Zahraee et al., 2016). In addition to finding the most economical system sizing, GA uses system parameters such as meteorological data, wind systems, battery storage model, solar irradiation data, and sludge volume in a biomass digester to find the best combination to achieve the optimal operation of a HES which will operate at a minimum cost. The GA toolbox in the MATLAB environment is used to identify the fitness function for optimization issues (Suresh et al., 2020). In GA, the first iteration is based on randomness to produce a vector code for the second iteration, which is based on lower and upper restrictions. The fitness function is then estimated, the number of each component is evaluated per generation, and each generation develops the subsequent iteration. This results in the optimal solution and choice of parameters for a particular HES (Suresh et al., 2020). Several studies have reported having successfully applied GA in the modeling of optimization of off-grid HESs (Das et al., 2021; Starke et al., 2018; Suresh et al., 2020).

Particle Swarm Optimization (PSO): PSO is based on swarm intelligence patterns as observed in birds or fishes and is often used for optimization problems presenting multiple optimal solutions (Jyoti et al., 2018; Sengupta et al., 2018). This algorithm searches for the swarm's optimal overall velocity and position by moving the constituent particles across a well-defined or constrained search space (Sengupta et al., 2018). To determine the overall optimum value, the position and velocity of each particle in the swarm are determined iteratively. Some of the renewable hybrid energy parameters considered for optimization by PSO include Net Present Cost (NPV), CO₂ emissions, energy storage capacity, and overall system investment (Suresh et al., 2022). PSO has been applied in hybrid systems sizing (Kurundkar, Karve, and Vaidya, 2021; Montoya et al., 2018), optimal design of HESs (Ibnelouad et al. 2020; Konneh et al., 2019), optimal control in microgrids with several distributed generation (DG) inputs (Radosavljević, Jevtić, and Klimenta, 2016; Zhang et al., 2020), dynamic economic dispatch (Chen et al. 2019; Sun and Wang, 2017), and optimal allocation of PV-biomass distributed generators (Al-Masri et al., 2022; Alshammari and Asumadu, 2020; Singh, Singh, and Kaushik, 2016).

Fuzzy Decision Making (FDM): Fuzzy logic decision-making involves comparing multiple logical inputs composed of only two states (true or false) (Jyoti Saharia et al., 2018). A fuzzy logic-making decision is composed of three main stages which are the fuzzification stage (input stage), the processing stage, and the output stage (defuzzification stage) (Jyoti Saharia et al., 2018). FDM is based on the rules of logic (Jyoti Saharia et al., 2018). During the fuzzification stage, the input values are transformed from input crisp to fuzzy set values, and then they are processed to provide the membership functions required for FDM (Jyoti Saharia et al., 2018). The control parameter value for the FDM is the final output, and its value can be scaled based on the desired output outcomes. FDM-

based optimization has been applied in several studies i.e., optimization of solar PV energy and HESs (Dhunny et al., 2019; Samala and Kotapuri, 2020; Yousefi, Hafeznia, and Yousefi-Sahzabi, 2018; Zoghi et al., 2017), Voltage and frequency control for Battery Energy Storage Systems (BESS), and PV-based microgrids (Atif and Khalid, 2020; Jena and Choudhury, 2017; Tephiruk et al., 2018),

Perturb and Observer Algorithm (POA): This optimization algorithm is majorly used to optimize solar array technology to establish the highest power point for a specific Solar PV array module (Gopal et al., 2017). POA is based on a trial and error method for finding the most optimal voltage value (Karami et al., 2017). It continuously increases or decreases the reference current or voltage based on the value of the most recent power sample obtained while monitoring the array output power. The system is first given a small disturbance, which affects the module's power (Gopal et al., 2017). If the disturbance results in an increase in power, the perturbation is kept in that direction. The perturbation is then reversed when the peak power is reached. POA has been widely applied in the solar PV module. optimization for maximum solar power gain (Ali, Sayed, and Mohamed, 2018; Kamran et al., 2020; Yan, Du, and Ren, 2019) and in the optimization of wind systems (Mousa, Youssef, and Mohamed 2019).

Artificial Neural Network (ANN): This is an optimization technique with the ability to store and learn to determine if the acquired experimental knowledge is valid for use or not (Elsheikh et al., 2019). It is a machine learning model with interconnected layers (input layer, hidden layers, and output layers) composed of artificial neurons with capabilities of processing and transmitting information. The hidden layer performs the task of extracting useful information before relaying it to the output layer (Elsheikh et al., 2019). ANN is

used in solar panels output optimization by predicting the output voltage of a solar power system. It can be trained to predict a solar panel's power output and appropriately adjust the panel's tilt angle and orientation based on characteristics such as temperature and sunlight intensity, and weather conditions to achieve the maximum power output (Elsheikh et al., 2019).

Constant Voltage (CV): This MPPT algorithm involves keeping the PV module closer to the maximum PowerPoint as possible. CV does this by varying and regulating the PV module output voltage by matching it to a reference (fixed) voltage. In case of a voltage mismatch, the reference voltage becomes the default voltage to be adopted. This optimization technique only uses one voltage sensor for PV array voltage measurement. CV MPPT has been widely applied in street lighting optimization to boost the performance of road side mounted solar PV modules to ensure the charging voltage for storage batteries is always constant (Mohammad, Prasetyono, and Murdianto, 2019).

2.6.2.2 Solar Tracking systems

Solar tracking systems play a vital role in solar energy applications where their benefits not only exist over fixed solar panels but also play a crucial role in the economic analysis of large-scale solar energy systems. The rotation of the earth along its axis changes the level of solar irradiance received by a mounted solar panel from the sun. To make full utilization of the solar irradiance as the earth rotates around the sun, the solar panel needs to be physically adjusted to track the sun. The solar panel tracking angle depends on the location of the site and the prevailing climatic condition of a given region (Hafez, Yousef, and Harag, 2018). Solar tracking, therefore, involves physically adjusting the position of the solar panel to follow the sun's movement (Kamran et al., 2020). This allows the panel to capture the maximum sunlight intensity, thereby increasing its overall power output efficiency.

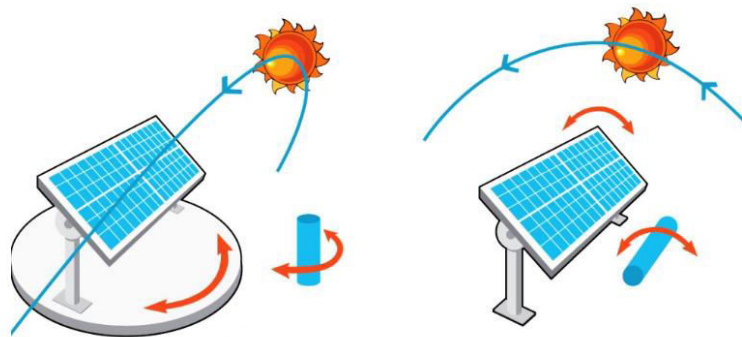


Figure 2.2:A single-axis tracking technique

The main technologies for solar tracking are single-axis and dual-axis tracking systems which are both based on a light-dependent resistor (LDR) sensor (Kamran et al., 2020). A single-axis tracking technique has a single pivot to enable its movement while tracking

the sun. Its rotational axis is vertical to the ground i.e., its axis of rotation lies between the horizontal and vertical axes (Hafez et al., 2018) as shown in Figure 2.2. Dual-axis solar tracking technology tracks the solar intensity using two sets of pivots to change the panel's relative position to the sun, hence, it has both vertical and horizontal axes (Hafez et al., 2018) as presented in Figure 2.3.

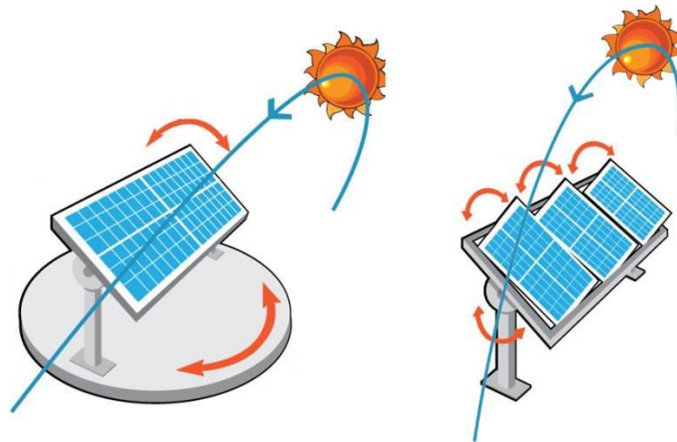


Figure 2.3: Dual-axis tracking technique

2.7 Sustainability Analysis on the Optimal Energy Mix

The Long-term well-being is ensured by determining how to meet current generations' expectations without risking future generations' ability to meet their own. Sustainability analysis aims at analyzing the overall effect of integrating economic, environmental, and social dimensional parameters into sustainable development. The economic parameters which this project shall be aiming at analyzing their viability include Net Present Cost (NPC), Capital Cost (CC), Capital Recover Factor (CRF), Operating Cost (OC), Return on Investment (RoI), Internal Rate of Return (IRR), Payback Period (PP) and Levelized Cost of Energy (LCOE).

Net Present Value (NPV) represents the life cycle cost and examines the current or potential investment. It is one way of determining the Return on Investment (ROI), which measures its profitability. Equation (1) illustrates how ROI shall be over a given period.

$$ROI = \frac{Investment\ gain - Investment\ cost}{Investment\ cost} \quad (1)$$

NPV is used to calculate the time value of money and it takes into the project expenses, which includes initial capital, component replacement, maintenance, and fuel costs. The calculations are done basing on the present values of the anticipated cash flows. Equation (2) illustrates *NPV*

$$NPV = \frac{Cash\ Flow}{(1 + i)^t} \quad (2)$$

The *CRF* shown in equation (3) illustrates how to calculate the present value of a series of cash flows with some interest applied to it over a given interval of time.

$$CRF = \frac{i}{1 - (1 + i)^{-t}} \quad (3)$$

The *IRR* is also used to determine if an investment is worthwhile and it examines the cash flow of a potential project against the investor's hurdles rate. *IRR* applies some discount rates to all investments. The discount rate is used in analyzing the discounted cash flow to produce the present value of future cash flows, and it fluctuates from year to year.

The environmental component of sustainability analysis shall also aim at analyzing harmful gaseous emission during the energy generation process. The levels of CO₂, carbon monoxide and nitrogen oxide emission is the basis of this analysis. According to Child et al, (2018) human beings are through civilization are exploiting natural resources at an

alarming rate than the rate at which renewal of such resources occur. The biosphere's capacity to absorb the effects of human action is currently being exceeded, resulting in dangerous interference with the global climate system, increased biodiversity loss, overstressed nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, chemical pollution, and a variety of other consequences (Child et al., 2018).

