

**MODELING AND OPTIMIZATION OF RENEWABLE ENERGY
ACCESSIBILITY IN UNDERSERVED REGIONS: A CASE OF MASHURU
AREA**

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Declaration

This research project is my original work and has not been submitted for examination to any other University.

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This research project is submitted for examination with my approval as the university supervisor.

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Dedication

To my parents, the late Hellen Nasambu Mutekhele and the late Dr. Joshua Khalaghai Mutekhele, for their exceptional achievement in teaching me to embrace the pursuit of knowledge. I am forever indebted.

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Abbreviations and Acronyms

WACC	Weighted Average Cost of Capital
LCOE	Levelized Cost of Energy
LCC	Life Cycle Costs
DRE	Decentralized Renewable Energy
KNES	Kenya National Electrification Strategy
KOSAP	Kenya Off-Grid Solar Access Project
MoE	Ministry of Energy
PV	Photovoltaics
EPRA	Energy and Petroleum Regulatory Authority
RE	Renewable Energy
REREC	Renewable Energy and Rural Electrification Corporation
GHG	Green House Gases

Definition of Terms

Energy Policy – A statement of intention in which the government addresses issues regarding the development of the energy sector (Solangi et al., 2011)

Modelling – The use of mathematical formulas and equations to represent situations in the real world. (Theo et al., 2017)

Optimization – The selection of the most effective decision, influenced by certain variables (Theo et al., 2017)

Solar Technologies – Different methods used to convert light energy to electricity such as solar photovoltaics, concentrated solar panels, solar thermal systems (Vezzoli et al., 2018)

Decentralization - Dispersing energy generation across many plants, geographically (Vezzoli et al., 2018)

Microgrid – A group of interconnected loads and distributed energy resources, mostly off-grid, ranging from 5 to 100kw that supplies electricity to a small locality, and often includes technologies like solar PV (Hirsch & Guerrero, 2018)

Solar Photovoltaic System – Converts energy from the sun using solar cells into electrical energy, through the photovoltaic effect (Vezzoli et al., 2018)

Abstract

Underserved regions have problems of inadequate access to energy. These regions are characterized by inadequate or no grid infrastructure, making it difficult to establish centralized energy systems. To address these challenges, various solutions have been undertaken such as the development of decentralized energy systems. Modeling tools are used to simulate energy systems. They, however, do not prioritize decentralized solutions. So far, less focus has been put on the evaluation of decentralized renewable energy modeling tools for promotion of access to energy in underserved regions. There is a demand for modeling tools to aid in the design of these solutions. The objective of this study is to develop, test and validate a renewable energy model that will optimize accessibility in underserved regions.

To achieve the objectives of research, this work focused on Mashuru area in Kajiado County. This area has inadequate grid infrastructure and is characterized by a population with low income and poor purchasing power. This research project targeted small-scale farmers, who use diesel pumps to provide energy for irrigation. The study proposes an optimization model for renewable energy systems consisting of photovoltaics, batteries, supercapacitors, and a diesel generator which act as back up, to provide energy for powering pumping systems. Four technologies were considered; solar PV with battery backup, solar PV with super capacitor backup, standalone solar PV system and solar PV system with a generator set backup. It is based on the selection of an optimal PV system, battery, supercapacitor, and generator capacity while minimizing the LCOE. It employed a debt-versus-equity financial model to compute the WACC used for LCOE calculations.

The study established that the total load was 1000 MWh. The optimal capacity requirements for various scenarios were; solar PV with battery backup (693.52kW), solar PV with super capacitor backup (679.71kW), standalone solar (668.45kW) and solar PV with genset backup (467.52kW). From the model results, the optimal LCOE was 8.95KES/kWh, 11.67KES/kWh, 14.47KES/kWh and 33.23KES/kWh for PV only, PV plus battery backup, PV plus supercapacitor back up and PV plus genset back up respectively. The model was validated using HOMER simulation tool to compare its performance and ascertain the correctness of the results.

Chapter 1: Introduction

1.1 Background of the Study

Energy access is an important milestone in the betterment of the quality of life of the community, education, gender equality and environmental safety (Franco et al., 2017; Socvacool & Ryan, 2016; Trotter et al., 2017). In developing countries, access to affordable energy services is necessary to eradicate energy poverty through the stimulation of economic growth and employment creation (Rawn & Louie, 2017). Governments have been trying to solve the energy access problems through the development of decentralized energy systems (Bhattacharyya, 2013; Rawn & Louie, 2017). Decentralized renewable energy is critical to increasing energy access for people living in off-grid areas. Kenya has one of the highest electricity connectivity rates in Sub-Saharan Africa, with over 70% of the country electrified. However, energy accessibility is still not optimal (Moner-Girona et al. 2019; Osiolo et al., 2017). Every household is entitled to affordable, clean, and modern energy services.

Decentralized renewable energy systems include energy generation from biomass, biogas, small hydros, wind and solar photovoltaic. However, all these sources have resource constraints except solar PV, which is abundant in most parts of the world (Franco et al., 2017; Kemeny et al. 2014; Vezzoli et al., 2018)). Some of the drivers of accessibility include policy support and various programs and projects to accelerate universal energy access such as the Kenya Off Grid Solar Access project (KOSAP)(Osiolo et al., 2017). However, KOSAP limits itself to areas with a certain number of people and a certain demand. This means many people may not benefit from the project due to low demand and highly dispersed population. Solar microgrids have been transformative for many households in Kenya and many other emerging markets, allowing them to improve their lives and move beyond kerosene lighting (Louie et al., 2015). This is specifically important as solar microgrids can serve areas with a low population density, that is, lower than 50 household/km².

Energy system planning models are developed using modelling tools that simulate the centralized energy system. This is done under different scenarios and variables such as costs, energy intensity, environmental impacts and climate targets (Conejo et al., 2016; Rawn & Louie, 2017; Trotter et al., 2017). However, these planning tools do not focus on expanding off-grid coverage (Osiolo et al., 2017; Pueyo et al., 2017). So far, these models have been developed for grid-connected solar PV. There is need for development of modelling tools that can help in design of decentralized solar PV systems. These tools can be used for comprehensive calculations and system analyses. This will assist energy planners and policymakers to plan for future demand, variable renewable energy and to determine which investments will meet these targets (Kemeny et al., 2014; Rawn & Louie, 2017). To meet the small-scale energy needs of populations in underserved regions, decentralized energy planning models are vital. They can incorporate renewable energy generation and energy storage.

Prior research on literature on development of modelling tools in underserved regions in Kenya yielded limited results. There is need for such. A model containing the technical, financial, implementation and regulatory aspects should be developed. This work attempts to develop, test,

and validate a renewable energy model that shall be used to optimize renewable energy accessibility. This shall assist in future energy policy formulation and decision-making

1.2 Problem Statement

Low energy access rate or no energy access in underserved areas remains to be a problem. For example, farmers in this areas, specifically semi-arid areas, use diesel pumps to pump water for irrigation, hence , not only do they impact the environment negatively due to the production of greenhouse gases but are also vulnerable to the fluctuating price of fuel. Energy access modelling tools are usually employed to support long-term capacity expansion planning through grid extension to off grid areas, which is cost prohibitive especially in areas with low demand and high connection costs (Lee et al., 2016; Osiolo et al., 2017). However, this does not include private models especially used to power underserved regions such as minigrids.

Presently used centralized planning models do not put into consideration the energy needs of populations in underserved regions. In these regions, the population's income is often irregular and power consumption is low, making the financial sustainability of small-scale private development projects tenuous (Rawn & Louie, 2017). There is limited Government support to small scale private models of delivery (Ockwel, 2014; Osiolo et al. 2017) . Most studies in Kenya focus on models used to analyze emissions data and evaluate impacts of greenhouse gas emissions. So far, less emphasis has been placed on the assessment of the renewable energy modelling tools used for promotion of accessibility using renewable energy in underserved regions (Rawn & Louie, 2017).

To address this issue, long-term planning strategies should include small-scale private development projects for such consumers. It is important to have models focusing on this class of consumers. This work attempts to develop, test, and validate a renewable energy model that shall be used to optimize renewable energy accessibility in underserved areas and to assist in future energy policy formulation. The study proposes an optimization model for renewable energy systems consisting of photovoltaics, batteries, supercapacitors, and a diesel generator which act as back up, to provide energy for powering pumping systems.

1.3 Research Objectives

General Objective

To model and optimize renewable energy accessibility in Mashuru area

Specific Objectives

- 1) To develop an RE optimization model for RE accessibility in underserved regions.
- 2) To test performance of RE optimization model for RE accessibility in underserved regions
- 3) To validate the developed model by comparing its performance with that of an existing model

1.4 Justification

This study is important because the results will be useful to a number of stakeholders. These include the government of Kenya, private minigrid developers, county governments, financiers, development partners, researchers, and academicians. The primary beneficiaries are rural communities, low-income households, informal settlements dwellers, isolated communities, and un-electrified communities. The secondary beneficiaries who include program implementers and decision makers are Government of Kenya, Ministry of Energy, County Governments, REREC, and Kenya's utility company, Kenya Power.

It will provide the Government of Kenya with information that will enhance the country's response to the development of solar energy projects. To help the country achieve its goal of universal access by 2030, the government has established a number of projects and programs to encourage the development of solar energy projects such as KOSAP and the Renewable Energy and Rural Electrification Corporation (REREC). In underserved counties, KOSAP seeks to make use of solar energy in place of diesel, dry cell batteries, kerosene, and other alternative fuels. REREC has entered into a partnership with the International Finance Corporation (IFC) to aid the implementation of the "Lighting Africa" initiative (KOSAP RPF, 2017). This partnership aims to improve the commercial market and thus the delivery of clean, reliable, and affordable solar energy.

In recent years, increased concern about the environmental impact of fossil fuels, such as Green House Gas (GHG) emissions, combined with government policies encouraging the use of renewable energy technologies, have fueled increased adoption of renewable energy technologies. As a result, Kenya's current policy document, Vision 2030, emphasizes the search for alternative means of providing sustainable energy to meet both the country's rural and urban development goals, for example, decentralized renewable energy. This system aligns with Vision 2030 by promoting sustainable development and enhancing energy security. A DRE produces clean energy with minimal to zero emissions and will reduce dependence on centralized fossil fuel plants and vulnerability to fluctuations in global oil prices (Solangi et al., 2011). Moreover, this system offers a cost-effective solution to off-grid communities thus enhancing energy access and fostering economic growth.

Currently, the Ministry of energy (MoE) is responsible for all energy policy formulation. The implementation and the outcome of this research topic will help to set policy direction and protect the populations in underserved regions. Academia and universities will use the information to create more knowledge and engage in further research. Private business models will have a better background for small-scale renewable energy investments.

1.5 Scope

The evaluation will focus on small-scale private models of energy delivery specifically small-scale solar energy systems as it is the most abundant. The study will attempt to develop, test and validate renewable energy models used to optimize renewable energy accessibility and suggest improvement to the models. Such improvements are hoped to assist in future energy policy formulation, for optimization of renewable energy accessibility in underserved regions. The study is limited to developing a model that will optimize renewable energy accessibility in these regions.

1.6 Limitations of the study

The study proposes an optimization model for renewable energy systems consisting of photovoltaics, batteries, supercapacitors, and a diesel generator which act as back up, to provide energy for powering pumping systems. Data was collected from only 10 farms which was found to be sufficient to give an overall energy consumption representation of Mashuru area. Mashuru is a semi-arid area with little to no rainfall most of the year. The study assumed the pump runs for 365 days, so any differences are negligible. The study did not consider variables such as derating and capacitor factors while sizing the solar PV pumping system and state of charge and depth of discharge values while determining battery capacity. The study may therefore yield slightly different result when this variables are considered. Grid connection is a possible energy source for underserved regions however it is a public resource that may be highly subsidized hence may not give accurate results in this context.

Chapter 2: Literature Review

2.1 Overview

This literature covers theories, concepts, and empirical studies about renewable energy access in underserved regions. The first section provides the concept of decentralised energy systems and its characteristics. In the second section of this chapter, concepts of modelling and simulation have been explained. The third section presents the concept of mathematical programming, and its application to decentralised energy systems. Critical review of empirical studies in decentralised energy modelling, policy issues and identification of the study gaps have been carried out in the last section.

2.2 Decentralised Renewable Energy System

Amongst the three broader objectives of energy transition, that is decentralization, decarbonisation and digitization, decentralization offers promising solutions to energy access for remote regions. In renewable energy particularly, this is a system whereby energy generation is dispersed across many smaller renewable energy plants, geographically (Vezzoli et al, 2018). Figure 2.1 illustrates an example of a decentralized renewable energy system.

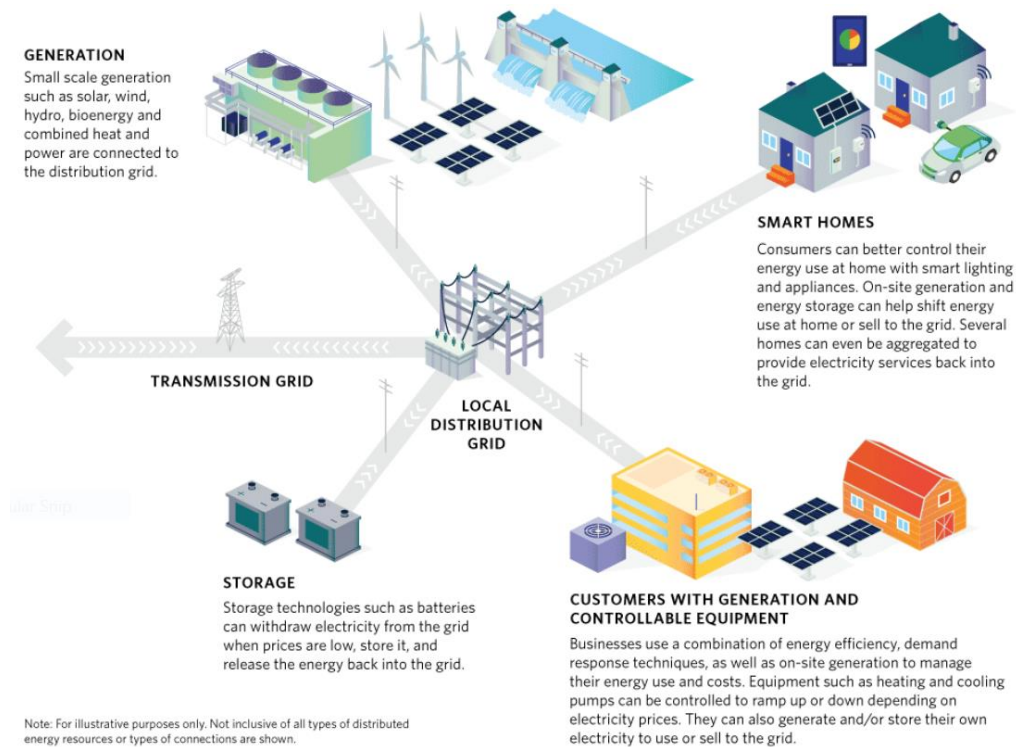


Figure 2.1 Decentralised Energy System (Source: IESO, 2018)

As presented in Figure 2.1, small scale generation entails renewable energy resources such as solar photovoltaics (PV), wind and hydro. The plants may be in the form of minigrids, microgrids or micro-hydro power plants, which is connected to a local distribution grid. This is meant to serve households, small business, and factories within a locality. Nearby systems may also be connected fostering supply reliability. These are called prosumers, who supply energy to the grid in case of shortages in generation.

The major components of a typical solar PV system are solar panels, also known as solar modules, mounting structure, inverter, charge controller and a battery bank for off-grid systems. Solar PV is a technology that converts sunlight directly into electricity through the photovoltaic effect. This is a phenomenon whereby, once an incident ray strikes the solar cells within the solar modules, it excites electrons whose movement from the valence to conduction band generates electric current. This will be in the form of a direct current (Bhatia, 2018; Boxwell, 2021). An inverter is incorporated to convert DC to AC, which is what most appliances and devices use to operate. A battery bank stores excess energy generated during the day. The flow of charge to the battery bank is regulated by a charge controller. Solar PV systems produce clean energy, reducing reliance on fossil fuels and mitigating environmental impact.

Wind energy is a technology that harnesses the power of the wind to generate electricity. It consists of a wind turbine with blades mounted on a rotor and connected to a generator. As the wind blows, the blades rotate converting the kinetic energy of the wind into mechanical energy. The generator then converts this energy to electrical energy (Burton et al., 2011; Kumar et al., 2016). Wind energy does not produce greenhouse gases or any air pollutants thus reducing environmental impact compared to fossil fuels. Hydroelectric power harnesses the energy of flowing water to generate electricity. A dam is built near rivers or other water bodies to create a reservoir of water. This water is directed towards turbines which spin, converting the kinetic energy of water into mechanical energy. These turbines are connected to generators which convert mechanical energy into electrical energy (Singh & Singal, 2017). Although hydropower is a clean source of energy, it has some disadvantages such as the distraction of habitats for aquatic life and displacement of communities living nearby.

The intermittency of solar PV and wind, however, still needs to be addressed for wider adoption of decentralized energy systems. Energy storage systems are key to dealing with the variability of these RE sources as they store energy for later use, thus balancing supply and demand. The most common type is battery storage systems, which store energy in chemical form using rechargeable batteries (Breeze, 2018). Supercapacitors store energy electrostatically and charge and discharge rapidly hence suitable for short term energy storage in RE systems (Libich et al., 2018). Gensets or generator sets are used to provide power when main source of power is unavailable. It consists of a generator and an engine, running on some fuel source such as diesel. The generator converts mechanical energy from the engine into electrical energy. Although gensets ensure continuous supply of electricity during shortages, they produce greenhouse gases and harmful air pollutants which negatively impact the environment.

2.2.1 Characteristics of a Decentralized Energy System

Decentralized systems, like any other type of energy system infrastructure, have distinct characteristics that set them apart from the traditional grid. The systems are distinguished by small-scale energy generation units that provide power to local customers. Vezzoli et al. (2018) go into great detail about these systems. According to the authors' description, these systems can operate independently or be linked to other nearby decentralized energy systems via a network to share resources or energy surplus. In essence, these systems can be self-sustaining, leaving enough room for use or production for the players.

In some cases, the users are also producers, and they are known as prosumers. They make use of renewable energy sources such as small-scale solar and wind generation units. Nguyen (2007) states that such an arrangement ensures that the systems are more reliable, and they experience less system losses as they cover a small locality. Reliability is demonstrated in a situation whereby several decentralized energy systems are interconnected such that in case of an individual failure, supply is guaranteed since each energy using node can be served by multiple energy production units.

2.2.2 Barriers to Decentralised Renewable Energy Systems

Although DREs can be useful in solving access problems, there are barriers to it. Vezzoli et al (2018) discussed some of these barriers, where they consign DREs to technical, economic, regulatory, and institutional disadvantage compared to centralized energy systems. It is critical to take these barriers under consideration and develop measures to overcome them. Technical barriers are impeding the spread of DREs. They include those associated with the system's resource, technology, and skill attributes that may hinder the energy system from attaining its full potential. These barriers are further subdivided by Yaqoot, Diwan, and Kandpal (2016) into resource availability, technology design, and operation, and maintenance.

The low-purchasing power of communities, spending priorities, unavailability of funds for development of a DRE, market structure and high energy pricing awareness and risk perception all contribute to economic barriers. Connecting low-income populations to solar PV minigrids is not profitable in many cases due to the irregular income of such populations coupled by the low energy consumption. According to Yadoo and Cruickshank (2012), economic challenges associated with donor-supported projects have led to the failure of several projects. As a result, government policies aimed at the development of DREs are critical.

Establishing a favorable institutional and regulatory framework is key to the dissemination of DREs and provide a level playing field for all electrification systems. However, ineffective government policies and inappropriate management hamper DRE progress and private sector investment. This may be through lack of incentives and institutional infrastructure for research, design, and aftersales services, lack of a regulatory framework, stakeholder and private sector participation and insufficient professional institutions (Gurung et al, 2012). There should be agencies in place to ensure the dissemination of information regarding DREs to the public.