The only safe solution towards efficient sustainability in the energy sector is to have plans and goals for the future and for the achievement of such, information about essential technologies that will drive the energy shift need be presented in a realistic and accurate manner. Policy makers with instincts for the future in the energy sector must consider proper adoption of renewable energy technologies for solar, wind, biomass, and hydropower solutions to protect the current environment for the future generation (Child et al., 2018).

Solar, wind, and biomass energy have all emerged as viable options for reaching sustainability goals according (Child et al., 2018). According to the International Renewable Energy Agency (IRENA), renewable energy might account for 25% of consumed primary energy and also account for 30% of primary energy by 2030. Furthermore, several studies suggest that the advantages of renewable energy go beyond the energy industry. Biomass as a renewable energy source must be carefully examined when developing future energy system scenarios that meet acceptable sustainability requirements. Sustainable bioenergy has no impact on natural ecosystems, soil fertility, water resources, livelihoods, people's access to food, or biodiversity.

For sustainability purposes, energy efficiency also needs to be factored. Systems that save energy, need to be considered over ones that consume too much energy. Moreover, carbon

capture and storage (CCS) is also highly advocated for. Carbon capture and storage if well utilized by industries and manufacturing companies could be of great help in eradicating emissions coming from their combustion engines.

Goal 7 of the Sustainable Development Goals asks for all people to have affordable, reliable, sustainable, and modern energy while goal 13 demands immediate action to fight climate change and its consequences. These two aims have a substantial impact on mankind without diminishing the impact of the other goals on society's growth. Even though they target distinct audiences, the impact they have is comparable. Because "energy generation is the largest contributor to climate change, accounting for approximately 60% of total Greenhouse Gas emissions. Combating climate change can be accomplished considerably more swiftly with clean and affordable energy. In terms of access, technology cost, and dependability, sustainable energy significantly improves the situation for energy users. It also has a significant environmental impact.

Sustainability indicators tools that help to track the progress of sustainable development through time. They address the most important issues in sustainable development's major categories. Furthermore, sustainability analysis gives a deeper understanding of the main issues, highlighting the essential relations without using basic statistics. Additionally, they are also crucial tools for communicating energy concerns related to sustainable development to policymakers and the general public, as well as for encouraging institutional debate. In order to reduce poverty and enhance living conditions, Sustainable Energy Indicators are focused with providing essential energy services. Other indicators are focused with the effects on the environment. It is necessary to assess economic, social,

and environmental concerns with institutional considerations in order to find long-term solutions in policymaking

2.8 Research gap

Table 2.4: Research gaps

Study	Brief Description	Methodology Used	Findings	Gap Identified	References
Optima design and sensitivity analysis of PV-B for remote villages in China	Ling Ji presented a research report on off-grid power generation based on PV, Biomass generators, and diesel generators for powering remote villages in North-West China	The Methodology used involved load and local renewable energy estimation, a mixed-integer linear programming optimization model was then used for techno-economic and sensitivity analysis.	The results showed that a hybrid energy system mix comprising of 909 kW PV, 133 kW B, 705 kW DG, 706 kW gas boiler, 430 kW battery, and 1649 kW thermal energy storage was optimal and would lead to a LCOE of 0.355\$/kWh.	Sustainability analysis to determine the level of GHG gases was not carried out in this research.	Ji et al., (2021)
Environment and Economic evaluation of PV-W-B hybrid energy system for rural electrification in Iran.	Jahangir and Cheraghi presented research on the analysis of HPS based on solar PV, Wind and Biomass for rural electrification in Fars Province in Iran.	The methodology used involved evaluation of the user load requirement, system design, carrying out techno-economic analysis, sensitivity and	The research revealed that a combination of 150 kW Bio Gen, 80.7 kW PV was sufficient to meet a load demand of 14.32kWh	This research didn't delve into sensitivity analysis based on Solar irradiation level	Jahangir & Cheraghi, (2020)

		sustainability analysis using HOMMER.	at a LCOE ranging from 0.128 to \$0.223/kWh.	irradiance levels and inflation rates	
Study on Techno-economic analysis of PV-B hybrid System Pakistani for rural electrification.	Shahzad Presented a report on off-grid power generation based on renewable technologies.	The methodology used involved evaluation of the user load requirement, system design, carrying out techno-economic analysis and sensitivity analysis using HOMMER.	The research revealed that the development of a PV-B system for rural Pakistan with a mix of 18kw could serve a peak load of 17.08kW at a COE of \$ 0.066.	Sustainability analysis to determine the level of GHG gases was not carried out in this research.	Shahzad et al., (2017)
PV-B HPS for the supply of off-grid cellular base station in Bangladesh.	Hossain presented research on an alternative way of powering Base stations for cellular networks based on PV and Biomass HPS.	The methodology used involved evaluation of the user load requirement, system design, carrying out techno-economic analysis and sustainability analysis using HOMMER.	The findings show that the proposed system has enough potential to power Base Transmitter Stations with reduced environmental pollution.	This research however didn't consider the sensitivity analysis based on the variations of	Hossain et al., (2020)

				renewable energy inputs.	
Feasibility and Cost analysis of PV-B HPS in off-grid areas of Bangladesh	Nusrat proposed research on the analysis of HPS based on PV-B for rural electrification in rural Bangladesh.	The methodology used involved evaluation of the user load requirement, system design, carrying out techno-economic analysis and sustainability analysis using RETScreen simulation software.	The results showed that a hybrid energy system mix comprising of 12.9 kW PV and a 1 kW DG was optimal.	This research however didn't consider the sensitivity and sustainability analysis based on the variations of renewable energy inputs.	Chowdhury et al., (2020)

CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter discusses hybrid power system modeling and simulation approach used in this study. The system was designed to generate energy based on the desired loads. The hybrid system designed consists of solar PV and biomass renewable energy sources as energy input for the system. The typical design and analysis were based on the fluctuation nature of the renewable energy inputs. Sensitivity, optimization, and sustainability analysis were also carried out in this section to determine the effectiveness of the designed hybrid energy system. The optimization analysis was carried out to technically determine the suitable renewable energy input for the renewable energy system while sensitivity analysis was done to determine the performance of the HPS for the changes and variability of the energy resources as well as the costs of the technology. The estimation of the electricity demand process, and describing the assessment of optimal energy generation systems through simulation and optimization was done using the HOMER Pro software whose results output were used for sustainability analysis using Multi Criteria Decision Making (MCDM) criteria for sustainability analysis. Figure 3.1 illustrates layout of the research methodology used in the study.

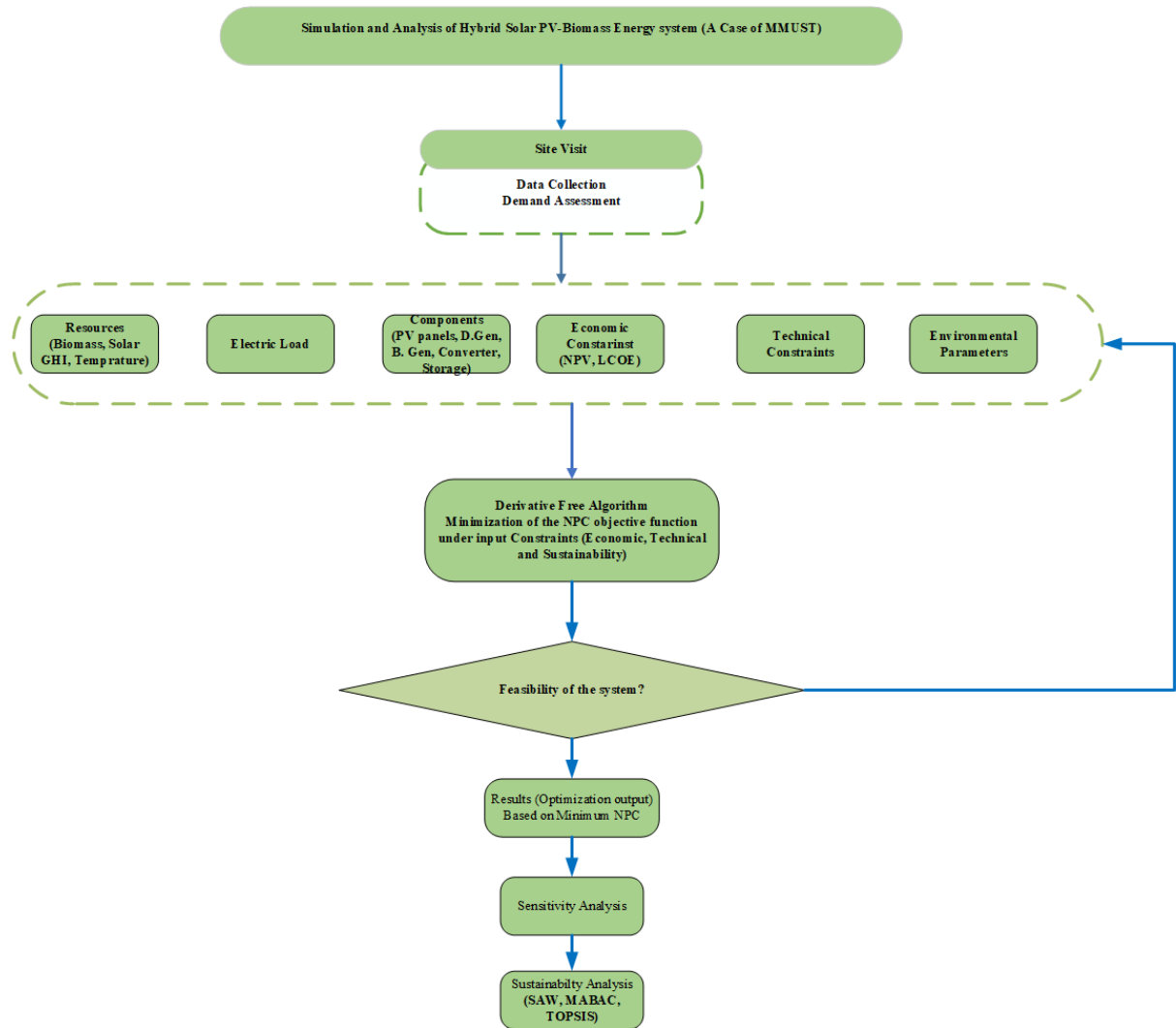


Figure 3.1: Research Methodology

3.1 The study area

In this research, the study site was Masinde Muliro University of Science and Technology (MMUST), a tertiary learning institution located in Kakamega, Kenya with latitude and Longitude coordinates of 0.288234° and 34.765522° respectively as shown in Figure 3.2. The university at its full peak is estimated to have a total population of over 21,000 students. Due to its location, the university receives plenty of solar irradiation throughout the year and the high population also leads to huge biomass resources.

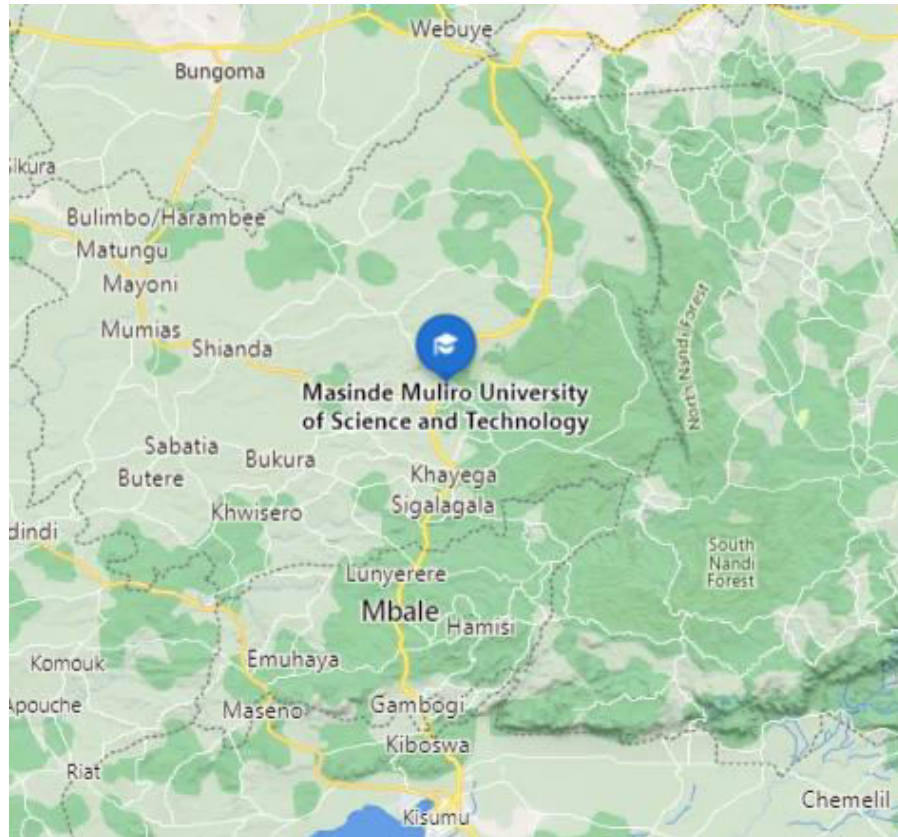


Figure 3.2: Location of MMUST (Google Maps)

3.2 Data Collection

3.3.1 Load Demand

Power consumption (energy) data was collected for a period of 12 months (September 2021- August 2022) using three power loggers ENOO38-EGauge (eGauge Systems LLC, version 4.5). The power loggers were connected to three different terminal intake points (Main campus gate, hall Four and Star Annex). Each power logger was connected to the three-phase supply terminal using three current transformers. Additionally, the power logger was connected to the internet for data transmission and retrieval using ENOO38-EGauge software installed in a remote computer Microsoft Windows 10 PC (intel core i7-4500U CPU, 4GHz, 8GB (intel, Santa Clara, CA, USA)).

The university has eight (8) diesel generators to cater for emergency back-up as shown in the table 3.1.

Table 3.1: Installed generators at MMUST

Generator Location	Hall Four	Science Lab Complex	Hall Two	Main Auditorium	Admin Block	Library	Multi-purpose Hall	Star Annex
Manufacturer	Cummins	Perkins	Caterpillar	Perkins	Cummins	Cummins	Cummins	Perkins
Rated Power	250kVA	200kVA	200kVA	200kVA	100kVA	100kVA	100kVA	50kVA
Phases	Three	Three	Three	Three	Three	Three	Three	one

3.2.2 Input Energy Resource Data

3.2.2.1 Biomass Energy Data

Biomass can only be made useful when it is converted into heat through combustion or a clean useable form of energy such as biofuel, bio-syngas or biogas through biological, chemical, and thermochemical biomass conversion processes (pyrolysis, gasification, and liquefaction) which eventually can be converted to electrical energy (Ahmed et al., 2015). The conversion to electrical energy is done by using steam turbine generators, high-temperature biomass fuel cells, and microbial fuel cells (Ahmed et al., 2015; W. Liu et al., 2020).

MMUST has a high potential for biomass due to the huge population (high population density) and agricultural biomass. Therefore, the biomass data applied in this study were from agricultural biomass and animal wastes.

The mass of sludge was computed by sampling the sewage at the inlet valve. The sewer flow rate was determined by a venturi meter connected to the inlet. The sample collected was poured into a V-shaped volumetric flask. The mixture was allowed to settle and the volume of sludge was gotten which further led to the determination of the mass of sludge in the same sample. Equation (4) shows the expression for the daily mass of sludge in tons.

$$M = \frac{V*m}{v} \quad (4)$$

Where: M is the Daily mass of sludge in tons, V is the daily sludge volume, m is the mass of solid sludge in the collected sample, v is the volume of collected sewer sample

The agricultural biomass from animals estimation from the farm was calculated by Equation (5) (Shahzad et al., 2017).

$$B_M = \sum_{n=1}^i N_i m_i + \sum_k PY \quad (5)$$

Where, B_M is the Total Biomass produced in tons, n is the number of specified animals' groups, N_i is the total number of animals, m_i is the manure produced per head of the animal (cattle), PY is the monthly agricultural production in tons per acre, k is the number of acres for agricultural produce wastes.

3.2.2.2 Solar Energy and Temperature Resource Data

The solar irradiance data used in this study was based on the Global Horizontal Irradiance (GHI) which represents solar irradiance level on a horizontal surface (Yan et al. 2019). The average monthly GHI is based on data collected over 22 years and recorded by the National Aeronautics and Space Administration (NASA) in their online public repository in Hybrid Optimization of Multiple Energy Resources software (3.16.1, NREL, Colorado) (HOMER).

The monthly temperatures were collected for over 30 years, from January 1984 to December 2013 and from the NASA database in HOMER Pro. The GHI is used together with the clearness Index. The clearness index is a dimensionless value between 0 and 1 that defines the clearness of the atmosphere.

3.3 System Design and Optimization Methodology

This research aimed at designing an optimal solar PV-B with storage as a green energy solution alternative. Based on energy demand and load optimization, sensitivity and sustainability analysis were key approaches for the analysis of the HPS. HOMER pro software was applied in the simulation of the design, optimization, and sensitivity of the proposed energy mix. Figure 3.3 presents the generalized layout of the proposed system.

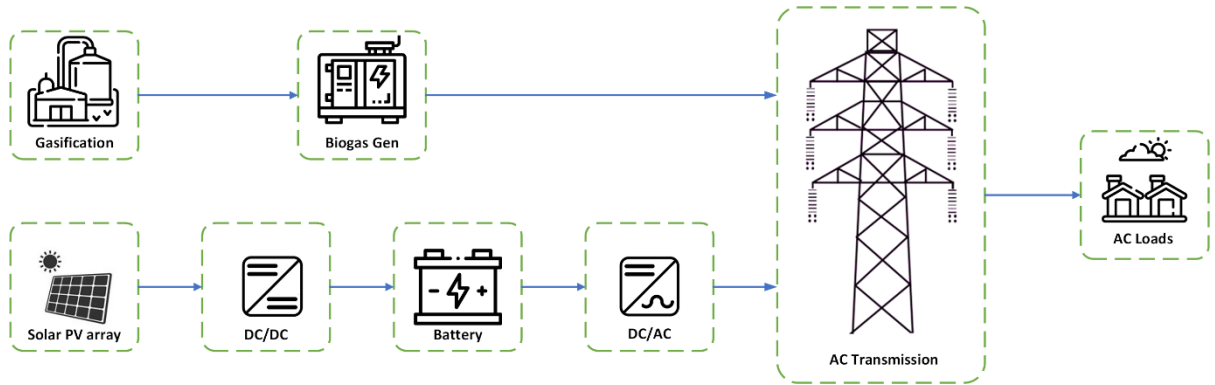


Figure 3.3: Hybrid Power System Conceptual Framework for Solar PV-Biomass Hybrid System

HOMER Pro is a hybrid energy optimization software used in the design and modelling of hybrid microgrid energy systems whose capabilities are simulation, optimization, and sensitivity analysis. It uses economic, technical, and environmental parameters as input variables to achieve the most optimal energy mix during the design stage (Dawoud, 2021; Uwineza et al., 2021). In this study, a simulation of several energy alternatives was performed to achieve the most optimal alternative energy mix.

Based on cost minimization (least NPV and LCOE), HOMER Pro uses user input parameters of energy demand profiles, renewable energy resources available and conventional energy resources to select system components to be included in the microgrid being modelled (Shahzad et al., 2017). The guiding optimization equations for these operations are the economic, technical, and environmental objective constraints. HOMER Pro uses two main algorithms which are Grid search Algorithm and Derivative free Algorithm in performing optimization. These optimization algorithms help in determining the optimal control strategies which help to achieve minimum operating costs and maximize renewable energy penetration. This study applied the Derivative-Free Algorithm (DFO) which is preferred in HOMER optimization due to its faster convergence and its inexpensive nature compared to the grid search algorithm (Rios and Sahinidis, 2013). Moreover, HOMER Pro assesses different other system configurations and ranks different hybrid energy alternatives from the renewable energy, conventional and storage inputs-based Techno-economic parameters. Figure 3.4 shows the design of the proposed system as implemented in a HOMER Pro environment.

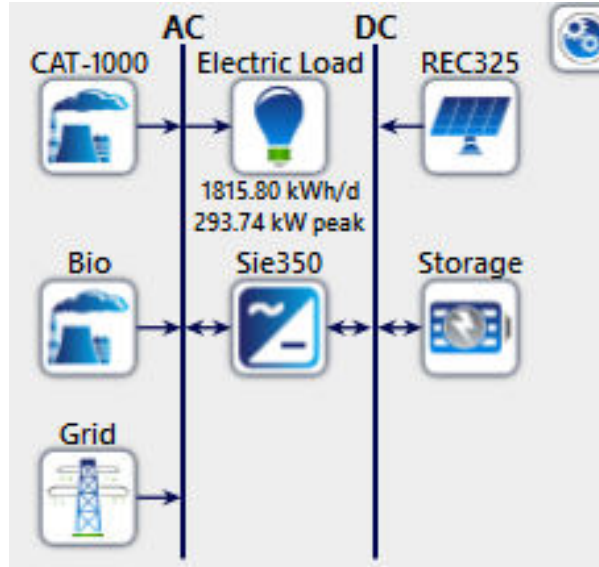


Figure 3.4: Schematic Design of the proposed Hybrid energy system in HOMER Pro

3.3.1 Solar PV Modules

The amount of energy generated from the solar PV depends on factors such as Solar insolation incident on the panel, relative humidity, the Sky Clearness Index ambient temperature levels, panel type, shading, efficiency of conversion, and orientation. The power generated by a PV module is given by Equation (6) (Singh and Baredar, 2016). Table 3.2 presents the properties of the simulated solar module applied in this study.

$$P_{PV\ output} = P_{NPV} * \left(\frac{G}{G_{Ref}} \right) * [1 + K_T (T_C - T_{ref})] \quad (6)$$

Where, G is the solar irradiation (Wm^{-1}), P_{NPV} is the rated power at reference conditions, G_{ref} is the solar irradiation at reference conditions ($G_{ref} = 1000 Wm^{-1}$), T_{ref} is the reference temperature ($T_{ref} = 25^{\circ}C$), K_T is the maximum power temperature coefficient for monocrystalline silicon, T_C is the temperature for individual modules.