Socio-cultural barriers include a lack of consumer awareness about the benefits and opportunities of a decentralized renewable energy system, risk perception, and behavioural or lifestyle issues. This normally occurs when local stakeholders are not involved in the planning and promotion of DREs. According to Yaqoot, Diwan and Kandpal (2016), they may also be in the form of

conservative traditions and beliefs within a particular community. They give the example of a biogas project that stalled in Indonesia because it was conflicting with local beliefs that held rice fields to be sacred and installing biogas units on them was looked down upon. These barriers will affect the dissemination of DREs in underserved regions and hamper efforts to increase renewable energy access in underserved regions.

2.3 Hybrid Energy Systems

Hybrid energy systems combine two or more energy sources or technologies to generate power and meet energy demands. They offer a more reliable and efficient energy supply (Krishna & Kujmar, 2015). Hybrid energy systems are commonly developed in off-grid locations or areas with unreliable grid connection. Decentralized solar PV systems normally employ the solar-diesel hybrid system or the battery storage hybrid system (Marqusee et al., 2021). The solar-diesel hybrid system combines solar photovoltaics modules with a diesel generator to generate electricity. Energy produced from the diesel generator acts as backup energy source when solar is unavailable. The system reduces the consumption of diesel fuel during the day which leads to significant cost-savings and the reduction of greenhouse gas emissions, thus mitigating environmental impacts.

The battery storage hybrid system combines photovoltaic modules with supercapacitors or a battery bank such as lithium-ion or lead-acid batteries. The battery or supercapacitor stores excess solar energy generated during periods of high production for use during periods of low solar irradiation or high demand. Lithium-ion batteries are commonly used due to their high energy density making them suitable for applications that require longer periods of energy release, high efficiency, and low maintenance costs. Supercapacitors have a higher power density, enabling them to charge and discharge rapidly, hence faster response time. They will be presented as storage options due to their longer life cycles (Prasad et al, 2019).

2.4 Modelling, Simulation and Optimization

Modelling refers to the use of mathematical formulas and equations to represent situations in the real world. Globally, researchers have come up with models to aid in the deployment of RE technologies to determine options that are both technically and economically sound. Simulation is the imitation of a real-life situation under different scenarios to assess its properties such as cost or environmental impacts of an energy system. Optimization is the selection of the most effective decision, influenced by certain variables. Yusta and Rojas-Zerpa (2014), state that decision criteria analysis is divided into seven sub-categories: Linear Programming (LP), Multi-Criteria Decision Making (MCDM), Multi-Objective Programming (MOP), Non- Linear Programming (NLP), Dynamic Programming (DP) and Enumerative Optimisation (EO).

Modelling and simulation have been instrumental in the domain of energy policy and issues related to energy policy. Numerous mathematical models have attempted to address issues related to the optimal design and operation of decentralized energy systems. These models use various mathematical programming techniques such as mixed-integer programming (MIP) and multi objective programming (MOP) (Liu, Georgiadis & Pistikopoulos, 2011). The models can be either

deterministic or stochastic, and the model used to solve problems is determined by the nature of the problem.

Deterministic models are predictable. Given a set of inputs, the model will produce a distinct set of outputs (Renard, Alcolea & Ginsbourger, 2013). Stochastic models have random variables as inputs and, as a result, random outputs. Model uncertainties such as energy demand, supply, unit investment cost, price, and technological parameters such as efficiency are all considered by stochastic models. Zhou et al. (2013) employ a two-stage stochastic programming model that considers both demand and supply uncertainties. The proposed distributed energy system, which includes storage and grid connectivity, has deep-seated robustness. For the best design of DREs with fluctuating energy demand and supply, the deterministic model is favored.

Optimisation models optimise a given quantity. This quantity is often associated with system operation or investment or several aspects at the same time. Many of these optimization models employ a linear programming (LP) approach to determine a level of operational activity to achieve an objective (Rader, 2010). It consists of decision variables and an objective function that is either maximized or minimized in response to a set of constraints. Sanjel and Baral's (2021) analytical model compare the life-cycle costs (LCC) of various energy systems and examines the economic distance limit (EDL) from the grid. LCC is an economic analysis of all costs incurred in the life of a technical system. The EDL assists in comparing the economic distance of decentralized energy systems with grid expansion. The LCC is normally used in conjunction with the LCOE

The Levelized Cost of Energy (LCOE) is a popular metric for determining the financial viability of energy projects (Obi et al., 2017). It is the energy price per unit of energy output at which the Net Present Value of the investment is zero over the life of a project. This allows the plant to break even. It thus represents the lifetime average cost of energy for a specific project, comparing the lifetime costs of various power generation technologies. These costs include capital costs, operations and maintenance costs, fuel costs, discount rates, and future replacement and degradation costs. According to Ouedraogo et al. (2015), while policymakers need accurate data to define the economics of energy production, financiers must evaluate proposed technology, and technology developers must focus on how they will increase competitiveness.

2.5 Empirical Review

There has been interest in optimizing the cost of energy for off-grid systems using various modeling software. Kanase-Patil et al. (2010) used LINGO to calculate the cost of off-grid systems in India. The researchers concentrated on seven unconnected villages and created four scenarios. The results showed that the system considered in scenario 4, Micro Hydropower-Biomass-Biogas-Wind-Solar Photovoltaics, was the most dependable, sustainable, and cost effective. However, this model only considers renewable energy resources for the study area on a yearly basis, ignoring the costs of the converter, local grid, and battery backup. The model also assumes that an energy system can supply 100% of the energy generated. Energy conversion and reconversion reduces system efficiency and increases system costs.

Some studies have attempted to model rural energy planning. Nerini et al. (2015) used OSeMOSYS to plan the energy of Suro Craic village in Timor Leste. The researchers modeled three scenarios using the multi-tier definition of energy access. The results showed that getting the

best tier of electrical access cost 75 times more than getting the worst tier. Low-cost choices move from standalone to mini-grid and then to grid-connected options as availability increases. Lower total expenditures resulted from switching from open fires to contemporary methods. However, the focus of this work was a solitary, remote community. The scenarios created can be impacted by broad-scale variables including economic growth, health, and transportation policies.

Efforts to solve problems involving multiple evaluation criteria, such as cost, efficiency and emissions, and social aspects, have inspired the use of Multi-Criteria Decision Making (MCDM). Deveci and Guler's (2020) two-step MOP framework for renewable energy planning in Turkey was published. The model is examined in three financial scenarios. A solution was chosen using an MCDM-based selection strategy. The results show that Turkey's 2023 targets for hydropower and biomass plants are not optimal with any renewable energy investment case. Solar PV and onshore wind energy were the most popular renewable energy sources. Because this model employs a top-down approach to RE planning, it does not consider the effects of energy services, demand, and incentives.

For decentralized energy planning, several studies have used a bottom-up approach. Hiremath et al. (2010), published a study where he used MOP to carry out decentralized energy planning in Tumkur, India. The analysis was done at the village, local council, and district levels. Their optimization problem modeled four scenarios and had seven objective functions. In comparison to other renewables, the results showed that decentralized bioenergy systems promoted more development through self-sufficiency, local employment, and land reclamation. Nonetheless, because the number of optimisation runs grows exponentially with the number of objectives, this model had high computational costs.

Connecting low-income populations to DREs is not always profitable due to their fluctuating income and low energy consumption. Phrakonkham et al. (2012) used a genetic algorithm implemented in MATLAB to design an off-grid supply for a remote village in Northern Laos. The system was optimized with a single objective function. It was subjected to static constraints on PV, hydroelectric turbine, genset characteristics, and zero Loss of Power Supply Probability (LPSP). Despite their small energy price differences, the results show that pico hydro ensures greater energy availability and reliability than micro hydro. However, this model does not consider change of weather patterns that might lead to low water levels.

Spatial mapping is being used to accelerate decentralized energy access in rural Kenya. Moner-Girona et al. (2019) created a rural electrification spatial model for Kenya to identify optimal strategies for different locations. The model estimated the population per location, calculated the LCOE based on available resources and consumption patterns, and then compared decentralized systems with grid extension. The findings suggest that a high proportion of renewables be used in remote areas, recognizing the benefits of avoiding fuel transportation costs and reducing Kenya's reliance on fossil fuel imports. According to this concept, the central grid will electrify populations within ten kilometers of the existing grid, at a lesser cost than creating off-grid systems, which is not typically the case. Moreover, it also ignores terrain barriers that prevent extensions even near existing infrastructure.

Similarly, Sanjel and Baral (2021) attempt to optimize renewable energy accessibility in Nepal. This is through a comparison between decentralized renewable-energy systems and grid expansion. The LCC and EDL were employed for modeling and analysis of electrification options. Gorkha district was chosen as the location. A techno-economic analysis is performed for various off-grid and hybrid configurations. The study concluded that grid expansion is the most cost-

effective under high-load conditions, whereas solar PV backed up by a diesel generator is the most cost-effective under low-load conditions. The study makes a lot of assumptions especially on diversity factor, connected load, transmission, and distribution losses. The researchers have also not considered the converter costs, cost of labor and transport and grid densification and intensification costs as part of O&M costs.

2.5.1 Summary of Gaps

In the reviewed literature, it has been illustrated that energy modelling is indeed a viable tool for optimization of decentralised renewable energy. As well, the analysis of the literature has shown that there is still room for improvement in the adopted or developed models. All studies have not attempted to make use of super capacitors as means of energy storage and back-up compared to battery banks and diesel generators. Although some studies have focused on the optimization of hybrid technology renewable energy applications, very few of these studies attempt to integrate technologies for the most suitable location and size for off-grid photovoltaic (PV) systems and storage. The major focus of existing studies is to lower the total cost of the hybrid system.

Although losses are critical to any energy systems performance, most of the models used have either ignored them or made assumptions on its value. Some of the models which consider micro hydropower as a source of DRE fail to consider change of weather patterns that might lead to low water levels. It has been illustrated that grid expansion is one method to improve energy access in underserved regions. Some studies, however, assume that populations within 10 kilometers of the existing grid will be electrified by the central grid at a lower cost than that of developing off-grid systems.

Terrain barriers, islands or physical obstacles that derail extensions even near existing infrastructure are ignored. A lot of assumptions are made, especially on diversity factor, connected load, transmission, and distribution losses. The researchers have also not considered the cost of labor and transport and grid densification and intensification costs as part of O&M costs. The present study therefore capitalizes on some of the gaps presented and employs improved approaches of energy modelling to optimize renewable energy access in underserved regions.

Chapter 3: Research Methodology

3.1 Introduction

The main objective of this study was to develop, test and validate a renewable energy model to optimize accessibility in underserved regions. This chapter discusses the study geographical area, tools and methods used to achieve the intended objectives. The chapter explores these areas in four sections. The first section presents the geographical study area. In the second section, the governing equations for model development have been presented and explained. The third section reviews the instruments that were used in collecting and analyzing the research methodology adopted by the study. The concept of research validation and the tool used for validity are presented in the last section.

3.2 Geographical Study Area

To achieve the objectives of research, this work focussed on Mashuru area in Kajiado County. Figure 3.1 presents a map of Mashuru, with GPS coordinates.

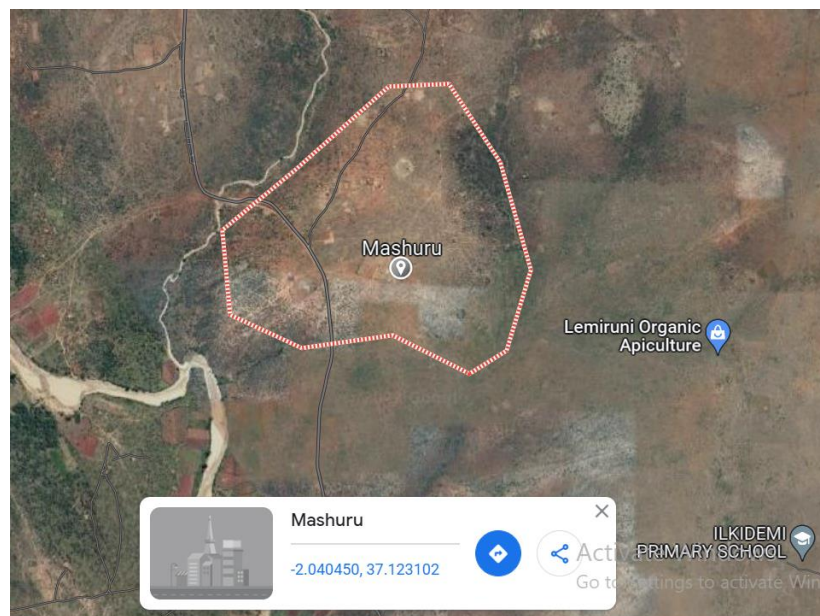


Figure 3.1 A map of Mashuru town

3.3 Governing Equations for Model Development

The study made use of the thermofluid equations to calculate the daily energy consumption. For diesel pumping systems, the consumption data analysis was computed as follows. The hydraulic pump output power (P), in kW, was computed as shown in equation (1). This is the mechanical power that the pump impeller imparted on the fluid.

$$P = \frac{\rho ghQ}{3.6 * 10^6} \quad (1)$$

Where;

ρ is the density of water (1000 kg/m³)

g is the gravitational acceleration (9.81 m/s²)

h is the total hydraulic head in meters

Q is the volume of water required per time unit (m³/h).

Due to the losses within the pump, the mechanical power, M_p , given to the pump by the motor shaft should be more than the required fluid power. Equation (2) catered for this loss.

$$M_p = \left(\frac{\rho ghQ}{3.6 * 10^6} \right) / \eta_p \quad (2)$$

Where;

η_p was the efficiency of the pump

The required electrical power, E_p , was determined as shown in equation (3).

$$E_p = \left(\frac{M_p}{\eta_m} \right) 0.8 \quad (3)$$

Where;

η_m is motor efficiency

0.8 is the loading factor

A loading factor of 0.8 was used for computation since it is a common benchmark used by many energy systems. Moreover, many energy systems achieve their highest efficiency levels at around 80% of their maximum capacity, making a loading factor of 0.8 a practical target for optimization.

The total daily energy consumption for each farm was determined together with total fuel costs. This was undertaken to determine an approximation of the expected daily energy usage. From these, the LCOE was calculated for each farm, using the equation (4). This formula was used during calculation of the LCOE of the existing diesel pumping energy system. It is different from the equation (16) which was developed according to the inputs of the developed model.

$$LCOE = \frac{C_t + \sum_{t=1}^T \frac{M_t}{(1+r)^t}}{\sum_{t=1}^T \frac{E_t}{(1+r)^t}} \quad (4)$$

Where;

- C_t represents the capital cost of the diesel pump and engine
- M_t represents annual operations and maintenance costs and fuel costs
- E_t is energy produced in year t
- r represents the discount rate
- T is the assumed lifetime of the diesel pump

The following assumptions were made;

- 1) Capital costs only included the cost of the pump and engine
- 2) Fuel consumption in liters per hour, Q , was calculated using the formula

$$Q = \frac{N * q}{R} \quad (5)$$

Where;

- N is engine power (kW)
- q is specific fuel consumption (g/kwh)
- R is fuel density (kg/m³)

- 3) The discount rate was estimated using the current inflation rate, subtracted from the current lending rate
- 4) A standard motor was used for electrical power calculation and analysis

This work considered the method used by Sanjel and Baral (2021) in modelling LCC given by

$$LCC_{PV} = \frac{C_{PV} + C_B + ((C_{PV} + C_B) \cdot \beta \cdot P(d, n)) + (C_R \cdot P(d, n_1))}{L \cdot h \cdot n} \quad (6)$$

Where

LCC_{PV} is the LCC of PV generation with battery backup

C_{PV} is the capital cost of a PV system

C_B is capital cost of battery.

β is capital-cost fraction for annual O&M.

$P(d, n)$ is the present net worth factor of annual O&M.

n is the life of the complete system in years.

d is the discount rate as a percentage

C_R is the replacement cost of a battery or super capacitor

$P(d, n_1)$ is the present net worth factor of components

n_1 is the life of replacement of components.

L is the system capacity (kW)

h is the annual operating hours.

$$LCC_{DG} = \frac{C_{DG} + ((C_{DG}) \cdot \beta \cdot P(d, n)) + (C_R \cdot P(d, n_1)) + C_{FUEL} \cdot n}{L \cdot h \cdot n} \quad (7)$$

Where

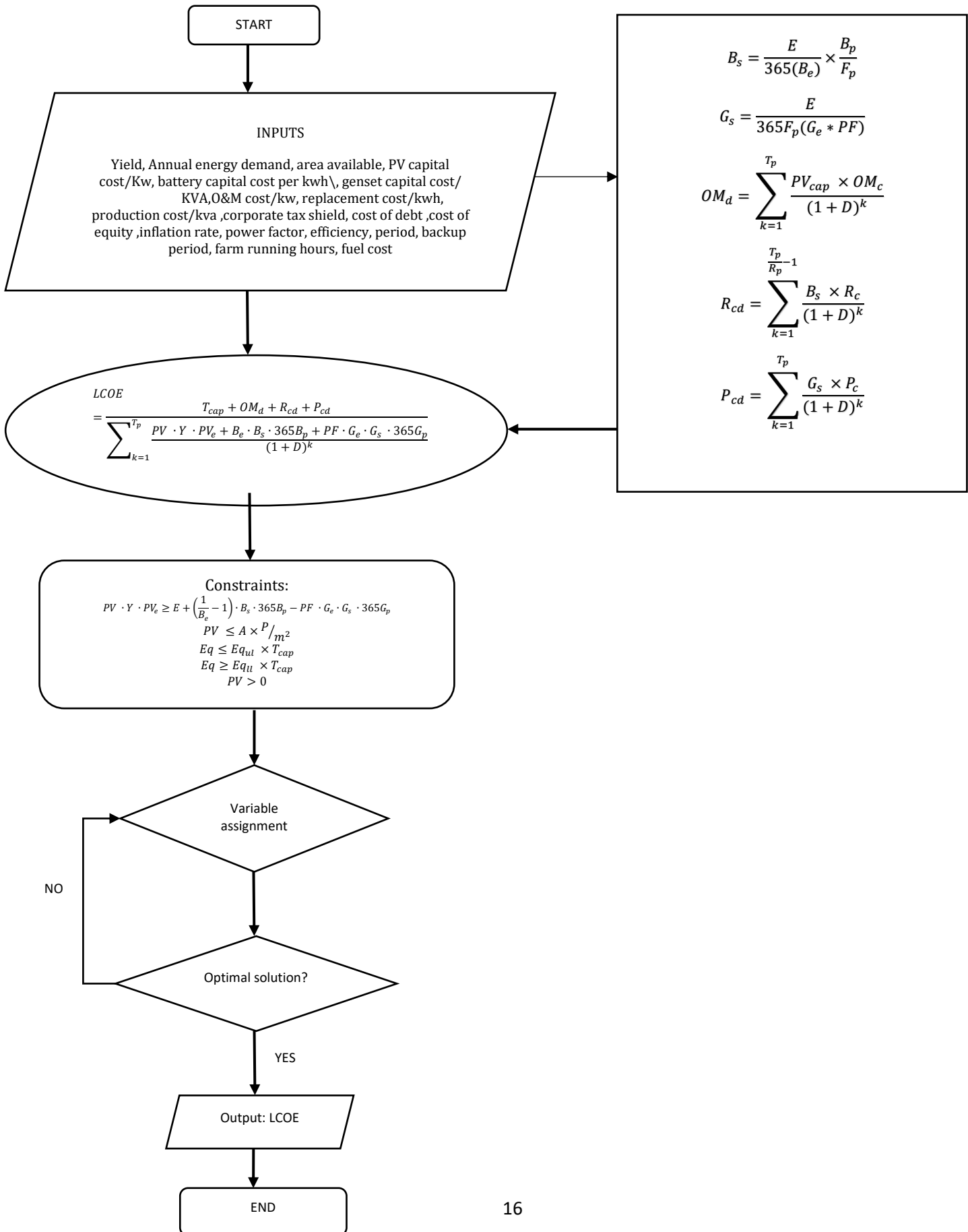
LCC_{DG} is the LCC of DG generation

C_{DG} is the capital cost of a diesel generator

C_{FUEL} is the cost of fuel annually.