Table 3.2: Properties of the simulated solar PV module

Solar PV Properties	Specifications
Selected PV Module	REC Solar325REC325PEM 72 PV
Life Cycle	25-year

Derating Factor Is	85%
Temperature Coefficient	0.4520% per degree Celsius
Standard Conditions	13%
Tracking System	No tracking system
Module Costs	\$650 per kW
O&M Fee	\$10 per year
Replacement Cost	\$550

3.3.2 Storage Battery

Battery storage was incorporated into this HPS due to the intermittency nature of the renewable energy resources (Sánchez et al., 2022). Additionally, they boost system stability and reliability (Tephiruk et al., 2018). According to (Singh and Baredar 2016), The battery storage capacity is calculated by Equation (7). Table 3.3 presents the properties of the simulated battery storage module applied in this study.

$$C_{wh} = [E_L * AD] * n_{inv} * n_b * DOD \quad (7)$$

Where: E_L is the total energy demand, AD is the Daily autonomy, DOD is the depth of discharge, n_{inv} is the efficiency of the inverter, n_b is the battery efficiency

Table 3.3: Properties of the simulated battery storage

Battery properties	Specifications
Selected Storage Module	lead acid, Gel Solar Cell from chloride Exide battery technologies
Max. Charge capacity	3.04kAh
Max Charge Current	1.06kA
Terminal voltage	2V
life cycle	10-year
Depth of Discharge	40%
Round trip efficiency	95%
Battery rating	6.07kW
module costs	\$610 per kW
O&M fee	\$10 per year
replacement cost	\$600

3.3.3 Grid

This research aimed at reducing overreliance on the grid. There were no extra connection costs for the grid as the university had already been connected to the grid. With the rapidly

growing net metering system, it was to cater for the sales of the excess power produced by the solar PV-Biomass hybrid energy system. The sellback price was set at \$ 0.05/kWh.

3.3.4 Converter

Converters are electronic devices which raise the level of the DC power produced by solar Panels from a lower level to a higher level maintain it at a specific level and convert it to AC power to be used by AC loads (Lupangu and Bansal, 2017). Table 3.4 presents the properties of the converter module applied in this study.

Table 3.4: Properties of the converter module

Converter properties	Specifications
Selected Converter Module	Siemens Industry SININVERT PVS351
Max. capacity	350kW
Inverter design	Inbuilt
Efficiency	96%
Connection Mode	parallel with the biomass AC generator
Life cycle	15-year
module costs	\$280
O&M fee	\$30 per year
replacement cost	\$280

3.3.5 Biomass Generator

Table 3.5 shows the specifications of the biomass generator chosen for this project.

Table 3.5: Specifications of the biomass generator

Biomass Gen set properties	Specifications
Selected Genset Module	Free size
Max. rated capacity	540kW
Rated voltage	400 (50Hz)
Phases	3 phase, 4 wires
Gasification ratio	0.7
Rated rotation speed	600rpm
Life cycle	25-year
module costs	\$90,180
O&M fee	\$88,337.58.
replacement cost	\$90,180

3.3.6 Diesel Generator

Table 3.6 shows the specifications of the diesel generator used for this project.

Table 3.6: Specifications of the diesel generator

Diesel Gen-set properties	Specifications
Selected Genset Module	800KW Cummins Generator Set
Prime power	800kw/1000kva
Standby power	880Kw/1100kVA
Phases	3 phase, 4 wires
Diesel Engine	Cummins KTA38-G5
Rated rotation speed	1500rpm/50Hz
Power factor	0.8Lag
Weight	12300kg
Space size	6000x2600x2800mm
Life cycle	25-year
Module costs	\$200,000
Replacement cost	\$200,000

3.3.7 Economic Parameters

HOMER Pro carries out optimization feasibility through cost-benefit analysis considering cash flow for the 25-year expected life span. Net Present Value (NPV), Least Cost of Energy (LCOE), Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) are some key economic parameters utilized in the HOMER tool for optimal economic analysis and optimal configurations. However, NPV and LCOE are the most cost-effective metrics in the HOMER tool for optimization (Uwineza et al., 2021).

NPV represents the life cycle cost and examines the current or potential investment (Roche and Blanchard 2018). It is a way of determining the Return on Investment (*ROI*), which measures its profitability as shown by Equation (8).

$$ROI = \frac{I-P}{P} \quad (8)$$

Where, *I* is the investment gain, *P* is the investment cost. NPV is used to calculate the time value of money and it takes into the project expenses, which include initial capital, component replacement, maintenance, and fuel costs. The calculations are done based on the present values of the anticipated cash flows as shown by Equation (9).

$$NPV = -C_0 + \sum_{t=1}^n \frac{C}{(1+i)^t} \quad (9)$$

Where, C_0 is the initial capital, C is the cash flow, t is time in years, i is the interest rate. LCOE is the cost per unit of electricity which considers all the project's lifetime costs against the total produced electricity and was calculated by Equation 10 (Roche and Blanchard 2018).

$$LCOE = \frac{C_0 + \sum_{t=1}^n \frac{L_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n E_t} \quad (10)$$

Where, L_t is the investment expenses in year t , M_t is the O&M costs expenses in year t , E_t is the produced electricity in year t , F_t is the fuel expenses in year t , r is the discount rate, n is the system life.

CAPEX and OPEX : CAPEX is the expenditure incurred while purchasing the HPS fixed assets such as solar PV, Biomass generator, storage and converters while OPEX is the daily to daily expenses incurred while operating the HPS such as cost of fuel, labour payments and routine maintenance aimed at keeping the HPS in good working conditions (Uwineza et al., 2021).

3.4 Sensitivity Analysis

Sensitivity analysis is a technique for analyzing how the optimal components of a system fluctuate when some input variables are changed and measuring the impact of each change on the project's result (Ji et al., 2021; Roche and Blanchard, 2018). It evaluates the impacts of changes in various parameters on the energy systems' technical, economic, and environmental performance indicators, e.g., storage capacity, LCOE and system costs. Through sensitivity analysis, the ranges of the sensitivity parameters beyond which the system becomes infeasible were known for the microgrid designed. In this study, solar irradiation and inflation rates were the chosen sensitivity parameters and they were varied in the HOMER optimization environment. The costs of solar panels and storage accounted for high costs during the optimization analysis, a sensitivity analysis was then conducted on solar irradiation levels to evaluate its effect on the system cost and overall sizing of the hybrid energy system. The effect of expected inflation on sensitivity analysis will help evaluate how resistant the design is to economic changes due to global economic practices.

The choice of expected inflation as a sensitivity parameter was informed based on its importance in risk management, its impact on capital cost and future project viability. Table 3.7 lists the sensitivity variables that were used in the simulations.

Table 3.7: Sensitivity variables

Solar Irradiation (kWhm⁻² day⁻¹)	Expected Inflation (%)
4	9.2
5.90	10
6.5	8

3.5 Sustainability Analysis

Sustainability analysis aims to evaluate the environmental, economic, technical, and social impact of the project’s energy-generating capability to provide long-term energy planning and selection of sustainable energy resources based on the optimized solutions from optimization analysis (Ojong, 2021). The main indicators for sustainability analysis are economic parameters (Capital Cost (CC), NPV, Operating Cost (OC), Internal Rate of Return (IRR), Return on Investment (ROI), Simple Payback period (SPP), and LCOE), environmental impact parameters such as pollution, land use and GHG emissions (Carbon dioxide, carbon monoxide, Sulfur Dioxide, and Nitrogen Oxides levels emitted during energy generation), social parameters such as regional development and job creation, maximum capacity parameters (Technical parameters) such as reliability, service life and even the installed capacity (Campos-Guzmán et al., 2019). Sustainability analysis enabled the making of informed decisions by efficiently exploring energy alternatives and it was performed on the optimal hybrid energy alternatives from HOMER optimization.

The multi-criteria decision-making model (MCDM) approach was used for the performance of sustainability analysis. This approach enabled all the critical evaluation criteria to be merged and analyzed in a decision-making process. MCDM thus helped in evaluating the most feasible energy alternative from the available options. Four MCDM approaches were used for this project which were; Simple Additive Weighting (SAW), Multi-Attributive Border Approximation Area Comparison (MABAC), COmplex PRoportional Assessment (COPRAS) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The methodology for the approaches is as described below.

SAW: This MCDM method consists of three major steps which are decision matrix X normalization, weight vector assigning and finally overall score calculation for each alternative (Goodridge, 2016). Algorithm 1 illustrates the SAW methodology.

Algorithm 1:SAW Methodology

Input	
1	Column normalization for each i^{th} row and results stored in the n^{th} column
2	For $i =$ matrix row, $j =$ matrix column, $n =$ number of criteria, $S_i =$ overall score
3	For $W_{ij} = N_{ij} * W_j$
4	$S_i = \sum_{j=1}^n (W_{ij})$

TOPSIS: The TOPSIS method used in this research involved assigning two sets of reference points when finding the ideal solution (positive and negative). According to (Goodridge, 2016) the negative ideal solution maximizes the cost criterion and minimizes the benefit criteria, while the positive ideal solution maximizes the benefit criteria and minimizes the cost criteria. By maximizing the distance to the negative ideal solution and decreasing the distance to the ideal solution, TOPSIS finds the optimal course of action. Every property is assumed to be rising or decreasing monotonically in this procedure. TOPSIS measured the alternatives with their positive and negative ideal solutions using Euclidean distances. By comparing the Euclidean distances, the preferred order of the alternatives can be determined. Euclidean distance comparison yields the preference order of the alternatives (Goodridge, 2016; Yadav, Joseph, and Jigeesh, 2018). Algorithm 2 shows the TOPSIS methodology.