The combination of equations (6) and (7) shall be the LCC calculation of a PV system backed up by a DG. The equations were adopted and modified to aid in the achievement of the objectives of this study. The study calculated the LCOE (Levelized Cost of Energy) for each energy technology considered in this research, for analysis and comparison. These are PV with battery backup, PV with super capacitor back up, standalone PV, and PV with diesel generator backup.

The application of the optimization model in this study is illustrated using the flowchart diagram.



The modified governing equations as well as the system cost analysis based on the LCOE have been presented and described in detail. This method is based on the optimal PV system size, diesel generator and energy storage capacity while minimizing the LCOE over a period of 25 years. Inputs to the model were the yield, annual energy demand, area available, power per square meter, PV Capital cost per kW, battery capital cost per kWh, genset capital cost per KVA, O&M cost per kW, replacement costs per kWh, production cost per KVA, corporate tax shield, cost of equity, cost of debt, inflation rate, assumed power factor, PV efficiency, battery or supercapacitor efficiency, genset efficiency, battery replacement period, system lifetime period, battery backup period, genset back up period, farm running period, fuel cost, equity upper and lower limit.

The model parameters were the discount rate, battery, or supercapacitor size, genset size, total capital cost, discounted O&M cost, discounted replacement cost and the discounted production cost. The model used the discounted cash flow method for analysis and computation of the LCOE. The Weighted Average Cost of Capital (WACC) was used to compute the discount rates. The WACC was determined by:

$$WACC = Eq_c * \frac{Eq}{T_{cap}} + D_c * \left(1 - \frac{Eq}{T_{cap}}\right) (1 - T_s) \quad (8)$$

Where ;

Eq_c is cost of equity

Eq is equity value

T_{cap} is total capital cost based on amount of equity and debt

D_c is cost of debt

T_s is the corporate tax shield

The discount rate, D, was given by;

$$D = WACC - I \quad (9)$$

Where I is the inflation rate.

The feasible size of battery or super capacitor, B_s, was given by:

$$B_s = \frac{E}{365(B_e)} \times \frac{B_p}{F_p} \quad (10)$$

Where

E is the annual energy demand

B_e is the efficiency of battery or supercapacitor

B_p is battery backup period

F_p is total farm running hours

The annual energy demand is divided by 365 to obtain the daily energy demand and the efficiency of the battery or supercapacitor to determine exactly how much energy can be provided by back up storage. It is multiplied by a factor of 0.3 since the backup is only for 3 hrs out of the 10 farm running hours.

The feasible size of the generator, G_s , was given by:

$$G_s = \frac{E}{365F_p(G_e * PF)} \quad (11)$$

Where

E is the annual energy demand

G_e is the efficiency of the generator

PF is the assumed power factor

F_p is total farm running hours

The annual energy demand is divided by 365 to obtain the daily energy demand in kWh. This value is divided by the farm period to get hourly demand which suggests the capacity of the genset we need in kW and the efficiency of the Genset to determine exactly how much energy can be provided by the diesel generator. The power factor aids in converting this value to KVA.

Total Capital required, T_{cap} , for the system was given by:

$$T_{cap} = PV_{cap} \cdot P + G \cdot G_s \cdot G_{cap} + B \cdot B_s \cdot B_{cap} \quad (12)$$

Where

PV_{cap} is PV capital cost per kW

P is PV power rating in kW

G represents a binary selection of whether the model should consider generator technology

G_s is genset size

G_{cap} is genset capital cost per KVA

B represents a binary selection of whether the model should consider battery technology

B_s is battery or supercapacitor size

B_{cap} is battery capital cost per kWh

This is the discounted PV O&M Cost, OM_d , was given by:

$$OM_d = \sum_{k=1}^{T_p} \frac{PV_{cap} \times OM_c}{(1 + D)^k} \quad (13)$$

Where

PV_{cap} is PV capital cost per kW

OM_c is O&M cost per kW

D is the discount rate

T_p is modelled system lifetime period

The discounted Battery or supercapacitor Replacement Cost, R_{cd} , was given by:

$$R_{cd} = \sum_{k=1}^{\frac{T_p}{R_p}-1} \frac{B_s \times R_c}{(1 + D)^k} \quad (14)$$

Where

B_s is battery or supercapacitor size

R_c is replacement cost per kWh

D is the discount rate

T_p is modelled system lifetime period

R_p is battery or supercapacitor replacement period

k is a new variable in years that increases from 1 to 4

The discounted production or Generator running Cost, P_{cd} , was given by:

$$P_{cd} = \sum_{k=1}^{T_p} \frac{G_s \times P_c}{(1 + D)^k} \quad (15)$$

Where;

G_s is generator size
 P_c is production cost per KVA
 D is the discount rate
 T_p is modelled system lifetime period
 k is a new variable in years that increases from 1 to 25

The variables to the developed model are the optimal PV system power rating and the optimal equity value. There are four constraints;

1) Demand Constraint

The power generated must fulfill the farms demand.

$$PV \cdot Y \cdot PV_e \geq E + \left(\frac{1}{B_e} - 1 \right) \cdot B_s \cdot 365B_p - PF \cdot G_e \cdot G_s \cdot 365G_p$$

Where

PV is PV system power rating in kW
 Y is the yield of the area
 PV_e is the efficiency of the PV system
 E is annual energy demand
 B_e is the battery or supercapacitor efficiency
 B_p is battery or supercapacitor backup period
 PF is assumed power factor
 G_e is the genset efficiency
 G_s is genset size
 G_p is genset backup period

The total annual energy generated by the PV array is calculated by getting the product of the PV capacity in kw, the annual PV yield of the location and the PV efficiency. This annual energy generated should be sufficient for the farms demand and annual storage losses, less the annual generator compensation.

2) Area Constraint

There must be enough area, A , to accommodate the optimal PV system

$$PV \leq A \times P/m^2$$

Where;

PV is PV system power rating in kW

Y is the yield of the area

P/m² is the average power rating PV that can be installed in one square meter area

3) Equity Constraint

Equity value, Eq, must not exceed the specified fraction of the total Capital Cost:

$$Eq \leq Eq_{ul} \times T_{cap}$$

Equity value, Eq, must not be less than the specified fraction of the total Capital Cost:

$$Eq \geq Eq_{ll} \times T_{cap}$$

Where;

Eq_{ul} is equity upper limit, which is the maximum value of equity allowable

Eq_{ll} is equity lower limit which is the minimum value of equity allowable

T_{cap} is total capital cost

4) PV system size constraint

The PV system must be used.

$$PV > 0$$

Computation of the LCOE of our modelled energy system was given by:

$$LCOE = \frac{T_{cap} + OM_d + R_{cd} + P_{cd}}{\sum_{k=1}^{T_p} \frac{PV \cdot Y \cdot PV_e + B_e \cdot B_s \cdot 365B_p + PF \cdot G_e \cdot G_s \cdot 365G_p}{(1 + D)^k}} \quad (16)$$

Where;

T_{cap} is total capital cost

OM_d is discounted O&M cost

R_{cd} is discounted battery or supercapacitor cost

P_{cd} is discount production costs

PV is the PV system power rating

Y is the yield of the area

PV_e is the efficiency of the PV system

B_e is the efficiency of the battery or supercapacitor

B_s is battery or supercapacitor size

B_p is battery or supercapacitor back up period
 PF is assumed power factor
 G_e is the genset efficiency
 G_s is genset size
 G_p is genset backup period
 D is the discount rate
 k is a new variable in years that increases from 1 to 25
 T_p is the modelled system lifetime period

The LCOE is given by the total capital costs plus discounted operation costs (O&M, replacement, and production) divided by the discounted energy generated in kwh from all the technologies in use, considering all the system losses.

With only PV

$$LCOE = \frac{T_{cap} + OM_d}{\sum_{k=1}^{T_p} \frac{PV \cdot Y \cdot PV_e}{(1 + D)^k}} \quad (16.1)$$

With PV and Battery or Super Capacitor

$$LCOE = \frac{T_{cap} + OM_d + R_{cd}}{\sum_{k=1}^{T_p} \frac{PV \cdot Y \cdot PV_e + B_e \cdot B_s \cdot 365B_p}{(1 + D)^k}} \quad (16.2)$$

With PV and Genset

$$LCOE = \frac{T_{cap} + OM_d + P_{cd}}{\sum_{k=1}^{T_p} \frac{PV \cdot Y \cdot PV_e + PF \cdot G_e \cdot G_s \cdot 365G_p}{(1 + D)^k}} \quad (16.3)$$

3.4 Data Collection

To establish the demand and energy consumption, site visits to Mashuru town was carried out. The study randomly sampled 10 farms in Mashuru area currently using diesel pumps to provide energy for pumping water for irrigation. Data regarding the pump and diesel engine models was collected from site and from equipment datasheets online. The data was obtained using a printed copy of a questionnaire which was physically presented to the respondents. The study focused only on farmers currently using diesel pumps to provide water for irrigation, keeping in mind that Mashuru is a semi-arid area with most of the year experiencing little rainfall. The data contained specifications on the pump and diesel engine including the pump model, head, flow rate, pump efficiency, engine model, power, specific fuel consumption and run hours.

This work collected data to determine development costs for solar PV systems including panels, mounting structure, inverters, battery, super capacitor costs, cable connections, operations and maintenance and labour costs. This data was obtained from the internet. The data was also collected from PV panel installers, manufacturers, and expert engineers in the field. This study sampled 4 PV panel installers, 3 PV manufacturers and 3 expert engineers. The study focused on PV plus back up using batteries, PV plus back up using super capacitors, and PV plus back up using diesel generators (DG).

3.5 Research Validity

The model was coded and executed in excel and tested and validated using the HOMER (Hybrid Optimization Model for Electric Renewables) simulation tool, to ensure the correctness of the results. Homer aids in determining optimal system configurations suitable for renewable energy accessibility in underserved regions. This was done by modelling its performance through a techno-economic analysis. An energy system composed of PV modules, battery, an AC-DC converter and a generator were designed in Homer to simulate a real energy system.

The study location, Mashuru was input in the embedded Homer global solar resource map. The daily energy consumption for Mashuru area, was input into the system, a commercial profile selection was done followed by the adjustment of component prices. While these technologies work together in Homer to optimize the system, the battery or supercapacitor and diesel generator were designed to supplement the PV output separately to meet the demand in the developed model. The study compared the findings in the developed model to those obtained in Homer.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter presents performance testing results from the developed model. The chapter is organized into three sections. The first section presents energy consumption results of the farms, the total capital costs and total fuel costs for each farm, and LCOE calculation for each farm. The second section presents the performance of the optimization model using energy consumption data obtained from the farms and the costs obtained for each energy technology used to design the model. The model is validated in the third section. A comparison of the model with the homer simulation tool was also carried out and has been presented and discussed.

4.2 Load Demand Analysis

Table 4.1 shows the data regarding pump specifications from the 10 farms, the hydraulic power, motor rated power, electrical power, and daily energy consumption for each farm.

Table 4.1 Pump specifications for each farm

Farm	A	B	C	D	E	F	G	H	I	J
Pump Model	80BPZ-100	80BPZ-120	80BPZ-100	80BPZ-240	0BPZ-100	80BPZ-100	80BPZ-65	80BPZ-100	80BPZ-40	80BPZ-100
Head (m)	100	120	100	100	100	100	65	100	40	100
Suction (m)	7	7	7	9	7	7	6.5	7	6.5	7
Inlet and Outlet diameter (cm)	7.62	7.62	7.62	7.62	7.62	7.62	7.62	7.62	7.62	7.62
Pump Power (kW)	15	20	15	15.5	22	15	15	15	8.44	15
Pump Flow Rate (m ³ /hr)	80	85	80	48	80	80	48	80	48	80
Speed rpm	2600	2900	2600	2600	2900	2600	2900	2600	2900	2600
Efficiency	58%	51%	58%	59%	58%	58%	58%	58%	62%	58%
Hydraulic pump power output (kW)	21.8	27.795	21.8	13.08	21.8	21.8	8.502	21.8	5.232	21.8
Motor rated power (kW)	37.59	54.50	37.59	22.17	37.59	37.59	14.66	37.59	8.44	37.59
Computed Electrical Power (kW)	33.79	48.99	33.79	19.93	33.79	33.79	13.18	33.79	7.59	33.79
Run hrs	10	10	10	10	10	10	10	10	10	10
Daily Energy Consumption (kwh)	337.85	489.89	337.85	199.28	337.85	337.85	131.76	337.85	75.85	337.85
Total Daily Energy Consumption (KWh)						2923.90				

The values were substituted in equation (3) to get electrical energy consumption. For example, the energy for Farm A was computed as follows

To obtain the hydraulic power, values were substituted in equation (1)

$$\text{Hydraulic Power} = \frac{1000 \text{ kg/m}^3 \cdot 9.81 \text{ m/s}^2 \cdot 100\text{m} \cdot 80\text{m}^3/\text{h}}{3.6 * 10^6}$$

$$\text{Hydraulic Power} = 21.8\text{kW}$$

Equation (2) was used to obtain the motor rated power. Efficiency of the pump was 58%

$$\text{Motor Rated Power} = \frac{21.8}{0.58}$$

$$\text{Motor Rated Power} = 37.59\text{kW}$$

The electrical power output was computed using equation (3). The efficiency of the standard motor within the engine was 89%, with a load factor of 0.8. The farms run for 10 hours daily.

$$\text{Electrical Power} = \frac{21.8 \cdot 0.8 \cdot}{0.89}$$

$$\text{Electrical Power} = 33.79\text{kW}$$

$$\text{Daily Energy Consumption, } Ep = \frac{21.8 \cdot 0.8 \cdot 10}{0.89}$$

$$\text{Daily Energy Consumption} = 337.85\text{kWh}$$

The same computation was done to all the other farms and the total energy required was 2923.9 kWh.

Table 4.2 shows the data regarding engine specifications from the 10 farms, the specific fuel consumption (g/kwh), fuel consumption (liters/hour) and the cost of fuel per day for each farm. The table also contains the capital costs for pump and engine.

Table 4.2 Engine specifications for each farm

Farm	A	B	C	D	E	F	G	H	I	J
Engine Model	JD1110P	JD1110P	JD1130P	ZH111WP	JD1115P	JD1110P	JD1130P	JD1110P	JD1115P	ZS1115G
Engine Power (kW)	16.41	16.41	22.38	17.90	17.90	16.41	22.38	16.41	14.92	14.2
Specific fuel consumption (g/kWh)	242	242	242	270	242	242	242	242	242	238
Fuel consumption (L/h)	4.673	4.673	6.372	5.687	5.097	4.673	6.372	4.673	4.248	3.969
Run hrs	10	10	10	10	10	10	10	10	10	10
Usage per day (litres)	46.73	46.73	63.72	56.87	50.97	46.73	63.72	46.73	42.48	39.69
Cost of Fuel per day	9,600.78	9,600.78	13,091.97	11,685.39	10,473.57	9,600.78	13,091.97	9,600.78	8,727.98	8,154.53
Capital Costs	117,000.00	137,000.00	187,000.00	152,260.00	120,000.00	148,000.00	202,000.00	145,000.00	156,000.00	238,000.00
Total Capital Costs	1,602,260.00									
Total fuel costs per day	103,628.52									

These values were substituted in equation (5) to get the total fuel costs. The cost of fuel per liter was KES 205.47 and diesel fuel density is 850kg/m³. For example, the total fuel costs for farm A was computed as follows

To get fuel consumption, Q, in liters, we had

$$\text{Fuel Consumption} = \frac{16.41\text{kW} \cdot 242\text{g/kwh}}{850\text{kg/m}^3}$$

$$\text{Fuel Consumption} = 4.673\text{litres/hour}$$

To obtain the cost of fuel per day, we had

$$\text{Cost of fuel per day} = 4.673\text{litres} \cdot 10 \cdot 205.47$$

$$\text{Cost of fuel per day} = \text{Ksh } 9600.78$$

The same computation was done to all the other farms and the total fuel costs per day was ksh 103,628.52

The LCOE was calculated separately for each of the 10 farms using equation 4. To determine the LCOE for farm A, the following assumptions were made;

- 1) The life of the system was 12 years
- 2) The cost of fuel per liter was KES 205.47
- 3) The discount rate used was 5.5%. . The discount rate was estimated using the current inflation rate, of 7.5% subtracted from the current lending rate of 13%.
- 4) The O&M costs was 1.5% of the capital cost, C_t
- 5) Mashuru being a semi-arid area, the pump ran for 365 days
- 6) A standard motor was used for electrical power calculation and analysis hence the motor efficiency was taken as 89%
- 7) The loading factor was 0.8

Hence, annual O&M and fuel costs, M_t , and energy produced annually, E_t were calculated as follows

$$M_t = (0.015 \cdot 117000) + (365 \cdot 205.47 \cdot 10 \cdot 4.673)$$

$$E_t = 337.85 \cdot 365 \cdot 10$$

Substituting the values in equation (4), the LCOE for farm A was computed as follows

$$LCOE = \frac{117,000 + \sum_{t=1}^{12} \frac{1755 + 3,504,283.5}{(1 + 0.055)^t}}{\sum_{t=1}^{12} \frac{123,316.54}{(1 + 0.055r)^t}}$$

Table 4.3 Economic Modelling Data and LCOE Calculation for farm A

Economic Modelling Data							
Discount rate	System lifetime	O&M Cost		Fuel Cost (ksh/liter)			
5.5%	12 years	1.5% of initial cost		205.47			
LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	1,663.51		1	3,321,595.74		1	116,887.72
2	1,576.78		2	3,148,431.98		2	110,794.05
3	1,494.58		3	2,984,295.71		3	105,018.05
4	1,416.67		4	2,828,716.32		4	99,543.18
5	1,342.81		5	2,681,247.69		5	94,353.72
6	1,272.81		6	2,541,467.01		6	89,434.81
7	1,206.45		7	2,408,973.47		7	84,772.33
8	1,143.56		8	2,283,387.17		8	80,352.92
9	1,083.94		9	2,164,348.03		9	76,163.91
10	1,027.43		10	2,051,514.72		10	72,193.28
11	973.87		11	1,944,563.72		11	68,429.65
12	923.10		12	1,843,188.36		12	64,862.22
Sum of O&M PVs	15,125.50		Sum of FUEL PVs	30,201,729.90		Sum of Et PVs	1,062,805.84
Capital Cost	117,000.00						
Sum of PV O&M, Fuel plus Ct	30,333,855.40					Sum of Et PVS	1,062,805.84
	LCOE	28.54				KES/kWh	

LCOE for farm A = 28.54 Ksh/kW

Figure 4.1 shows how LCOE compares among the 10 farms and average LCOE of all 10 farms using the existing diesel energy pumping system.

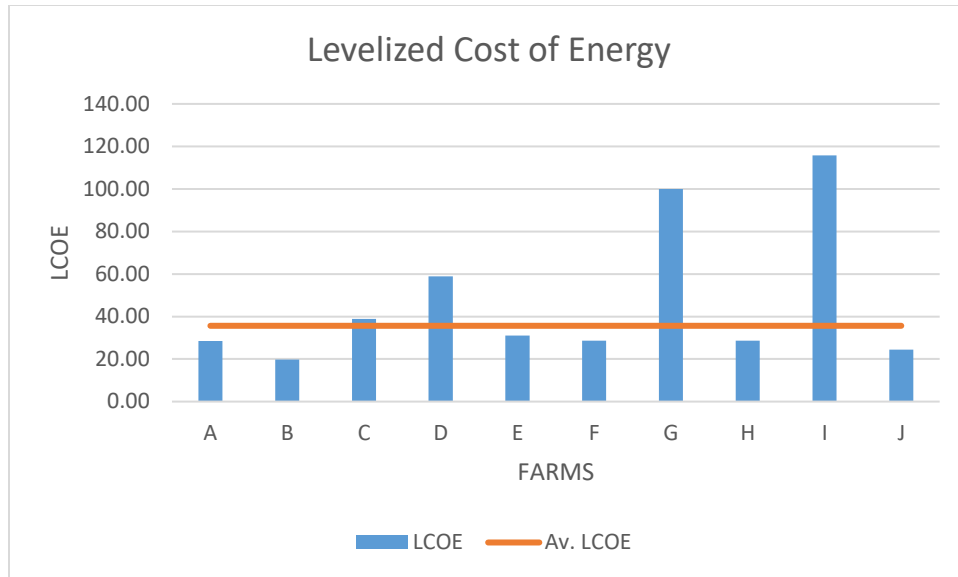


Figure 4.1 Graph of LCOE against each farm and overall LCOE

From the results shown in figure 4.1, statistical analysis was computed and demonstrated in table 4.4.