Algorithm 2: TOPSIS Methodology

Input	
1	Determination of the decision matrix $A, X = [X_{ij}]_{m \times n}$
2	For $P_{ij} =$ normalized decision matrix, $V_{ij} =$ weighted normalized decision matrix, $w_j =$ weight of the j^{th} criterion, $A^* =$ Positive ideal solution, $A^- =$ negative ideal solution, $S^*_i =$ $=$ Separation measures, $RC^*_i =$ Relative closeness to the ideal solution

- 3
$$P_{ij} = \frac{A_{ij}}{\sqrt{\sum_{i=1}^m (A_{ij}^2)}}$$
 - 4 *Weights coefficients assigning For $V_{ij} = P_{ij} * w_j$*
 - 5 $A^* = \{ \max v_{ij}, \min v_{ij} \}$ and $A^- = \{ \min v_{ij}, \max v_{ij} \}$
 - 6
$$S^*_i = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^*)^2}$$
 while $S^-_i = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^-)^2}$
 - 7
$$RC^*_i = \frac{S^-_i}{S^*_i + S^-_i}$$
 - 8 *Ranking of alternatives based on RC^*_i*
-

MABAC: The MABAC algorithm which was applied is as discussed below:

The first step involves the formation of a primary decision matrix (Bose et al., 2019). This was followed by the normalization of the ultimate decision matrix. Thirdly, the weighted normalized decision is calculated and finally, the overall alternative was computed (Adar et al., 2017; Bose et al., 2019). Algorithm 3 shows the MABAC methodology.

Algorithm 3: MABAC Methodology

Input	
1	<i>Formulation of the decision matrix X</i>
2	<i>For X_{ij} = performance of the i^{th} alternative wrt j^{th}, x_i^+ = max value of the observed alternatives, x_i^- = min value of the observed alternatives, n_{ij} = benefit type criteria V_{ij} = Weighted matrix, g_i = The boarder approximation</i>
3	<i>Decison matrix normalization</i>
4	<i>Weights coefficients assigning For $V_{ij} = w_i * (n_{ij} + 1)$</i>
5	$g_i = \left(\prod_{j=1}^m v_{ij} \right)^{\frac{1}{m}}$
6	<i>Distance from the boarder area (Q) = $V - G$</i>
7	<i>Ranking of alternatives</i>

COPRAS: This method involved ranking the alternatives in order of their relative importance. The first step involved the formulation of the decision matrix; the decision matrix is then normalized. Finally, the coefficient of efficiency is then determined and then the alternatives are ranked from higher percentage to lower percentage (Stanojkovic and Radovanovic, 2017). Algorithm 4 shows the COPRAS methodology.

Algorithm 4: COPRAS Methodology

Input
1 <i>Determination of the decision matrix $X, X = [X_{ij}]_{m \times n}$</i>
2 <i>For X_{ij} = performance of the i^{th} alternative wrt j^{th}, m = alternatives, n = number of criteria, Q_i = Relative significance, S_{+i} and S_{-i} are sums for max and min criteria</i>
<i>U_i = Coefficient of efficiency alternative</i>
3 <i>Decision matrix normalization,</i>
4 <i>Weights coefficients assigning For $W_{ij} = N_{ij} * W_j$</i>
5 $S_{+i} = \sum_{j=1}^n (W_{ij})$ and $S_{-i} = \sum_{j=1}^n (W_{ij})$
6 <i>Decision matrix normalization</i>
7 $Q_i = S_{+i} + \frac{S_{-min} \sum_{i=1}^m S_{-i}}{S_{-i} \sum_{i=1}^m \frac{S_{-min}}{S_{-i}}}$
8 $U_i = \frac{Q_i}{Q_{i \max}} * 100\%$
9 <i>Ranking of alternatives based on percentages</i>

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.0 Introduction

This section presents results and discussions of the research findings in this study. The results depicted in this chapter demonstrate the utility, feasibility and reliability of the overall proposed system and approach proposed in the previous chapters. Additionally, sensitivity and sustainability analysis results are also presented in this section. Moreover, this chapter gives detailed possible explanation of the optimization results, sensitivity results and sustainability results.

4.1 Load assessment

The total annual load as shown in Table 4.1 was established to be 662,682.99 kWh for a period between September 2021 and August 2022. Consumption was high at the main campus with a total of 569,625.38 kWh and low at Star-Annex with 8,185.32 kWh with the highest monthly consumption being in March with 69,573.88 kWh and the lowest consumption by month being in August 2022 at 41,021 kWh.

Table 4.1: MMUST Monthly power consumption

Month/Year	Main Campus (kWh)	Hall Four (kWh)	Star Annex (kWh)	Total Energy demand (kWh)
Sep-21	40,612.56	5,038.7	138.01	45,789.27
Oct-21	52,833.08	1,0375.38	918.77	64,127.23
Nov-21	55,773.35	12,542.57	1,009.46	69,325.38
Dec-21	44,563.55	8,343.65	918.77	53,825.97
Jan-22	48,422.66	9,020.9	500.1	57,943.66
Feb-22	52,189.89	10,700.46	869.42	63,759.77
Mar-22	56,600.31	12,271.67	701.9	69,573.88
Apr-22	54,854.52	10,890.09	920.68	66,665.29
May-22	42,450.23	1,462.85	619.09	44,532.17
Jun-22	41,255.74	1,083.6	662.46	43,001.8
Jul-22	41,531.39	1,002.32	583.6	43,117.31
Aug-22	38538.1	2140.1	343.06	41021.26
	569,625.38	84,872.29	8,185.32	662,682.99

A typical load profile for a selected day in March is given in Figure 4.1 while Figure 4.2 shows the seasonal load profile for an academic year.

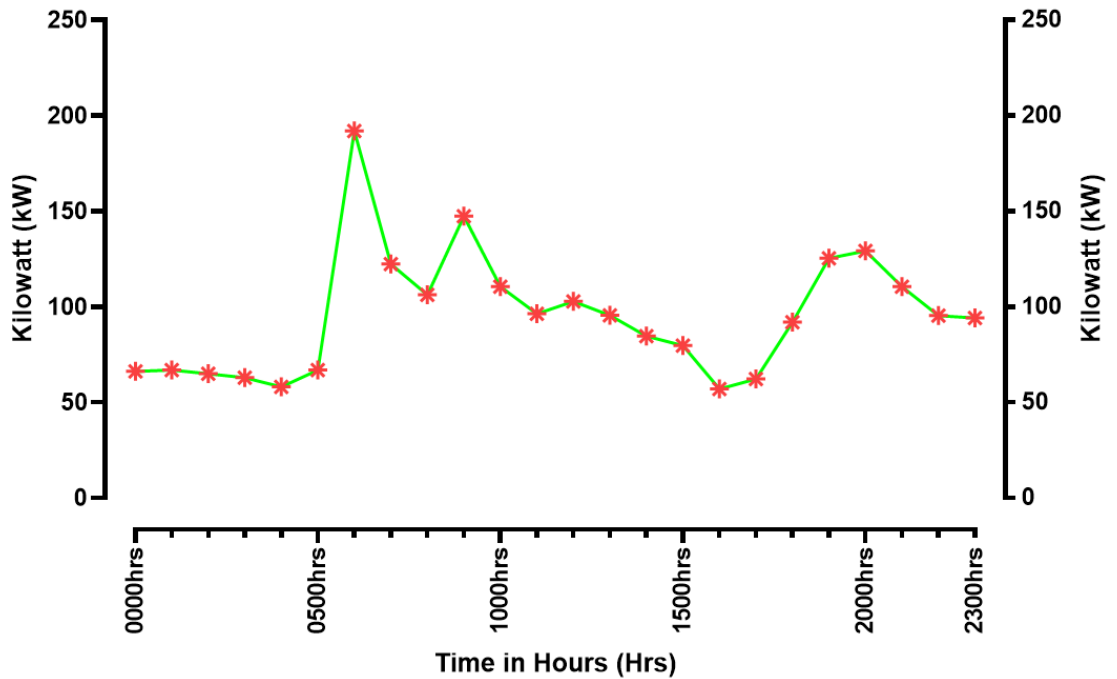


Figure 4.1: Daily load demand for a day in January



Figure 4.2: Seasonal load profile

The Average hourly Energy Demand was 75.66kW with the peak demand being 293.74kW (with the considered day-to-day swing of 5%). The monthly average load demand is 54,474 kWh.

The mean seasonal consumption was found to be 54,474.5825 kWh with a standard deviation of 11,274.07 as depicted in Table 4.2.

Table 4.2: Descriptive Statistics for the Seasonal Load and Biomass Resource

Descriptive Statistics	Load Assessment Values (kWh)	Biomass Values (tons)
Mean	54,474.5825	2.104545455
Standard Error	3254.542628	0.326113794
Median	55884.815	2.775
Standard Deviation	11,274.06638	1.081597094
Sample Variance	127,104,572.6	1.169852273
Kurtosis	-1.924501209	-0.899731796
Skewness	0.005797329	-1.065738749
Range	28552.62	2.475
Minimum	41,021.26	0.45
Maximum	69,573.88	2.925
Sum	662,682.99	23.15

The daily load curve in Figure 4.1 shows the electrical power consumption based on the activities taking place within the study area. The consumption remains relatively low 0000hrs to 0500hrs due to minimized students and learning activities (street and security lights mostly on). This reduced activities also relates to the power consumption between 1600hrs and 1700hrs.

Power consumption is high between 0600hrs and 1100hrs due to increased student activities and learning activities which start from 0700hrs. Moreover, between 1800hrs and 2200hrs, power consumption is also high due to increased student activities back in the hostels. The daily load demand as curve concurs with a study of Popoola et al. (2018) for covenant university based in Nigeria in their smart campus energy data research.

The high-power consumption between January to April and October to December as depicted in Figure 4.2 was attributed to increased academic activities (First and second

academic semesters) i.e., increased learning activities and student activities within the university. The period between May and September is associated with reduced power consumption due to reduced academic activities associated with semester breaks and minimal administrative work. The University also carries out scheduled maintenance during this period switching off many energy-consuming equipment hence reducing power consumption during this time. Only school-based students who are few are the ones present during that time and their power consumption is low. The seasonal load data trends evidenced in this research concur with the MMUST academic calendar (MMUST Almanac, 2021).

4.1.1 Biomass Energy Resource

It was established that the average monthly biomass was 2.1 tons of biomass with a standard deviation of 1.081597094. The minimum biomass collection was 0.45 tons and a maximum of 2.925 tons as shown in Table 4.2. The biomass resource was highest in November at 2.925 tons and was lowest in February, March, and April at 0.45 tons as depicted in Figure 4.3.

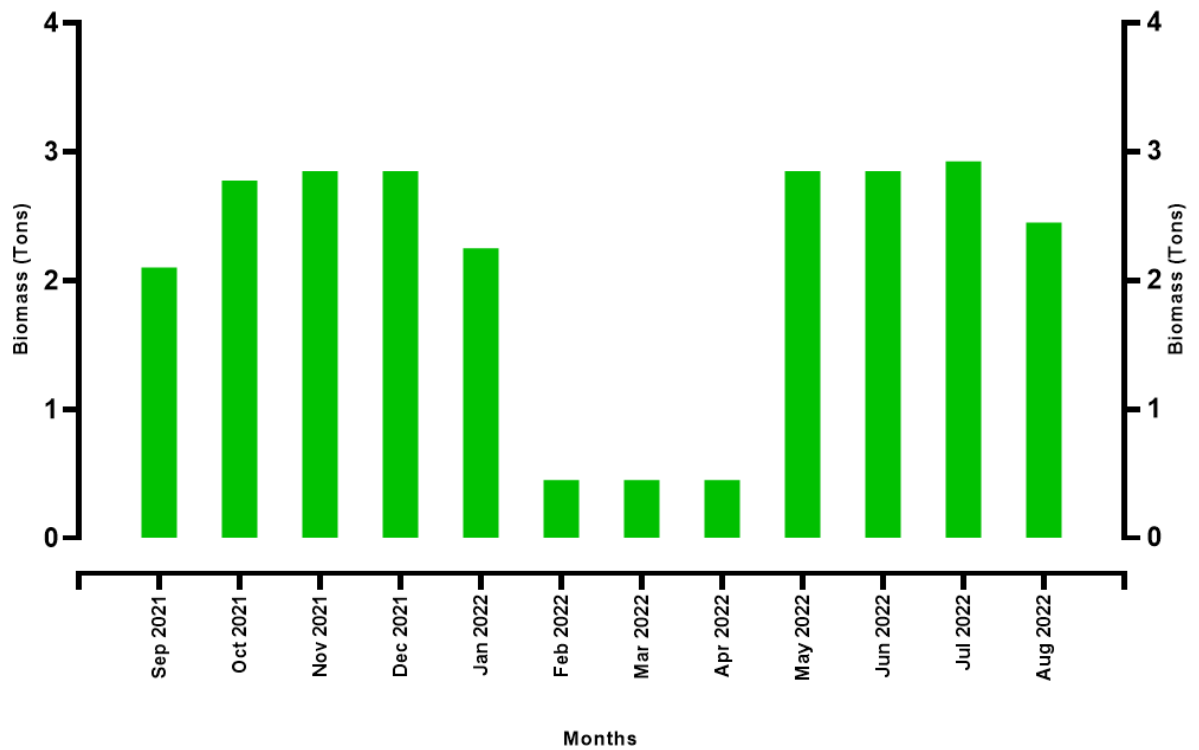


Figure 4.3:MMUST Biomass Resource

4.1.2 Solar Energy Resource

Solar irradiation data showed that the annual scaled average solar irradiation was $5.90 \text{ kWhm}^{-2} \text{ day}^{-1}$ with the scaled annual average clearness index being 0.5897. February had the highest solar irradiation of $6.279 \text{ kWhm}^{-2} \text{ day}^{-1}$ while May had the lowest solar irradiation levels at $5.3635.90 \text{ kWhm}^{-2} \text{ day}^{-1}$. Table 4.3 shows the GHI resource (clearness Index, Daily radiation, and Daily temperature)

Table 4.3:Solar Energy Resource Data

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Clearness Index	0.619	0.621	0.594	0.531	0.554	0.601	0.585	0.592	0.607	0.578	0.566	0.628	0.5897
Daily radiation ($\text{kWhm}^{-2} \text{ day}^{-1}$)	6.205	6.438	6.242	5.425	5.363	5.607	5.532	5.877	6.279	5.984	5.700	6.199	5.9043
Daily Temperature (°C)	21.18	22.20	22.69	21.60	20.60	19.80	19.38	19.81	20.63	20.84	20.56	20.65	20.8283

4.2 Optimization Analysis

The best architecture presented in Table 4.4 after optimization analysis based on NPV and LCOE was a combination of 360kW of REC Solar325REC325PEM 72 (Solar PV), 576 Strings of lead acid- Gel Solar Cell (storage battery), a 142 kW Siemens Industry SININVERT PVS351 (converter with inbuilt inverter), 800 kW diesel generator (standby supply for the hybrid system), and a 540kW biomass generator with HOMER Load Flow (LF) dispatch strategy at a NPV of US\$ 1.93M, Capital cost of \$ 915,505.30, LCOE of \$0.10032, operating costs of \$34,868.61 per year, electricity production of 74,790.1 kW and excess energy of 49,062.51kW with a potential of being sold back to the grid.

However, the base case scenario (Diesel generator) was established to be a diesel generator of 800 kW having capital expenditure (CAPEX) of \$200000, NPV of \$23.2M, operating cost (OPEX) of \$795,631 per year with an annual electricity production of 1,753,472kWh and 1,465,253 kilograms of CO₂ per year. With its standard capacity, it

consumes 554,381.5 litres of fuel per year which amounts to \$776,134.1. It had the LCOE of \$1.2 for every unit of electricity it produced.

The optimal alternative compared with the base case scenario, the NPV would rise to \$23.2M which is \$21.27M greater than the optimal scenario. Consequently, the LCOE also increased to \$1.2109 under the base case scenario which is \$1.1106 higher than the optimal scenario. The diesel generator used in the base case scenario would operate the whole year with an annual OPEX of \$795,631, and annual electricity production of 1,753,472kWh (which is higher than the electricity produced by optimal solution by 1,005,564.9 kWh/yr) while consuming 554,381.5 litres of fuel per year which amounts to \$776,134.1 while emitting 1,465,253 kilograms of CO₂. It had an investment cost of \$200,000.

Table 4.4 : Optimization Results

	PV	D. Gen (kW)	Bio Gen (kW)	Storage	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	OPEX (\$/yr)	Ren Frac (%)	Elec Prod (kWh/yr)	Excess Energy (kWh/yr)	Unmet load (kWh/yr)	Emissions (kg/yr)
A1	360	800	540	576	142	LF	1.93M	0.1003	34,868.61	915,505.30	20,276.27	98	747,907.10	49,062.51	0	150.30737
A2	360		540	576	142	LF	1.97M	0.1026	43,302.48	715,505.30	20,276.27	100	747,907.10	49,062.51	0	85.30737
A3	609	800		576	256	LF	2.41M	0.1255	47,966.72	1,019,070	25,710.12	97.21624	1,054,718	345,774.40	0	15,408.86
A4	902			816	274	LF	3.06M	0.1597	65,711.35	1,161,008	34,433.24	100	1,534,146	825,192.20	0	0
A5	920	800	540	576	1118	LF	6.72M	0.1016	178,489.70	1,552,698	-177,060.80	70.42544	2,456,648	28,304.23	0	564,993.90
A6	920	800	540		657	LF	8.00M	0.0976	239,189.40	1,072,252	-275,787.90	60.06177	2,906,469	12,966.90	0	945,011.30
A7		800	540	576	154	LF	8.28M	0.4314	262,297.30	684,765	18,960.65	25.68828	700,103.40	359.8881	0	411,732.90
A8	920	800		576	1125	LF	8.89M	0.1379	256,212.80	1,464,565	-172,215.60	62.26529	2,403,993	26,458.38	0	701,711.60
A9		800		576	157	LF	10.8M	0.5611	351,315.90	595,250	14,025.50	0	712,846.30	407.5748	0	595,709.70
A10	920	800			657	LF	10.8M	0.1298	340,077	982,072	-287,703.50	51.69023	2,956,314	12,966.90	0	1,163,033
A11		800	540	576	119	LF	12.7M	0.3826	415,377.30	674,790	-52658.23	13.62987	1,202,654	77.9827	0	827,727
A12	920	800	540		138	LF	13.8M	0.7203	445,389.60	926,750	33,619.70	0	2,675,986	2,007,791	0	759,103.40
A13		800		576	147	LF	14.6M	0.4736	484,892.90	592,590	-44,794.23	0	1,137,881	75.92556	0	950,968.30
A14		800	540			LF	15.5M	0.3179	524,281.90	290,180	-139,608.10	12.57025	1,680,721	0	0	1,228,009
A15		800	540			LF	17.5M	0.9101	593,153.10	290,180	12,792.80	0	1,487,966	825,199.30	0	1,072,192
A16		800				LF	18.5M	0.3643	632,001.60	200,000	-154,869.70	1.11E-14	1,753,632	0	0	1,465,253
A17	920	800			137.75	LF	19.8M	1.0210	653,726.40	836,570	29,487.50	0	2,956,714	2,289,194	0	1,163,368
A18		800				LF	23.2M	1.2109	795,631.30	200,000	8,760	0	1,753,632	1,090,865	0	1,465,253

The capital investment for this most optimal project would be \$ 915,505.27 where storage contributes to 38.38% followed by solar PV at 25.58%. Diesel generator, Biomass generator and converter would make up 21.85%, 9.85% and 4.34% respectively. The operational and Maintenance costs were \$ 587,072.30 with solar PV taking the bulk of this O&M at 35.54%, storage at 28.41% followed by converter at 21.00% and Biomass generator at 15.05%. Table 4.5 shows the NPV summary of the individual components of the optimal alternative.

Table 4.5 : Cost summary of the most Optimal architecture (A1)

Component	Capital (\$)	Replacement Cost (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Diesel Gen	200,000.00	0.00	0.00	0.00	(244,191.36)	(44,191.36)
Storage	351,360.00	830,696.10	166,773.02	0.00	(231,576.45)	1,117,225.67
Bio. Gen	90,180.00	105,062.98	88,337.58	0.00	(66,910.41)	216,670.16
PV	234,218.93	0.00	208,661.42	0.00	(0.00)	192,494.35
Converter	39,746.34	46,911.62	123,300.27	0.00	(17,464.17)	192,494.06
System	915,505.27	982,643.70	587,072.30	0.00	(560,142.39)	1,925,078.88

Figure 4.4 shows the shared energy generation between solar PV and Biomass generator. The results show that solar PV generated the bulk of the power throughout the year with an annual generation of 612,535.915kWh (81.9%) as compared to annual generation by biomass generator of 135,371.185kWh (18.1%).