Table 4.4 Summary of LCOE Data

<i>Summary of Data</i>	
Mean	47.45
Standard Error	10.68
Median	29.85
Standard Deviation	33.77
Sample Variance	1140.71
Range	96.10
Minimum	19.70
Maximum	115.80

Out of all the 10 farms, farm C, D,G and I were found to have a higher LCOE compared to the rest, although they are in the same environment. One of the reasons for this difference can be attributed to variations in production. Some farms are larger than others and engage in the production of a wider variety of agricultural products, while others are smaller and plant just one or two different crops. The larger farms would therefore use more water and require larger systems which cost more.

Bigger systems are expected to have better efficiency, however, this is not always the case. Oversizing or undersizing a system will impact their performance, efficiency and cost effectiveness as the engine or pump capacity selected is larger than necessary for irrigation purpose (Kumar et al.,2020). Furthermore, operating a pump at or near its maximum capacity disrupts its efficiency. Villars (2019) states that the best efficiency point (BEP) is the ideal operating efficiency

for the pump at which the maximum percentage of energy used to operate the pump is being transferred to the water. Once this point is shifted, the efficiency decreases requiring more power to be used by the pump leading to wastage and losses in terms of heat and vibration. This will contribute to a less sustainable and efficient system.

Irrigation diesel pumps have a pump-engine arrangement. The difference in the LCOE can be due to a mismatch in systems, where the engine used to drive the pump is not ideal for the operation of the pump. For example, a larger engine driving a smaller pump can result in poor fuel efficiency and wastage of energy as the engine converts fuel energy into mechanical energy which is then transferred to the pump. A mismatch in sizes also reduces the system’s ability to control the flow rate, which is critical to the hydraulic pump power output (Kumar et al., 2020). Larger systems also tend to have very high upfront costs in terms of purchase, installation, and maintenance. Since most of the farms pump directly from the nearby river, those farther away from the river incur higher costs with regards to piping.

Load variations is also crucial for selecting appropriately sized systems. Underloading of a pump system translated to operating a pump at a capacity that is significantly lower than its rated capacity. This means a lower flow rate, reduced efficiency, and higher energy usage (Kini & Bansal, 2009; Fatigati et al., 2021). Proper sizing ensures that the system operates optimally, improving efficiency and the lifespan of the system and reducing costs. This can be done using an optimization tool to verify that the proposed equipment will operate as expected based on the design, and therefore optimize the systems performance.

4.3 Solar PV Design

Data used for solar PV design is presented in Table 4.5. It shows the monthly averages of solar irradiance (direct normal irradiation) obtained from global solar atlas.

Table 4.5 Monthly averages of solar irradiance DNI in kWh/m²

Month	DNI (kWh/m ²)
Jan	188.1
Feb	168.7
Mar	169.3
Apr	124.4
May	101.5
Jun	78.6
Jul	79.6
Aug	87.5
Sep	124.5
Oct	140.8
Nov	131.1
Dec	163
Mean	129.76
Standard deviation	37.52
Yearly	1557.1

Highest energy consumption is expected in January since it is the hottest month with little to no rainfall.

Table 4.6 shows hourly solar irradiance for the month of January. The farms run for 10 hours between 7am and 5pm. From table 4.6, PV output is only able to supply between 8am and 3pm when solar irradiance is maximum, meaning the system needs a backup option for about 3hrs. This backup period was used during model development.

Table 4.6 Hourly Solar Irradiance in kWh/m² for the month of January

Time (hrs)	Irradiance (kWh/m²)
0 - 1	0
1 - 2	0
2 - 3	0
3 - 4	0
4 - 5	0
5 - 6	2
6 - 7	217
7 - 8	417
8 - 9	557
9 - 10	650
10 - 11	692
11 - 12	694
12 - 13	651
13 - 14	611
14 - 15	566
15 - 16	516
16 - 17	419
17 - 18	76
18 - 19	0
19 - 20	0
20 - 21	0
21 - 22	0
22 - 23	0
23 - 24	0
Total	6068

4.4 Model Development

This method is based on the optimal PV system, diesel generator and energy storage capacity while minimizing the LCOE over a period of 25 years. Figure 4.2 shows the developed optimization model.

Inputs		Parameters	
Farm Location	Kajiado	Discount rate	2.92%
Yield	1700.00 kWh/kWp	Battery/ Super Capacitor Size	0.00 kWh
Annual Energy Demand	1,000,000.00 kWh	Genset Size	381.00 kVA
Area Available	20,000.00 sq.M	Total Capital Cost	KES. 95,300,913.41
Power per Square Metre	0.13 kW/sq.M	Discounted O&M Cost	KES. 21,961,802.53
PV Capital Cost per kW	KES.171,245.00 /kW	Discounted Replacement Cost	KES. -
Battery Capital Cost per kWh	KES.7,000.00 /kWh	Discounted Production Cost	KES. 451,095,294.63
Genset Capital Cost per kVA	KES.40,000.00 /kVA		
O&M Cost per kW	KES.2,673.68 /kW	Variables	
Replacement Cost per kWh	KES.7,000.00 /kWh	PV Array Power Rating	467.52 kW
Production Cost per kVA	KES.184.50 /kVA	Equity Value	KES. 19,060,182.68
Corporate Tax Shield	30%		
Cost of Equity	20%	Constaints	
Cost of Debt	12%	PV energy*Efficiency >= Demand	467.52
Inflation Rate	8%	PV Power <= Area*Power per sq.M	2500.00
Battery/ Super Capacitor	0	Equity < 0.3*Total Capital	30%
Genset	1	P > 0	1.00
Assumed PF	80%		
PV Efficiency	88%	Objective	
Battery/SuperCapacitor Efficiency	90%	LCOE	KES. 24.87
Genset Efficiency	90%		
Battery Replace Period	5 Years		
Period	25 Years		
Battery Backup Period	3 Hours		
Genset Backup Period	3 Hours		
Farm Running Period	10 Hours		
Fuel Cost	KES. 205.00		




Figure 4.2 Developed Optimization Model

Cost of the module had offers ranging from 150,000KES/KWp to 200,000KES/kWp from selected distributors. This included the cost of converters, mounting structure, wiring and labour. The cost per kWh for each energy storage had offers ranging from 12,000 KES/kWh to 20,000KES/kWh, for lithium-ion batteries and supercapacitors, respectively. The capital cost for the generator set varied from 20,000 KES to 45,000 KES per KVA. The yield for Mashuru, Kajiado is 1700kWh/kWp .

The model used the discounted cash flow method for analysis and computation of the LCOE. The Weighted Average Cost of Capital (WACC) was used to compute the discount rates. The annual energy demand from the data collected was 1,067,223.5kWh. This was approximated to 1,000,000 kWh in the model. During model development, the following assumptions were held;

- 1) Area available for PV module installation is 20,000m²
- 2) Power generated per m² is 0.125Kw
- 3) O&M cost is 1.5% of the PV/Battery/Supercapacitor/Genset capital cost
- 4) Working value for cost of debt, cost of equity and corporate tax shield is 12%, 20% and 30% respectively

4.4.1 Levelized Cost of Energy (LCOE)

In this method, the capital cost, as well as the lifecycle cost, which includes operation, maintenance, and replacement expenditures during the power resource's lifetime, were calculated considering a discount rate computed from the model, based on the financial model used and inflation rate. The LCOE was calculated in KES/kWh.

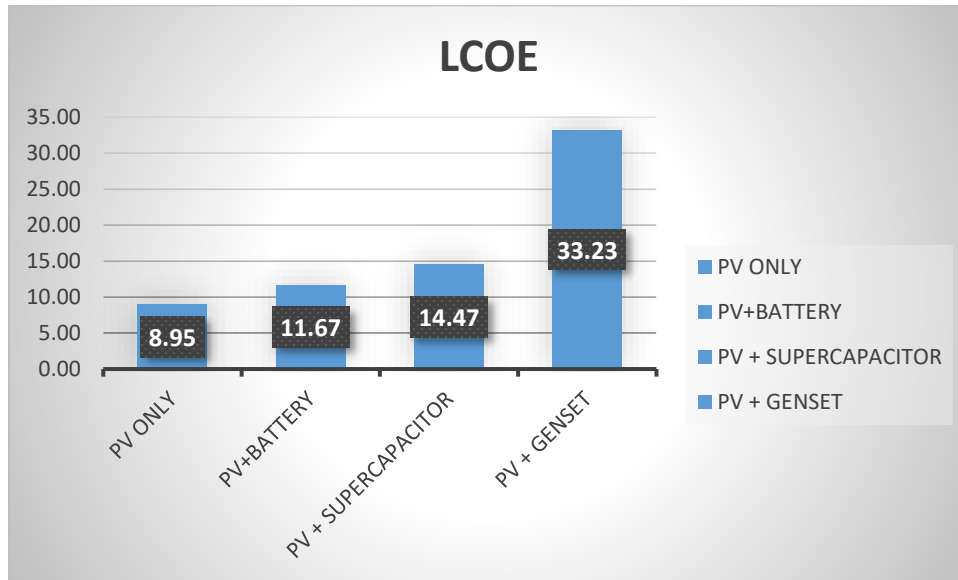


Figure 4.3 LCOE of each energy technology computed from the developed model

The model considered four different energy technologies; PV only, PV with battery backup, PV with supercapacitor backup and PV with genset back up. Among the different sources for electricity generation, the PV only technology had the lowest value of LCOE. The principle of load shifting was used, whereby instead of having back up storage, the PV system size was increased to cover the 3 hours when there is no PV output. According to an article done by Beatriz Santos (April 14, 2023) the LCOE of community, commercial and industrial solar ranges between 0.049 USD/kWh and 0.185 USD/kWh. Using a conversion rate of KES 160, the value ranges between 7.84 KES/kWh and 29.6KES/kWh. From the model, the PV only LCOE of 8.95KES/kWh was within the range mentioned.