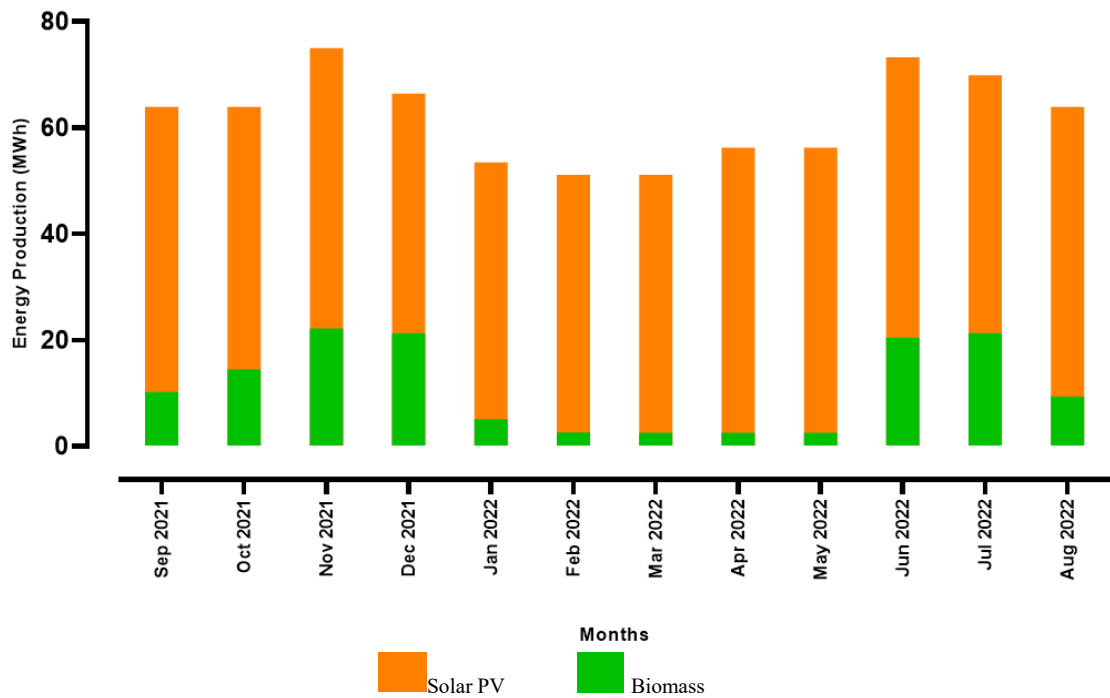


Figure 4.4: Shared energy generation between solar PV and Biomass generator

The PV and Biomass generator were considered a primary source of supplying the loads within the university due to the abundance of solar irradiation and biomass within the university. Solar PV and biomass HPS show a complementary characteristic which helps in minimizing the intermittency associated with individual renewable sources. Due to the variability of renewable energy resources throughout the year which is a design consideration for this project, there arose excess power generation which would be sent back to the grid using a net metering system. The introduction of a diesel generator in the optimization analysis provided a means of backup during extreme weather conditions as it contributed to almost 0% of the total energy generated due to the efficiency of the utilized LF dispatch strategy which declined the operating hours of the diesel generator, leading to negligible fuel consumption and limiting the GHG generation. This diesel generator behaviour concurs with a study by Elkadeem et al., (2019) where solar PV was used to generate 63.1% of total power supplied in Dongola, Sudan for rural agricultural electrification while wind generator generated only 33% and less than 1% of power demand was supplied by the diesel generator.

The availability of solar irradiation throughout the year as opposed to biomass whose bulk tends to be during academic peak moments, led to solar PV contributing to the bulk of power generation (81.9%) as opposed to biomass generator (18.1%) as depicted in Figure 4.4. Moreover, this availability of solar irradiation makes it cheaper to maximumly use solar panels to generate the bulk of power which concurs with a

study by Ghenai & Janajreh, (2016) where solar PV was used to generate 74% of total power supplied for electrification of Sharjah city, United Arab Emirates while Biomass generator generated only 26%.

From Table 4.5 on the Cost summary of the NPV of the optimal HPS, it is observed that storage constitutes the bulk of the capital invested for the project at 38.38% leading to the overall NPV of the system at \$1.93M. With the rapidly advancing technology, production of cheaper storage is expected and this will lead to reduced storage costs furthermore leading to reduced NPV and low COE.

The comparison between the optimal scenario and base case scenario (oversized diesel generator of 800 kW) reveals a high difference in NPV and LCOE due to the high maintenance costs of the diesel generator, high fuel consumption throughout the year and high GHG emission making it the least likely system to be used as the main power source for learning institutions. With the proposed project having the LCOE of \$0.1026 as compared to \$1.2109 of the base case scenario, this project will substantially lower the cost of power and with its breakeven period of 5.2 years, the project will be self-sustainable and generate profits to help the university be energy sufficient. This breakeven period is in line with studies of Chowdhury et al., (2020), where PV-B HPS yielded 7.2 years as its breakeven period.

According to Pradhan, (2017), the use of such hybrid energy system also leads to the advancement of technology within the country and in learning institutions and also improving the overall power efficiency at reduced levels of GHG emission as evidenced in this research where the optimal scenario had emissions of 150.30737 kg/yr compared to the base case which had 1,465,253 kg/yr. This finding concurs with Ayadi et al., (2020) in their research on renewable integration in smart grid, the environmental effects of fossil fuels as a result of renewable energy integration into the system were reduced and overreliance on fossil dropped as well as the creation of more jobs in the field of renewable energy development.

4.3 Sensitivity Analysis of the Hybrid Energy System

Based on inflation and irradiation factors, the sensitivity analysis established that the system was stable from a solar irradiation level of 5.904 to 6.5. An increase in solar irradiation levels from 4 to 6.5 kWhm⁻²day⁻¹ saw a reduction in the LCOE from \$0.1029471, \$0.09395795, and \$0.09271287. This is 9.94% reduction in the LCOE when the solar irradiation was at 6.5 kWhm⁻² day⁻¹ and the inflation rate at 10%.

Additionally, this saw an increment in the generated energy by 9.75% and the level of emissions was also reduced by 71.34% as bulk energy will be supplied by solar making biomass generator to only supply a small quantity of power. The capital investment and NPV also reduced by 6.67% and 9.94% respectively.

At an inflation rate of 8%, and with solar irradiation levels varying from 4 to 6.5 kWhm⁻² day⁻¹, saw an increment in the LCOE from a minimum of \$0.0927 which was realized at an inflation rate of 10% to a minimum of \$0.10797 at this discounted rate of 8%. However, at 8% of the expected inflation rate, there is an increment in the operation cost of the renewable energy system by 23.57%. With this inflation rate, the system becomes more sustainable as the diesel generator is eliminated from the system and the maximum emission produced at this level drops from 272.9243 kg/yr to 115.4709 kg/yr which is a 57.69% reduction in GHG emitted to the atmosphere. This inflation rate produced the least NPV of 1,789,013 indicating how viable the project would be with a drop in the inflation rate. The capital needed for investment during this period was also low at \$714,462.1 when compared to \$914,392.3 (21.86% reduction in investment cost) when the inflation rates were 10%. The system size was smaller in this scenario at 900kW as compared to inflation rates of 10% and 9.2% when the system size was 1700kW minimum.

However, as the inflation moves to 9.2%, the system size increases with the addition of the diesel generator. Consequently, the emissions to the atmosphere also increased beyond the levels experienced when the inflation rates were 8%. The optimal hybrid configuration was sensitive to both inflation rates and solar irradiation levels where low inflation rates and high solar insolation led to smaller energy system size with low NPV cost and smaller capital invested for the same project. Table 4.6 shows how the top two optimization results responded to the variations in solar irradiation levels and expected inflation rates.

From Figure 4.4, Solar PV constituted the bulk of the power generated, a sensitivity analysis was conducted to evaluate the impact of solar irradiation levels and variation in inflation rates on the economic, technical and sustainability parameters. With the increasing solar irradiation levels, there was a reduction in the solar PV capacity as well as the capital invested in the project i.e. more power would be drawn from the system and more batteries would be charged. Moreover, as the inflation rate increases, there is a corresponding increase in the system cost and the COE also increases. This

concur with Shahzad et al., (2017), who carried out a sensitivity analysis on PV-B for rural Pakistan where the higher the solar irradiation was, the smaller the system cost and the lower the COE.

As depicted in Table 4.6, the optimal configuration converged at an 8% inflation rate with solar irradiation of 6.5 kWh/m² /day as it had the lowest NPV making the system cost more attractive to investors due to the low capital investment required. At this inflation rate, PV-B HPS had superior economic and technical parameters compared to PV-B-DG. The exclusion of generator at this inflation rate led to a low GHG emission. The variations in inflation rates and climatic conditions have a greater impact on the system, these parameters thus need to be of key concern to renewable energy developers at the design stage.

Table 4.6: Sensitivity Analysis Results

Sensitivity Parameter		Sizes of the Individual System Architecture					Economic Parameters					Technical Parameters	Environmental Parameters	
Expected Inflation (%)	Solar Irradiation (kWhm ⁻² day ⁻¹)	Solar PV (kW)	D.Gen (kW)	B. Gen (kW)	Storage (No.)	Converter (kW)	LCOE (\$/kWh)	OC (\$/yr)	CAPEX (\$/yr)	OPEX (\$/yr)	NPV (\$)	Elec Prod (kWh/yr)	Excess Energy (kWh/yr)	CO ₂ Emissions (Kg/yr)
10	4	468.1599908	800	540	576	126.3133425	0.1029471	37579.86	981211.8	22885.3	2184269	722125.8	24954.59	272.9243
10	5.904	360	800	540	576	138.7580829	0.09395795	33709.39	914392.3	20235.84	1993543	749213.4	50336.55	86.59445
10	6.5	360.803463	800	540	576	141.693234	0.09271287	32842.21	915736.4	19948.47	1967126	792583.5	92933.16	78.21137
8	4	444.7178444		540	576	124.4000421	0.1192305	48404.47	765438.6	22795.46	1975550	708536.7	12559.96	115.4709
8	5.904	360		540	576	139.0075017	0.1093284	43880.79	714462.1	20240.63	1811482	749119	50241.77	86.53197
8	6.5	360		540	576	140.1577981	0.1079724	42969.16	714784.2	19907.93	1789013	791749.4	92132.23	78.65888
9.2	4	454.861939	800	540	576	124.3216789	0.1096056	39071.75	972010.3	22802.59	2103280	714844.5	18395.84	278.5603
9.2	5.904	360.3368172	800	540	576	141.9512247	0.1003193	34868.61	915505.3	20276.27	1925079	747907.1	49062.51	85.30737
9.2	6.5	360.8091684	800	540	576	141.6996138	0.09906077	34026.36	915741.9	19948.77	1900929	792594	92943.67	78.21135

Table 4.7: Hybrid energy alternatives System parameters considered for sustainable analysis

Hybrid Energy Systems Alternatives	Technical Parameters					Economic Parameters				Environmental Parameters			
	STC (kW)	EP (kW)	EE (kW)	UL (kW)	RF (%)	NPC (\$)	CAPEX (\$)	OC (\$/yr)	LCOE (\$/kWh)	CO ₂ (kg)	CO (kg)	SO ₂ (kg)	NO _x (kg)
PV-D. Gen-Storage-Bio Gen	1700	747,907.1	49,062.51	0	98	1.93M	915,505.3	34,868.61	0.1003	95.3	1.947	0	0.992
PV- Bio Gen -Storage	900	747,907.1	49,062.51	0	100	1.97M	715,505.3	43,302.48	0.103	85.3	0.947	0	0.592
PV-D. Gen-Storage	1409	105,4718	345,774.4	0	97.3	2.41M	1,019,070	47,966.72	0.1255	15,409	10.4	38.2	98.3
PV-Storage	902	1,534,146	825,192.2	0	100	3.06M	1,161,008	65,711.35	0.1597	0	0	0	0
PV-D. Gen-Storage-Bio Gen-Grid	2260	2,456,648	28,304.23	0	70.4	6.72M	1,552,698	178,489.7	0.1016	564994	384	1402	3604
D. Gen-Storage-Bio Gen-Grid	2260	2,906,469	12,966.9	0	60.06	8.0M	1,072,252	239,189.4	0.0976	945011	641	2345	6029
D. Gen -Bio Gen-Storage	1340	700,103.4	359.8881	0	25.69	8.3M	684,765	262,297.3	0.4314	411733	280	1022	2627
PV-D. Gen-Storage-Grid	1720	2,403,993	26,458.38	0	62.27	8.9M	1,464,565	256,212.8	0.1379	701712	475	1742	4477
D. Gen-Storage	800	712,846.3	407.5748	0	0	10.8M	595,250	351,315.9	0.5611	595710	403	1479	3800

4.4 Sustainability Analysis of the Hybrid Renewable Energy System

The sustainability result was based on four MCDM techniques to select the best of the nine alternatives. The parameters used for sustainability analysis are presented in Table 4.7.

SAW, TOPSIS, MABAC and COPRAS were used for the sustainability analysis and Table 4.8 shows the results obtained from each of the MCDM Criteria based on Sum and Vector, Maximum and Minimum, DEA. It was established that using the SAW MCDM technique, the best alternative was A3 using the sum-vector normalization, A2 using Max-Min normalization and A2 using DEA normalization. According to the TOPSIS technique, it was established that the best alternative was A3 using the sum-vector normalization, A2 using Max-Min normalization and A2 using DEA normalization. It was established that using the MABAC MCDM technique, the best alternative was A3 using the sum-vector normalization, A2 using Max-Min normalization and A2 using DEA normalization. According to the COPRAS technique, it was established that the best alternative was A2 using the sum-vector normalization, A2 using Max-Min normalization and A2 using DEA normalization.

The average rankings based on all the applied MCDM criteria is presented in Figure 4.5. It was established that A2 was the most sustainable alternative

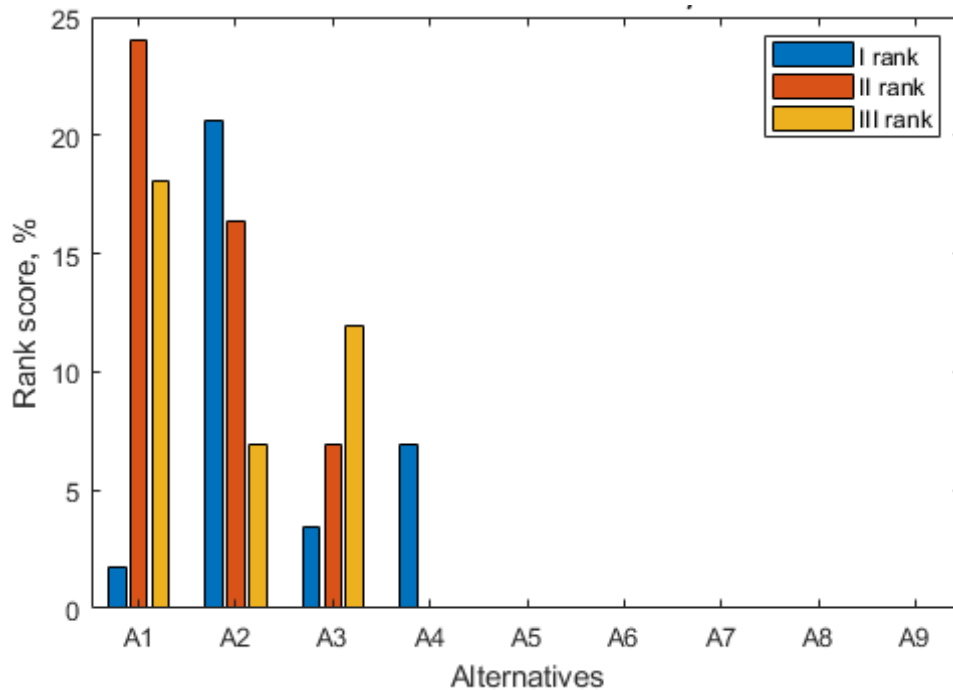


Figure 4.5: Ranking of the alternatives in sustainability analysis

Table 4.8 :Ranking of the alternatives in sustainability analysis

MCDM methods	Alternatives based on the Normalization of DM																											
	Sum and Vector									Max-Min									DEA									
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A1	A2	A3	A4	A5	A6	A7	A8	A9	A1	A2	A3	A4	A5	A6	A7	A8	A9	
SAW	3	2	1	4	7	5	8	9	6	2	1	3	4	7	5	8	9	6	2	1	3	7	5	8	9	6	4	
TOPSIS	3	2	1	4	7	5	8	9	6	2	1	3	4	7	5	8	9	6	2	1	3	4	7	5	8	9	6	
MABAC	3	2	1	4	7	5	8	9	6	2	1	3	4	7	5	8	9	6	2	1	3	7	5	8	9	6	4	
COPRAS	2	1	3	4	5	8	7	6	9	2	1	3	4	5	8	6	7	9	2	1	3	4	7	5	8	6	9	

The sustainability analysis revealed the most sustainable alternative had the following configurations:

A combination of 360kW of REC Solar325REC325PEM 72 (Solar PV), 576 Strings of lead acid- Gel Solar Cell (storage battery), a 142 kW Siemens Industry SININVERT PVS351 (converter with inbuilt inverter), and a 540kW biomass generator with HOMER Load Flow (LF) dispatch strategy at 100% renewable energy at a NPV of \$ 1.97M, Capital cost of \$ 715,505.30, LCOE of \$ 0.1026, operating costs of \$43,302.48 per year, electricity production of 74,790.1 kW and excess energy of 49,062.51kW with a potential of being sold back to the grid.

A comparison between the optimal HPS (A1) and Sustainable HPS (A2) shows a reduction of 43.24% in GHG emissions, reduced system capacity to 900kW and a 21.85% reduction in the capital expenditure for the energy system. Moreover, the renewable penetration also grew to 100% from 98% as depicted in Table 4.4. Table 4.9 presents the NPV Summary for the sustainable alternative.

Table 4.9: NPV Summary for the most sustainable alternative (Solar PV-Biomass Energy system)

Component	Capital (\$)	Replacement Cost (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
Storage	351,360.00	830,696.10	166,773.02	0.00	(231,576.45)	1117225.65
Bio. Gen	90,180.00	105,062.98	88,337.58	0.00	(66,910.41)	216,670.16
PV	234,218.93	0.00	208,661.42	0.00	(0.00)	442,880.35
Converter	39,746.34	46,911.62	123,300.27	0.00	(17,464.17)	192,494.06
System	715,505.27	982,643.70	587,072.30	0.00	(315,951.03)	1,969,270.23

Hybrid energy projects use modern technologies which promise affordable electricity costs and sustained environmental and improved social welfare of the people whose lives depend on such technological advancements. The elimination of the diesel generator from the system ensured reduced dependency on fossil fuels which contributes to GHG emissions. Moreover, it also resulted in reduced investment costs. The renewable energy penetration also increased to 100% as the system fully became dependent on PV-B HPS. This study concurs with a study by Elkadeem et al., (2019), where a sustainability analysis for techno-economic analysis for off-grid HPS (based on PV, W and DG) in Dongola, Sudan reduced the GHG emission from 351,3972 kg yr^{-1} to 168,786 kg yr^{-1} due to reduced dependency on diesel generator.

CONCLUSION AND RECOMMENDATIONS

This study presented a techno-economic analysis of renewable hybrid energy system in terms of optimization analysis, sensitivity analysis and sustainability analysis for MMUST. Different system configurations of hybrid PV-biomass units were analyzed in HOMER by simulating a dynamic hybrid model with an aim of minimizing GHG emissions, LCOE and NPC. These Hybrid configurations were assessed through sensitivity analysis using solar irradiation level and inflation rate variations.

The optimization analysis revealed that a combination of 360kW of REC Solar325REC325PEM 72 (Solar PV), 576 Strings of lead acid- Gel Solar Cell (storage battery), a 142 kW Siemens Industry SININVERT PVS351 (converter with inbuilt inverter), 800 kW diesel generator (standby supply for the hybrid system), and a 540kW biomass generator with HOMER Load Flow (LF) dispatch strategy was optimal in meeting the load demand.

The sensitivity analysis result showed that at an 8% inflation rate with solar irradiation of 6.5 kWh/m² /day the PV-B HPS had superior economic and technical parameters compared to PV-B-DG. With this sensitivity parameter at those values, it led to the exclusion of the diesel generator and consequently leading to low GHG emissions.

However, upon sustainability analysis of the optimization results, the results show that the integration of 360 kW of solar PV array, 540 kW of Biomass Generator, 142 kW converter and 576 strings of 1 kW lead-acid batteries storage bank is the most sustainable combination to run the electrical loads at the university. This hybrid system provides electricity to the consumers at LCOE of 0.1026 \$/kWh and saves about 0.1 \$/kWh when compared to the conventional grid electricity of 0.2 \$/kWh with a reduction in GHG emissions from 98.239 kg to 88.239kg when compared to the optimal scenario.

With the implementation of this HPS technology, there shall be increased renewable energy penetration as well as improved grid energy connection with a more reliable energy resource. This eventually leads to reduced reliability on the fossil-based fuels which consequently leads to a drop in the GHG emissions. With deep investment into this technology, there shall be enhanced grid stability, resilience, and energy security which fosters a sustainable future. the further use of storage technologies enables efficient utilization of the renewable energy resources amidst their fluctuating nature.

Embracing these technologies not only accelerates energy transition but also enables a paradigm shift towards a greener energy solution.

Factors considered for the development of system operational strategy were energy demand estimation; resource allocation; emissions generated by the system and comparison of economic aspects was crucial for the development of the sustainable future energy system to address the energy crisis issue and mitigate the greenhouse gas emission in Kenya.

The proposed system has been found techno-economically feasible. The study concluded that the cost of energy for a grid-connected hybrid system is higher compared to an off-grid hybrid system with similar load profiles. The techno-economic study given in this research shows that other places with similar climatic, economic and social conditions are prospective candidates for deployment of the proposed hybrid system for electricity generation.

It is recommended that for in the future, the study should be extended to other fields of energy planning, and the results should be compared with another MCDM method by using a specific normalization formula for each type of criterion. Moreover, the hybrid energy system being a reliable source of energy, the government of Kenya can play a significant role in formulating policies that boosts their uptake and to promote a reliable energy resource. Currently, the government of Kenya is supporting renewable energy through tax reductions on renewable energy resources which currently may not be sufficient for low-income populations and small institutions to uptake these technologies. To enhance rapid uptake of such technologies in learning institutions, the government may adopt incentives provisions to foster faster deployment of such renewable technologies.

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