The difference in the LCOE can be attributed to factors such as the geographical location, solar resource, project scale and financing models used. Kenya is located at the equator hence the solar resources is abundant in the country, specifically in Mashuru area where pumped water is needed for irrigation during the dry season. This being a community project targeting small-scale farmers, the energy required, and upfront and operating costs required are much smaller compared to larger projects, thus affecting the LCOE. The LCOE takes into account various financial parameters hence the financial model can impact the LCOE. The developed model makes use of debt versus equity ratio to finance the projected thus influencing the WACC, which directly impacts the LCOE.

The PV with genset backup technology had the highest LCOE at 33.23KES/kWh, which is still within market ranges but uneconomical. When compared to the other technologies, this technology, however, has the lowest capital costs as it only requires a diesel engine which normally has a short installation time. Furthermore, most diesel generators have a lifespan of approximately 30 years, almost as long as the lifespan of PV systems hence no replacement costs are incurred. However, the production costs for this technology were significantly high. High engine maintenance costs and high fuel price makes its operational costs very high, resulting in a higher value for LCOE and increased greenhouse gas emissions. Apart from the fact that it has no fuel costs, the PV only technology has little to no maintenance apart from solar panel cleaning.

Figure 4.4 shows the total capital costs for each technology

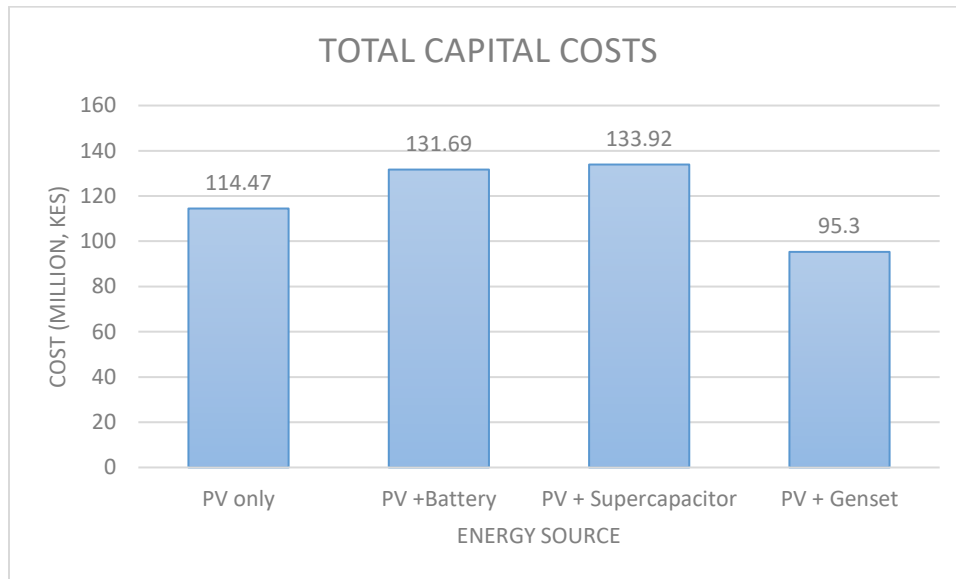


Figure 4.4 Total Capital Costs for each energy technology

Although the PV and battery and PV and supercapacitor backup technology have a very slight difference, supercapacitors are about 30% more expensive than batteries due to their higher efficiencies and higher charge-discharge cycles (Huang et al., 2019). Table 4.7, 4.9 and 4.11 illustrate how the LCOE changes with varied cost of debt, cost of equity and corporate tax shield respectively. This is the real discount rate computed from equation (2), where the inflation rate of 7.5% was subtracted from the computed WACC.

Table 4.7 Varied Cost of Debt against Discount and LCOE

COST OF DEBT	PV+BATTERY		PV+SUPERCAPACITOR		PV+GENSET		PV ONLY	
	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE
12	3.26	11.67	4.38	14.47	4.17	33.23	3.62	8.95
16	5.49	14.06	6.34	16.94	6.18	34.61	5.76	10.67
20	7.72	16.67	8.3	19.55	8.19	36.1	7.91	12.56
24	9.95	19.43	10.26	22.29	10.2	37.69	10.05	14.58
28	12.18	22.31	12.22	25.11	12.21	39.35	12.19	16.71

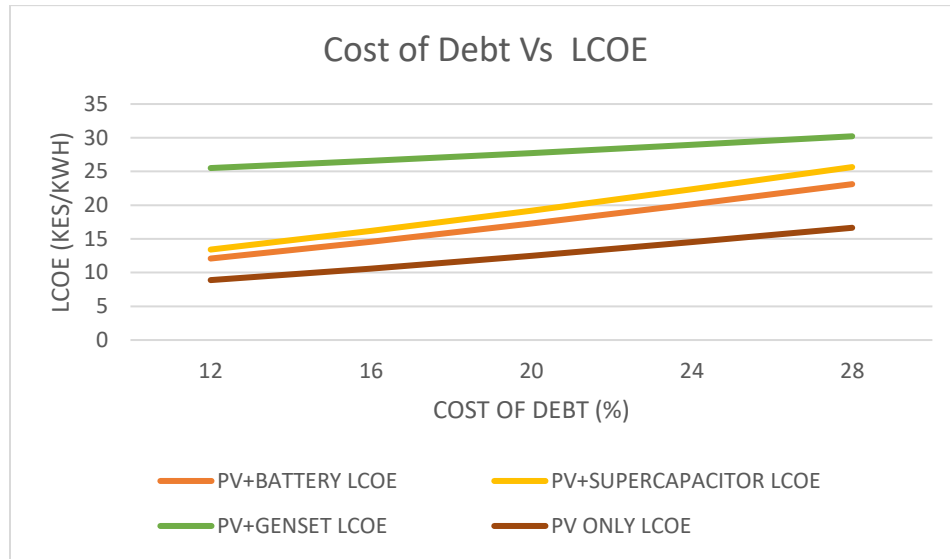


Figure 4.5 Cost of Debt Vs LCOE

Table 4.8 Change in LCOE as Cost of Debt increases

		PV+BATTERY	PV+SUPERCAPACITOR	PV+GENSET	PV ONLY
COST OF DEBT		LCOE	LCOE	LCOE	LCOE
	12	11.67	14.47	33.23	8.95
	24	19.43	22.29	37.69	14.58
% VARIATION		66.50	54.04	13.42	62.91

Table 4.8 demonstrates the change in LCOE when the cost of debt is doubled. There is a significant difference between the LCOE of these technologies as the rates increases except for the PV plus genset backup. This can be attributed to its lower capital costs compared to the other three technologies. Moreover, when the cost of debt is doubled, the discounted production costs reduce by about 75% compared to the others. For example, the discounted replacement costs for PV plus battery backup technology reduces by only 14%. These means the total present value of costs remain relatively higher resulting in a higher LCOE.

Table 4.9 Varied Cost of Equity against Discount and LCOE

COST OF EQUITY	PV+BATTERY		PV+SUPERCAPACITOR		PV+GENSET		PV ONLY	
	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE
20	3.26	11.67	4.38	14.47	4.17	33.23	3.62	8.95
22	3.67	12.09	4.98	15.21	4.73	33.6	4.09	9.31
24	4.08	12.52	5.58	15.96	5.29	33.99	4.56	9.68
26	4.49	12.95	6.18	16.73	5.86	34.38	5.03	10.06
28	4.9	13.4	6.78	17.51	6.42	34.78	5.5	10.45
30	5.3	13.85	7.38	18.31	6.98	35.19	5.97	10.84

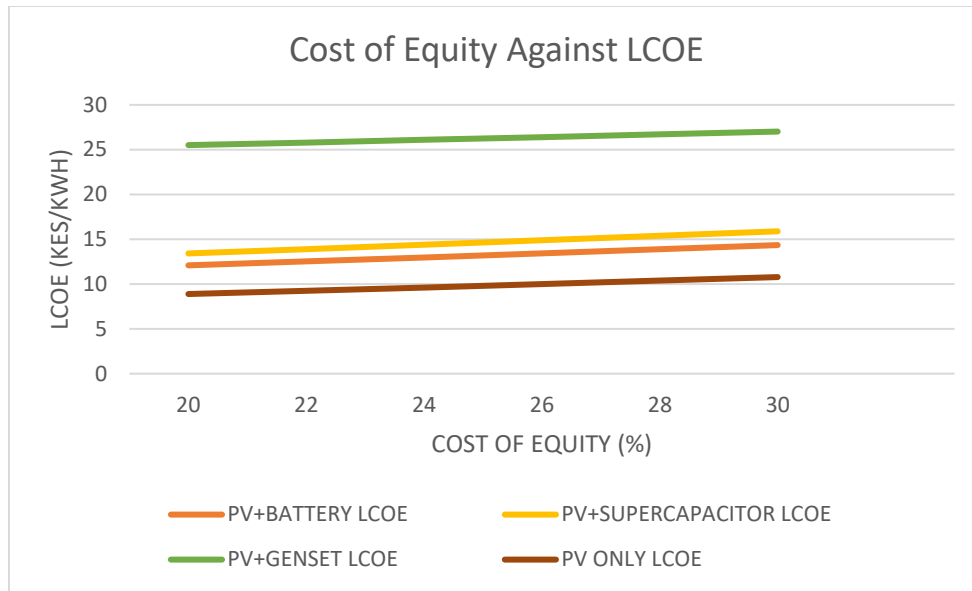


Figure 4.6 Cost of Equity Vs LCOE

Table 4.10 Change in LCOE as Cost of Equity increases

		PV+BATTERY	PV+SUPERCAPACITOR	PV+GENSET	PV ONLY
COST OF EQUITY		LCOE	LCOE	LCOE	LCOE
	20	11.67	14.47	33.23	8.95
	30	13.85	18.31	35.19	10.84
% VARIATION		18.68	26.54	5.90	21.12

Table 4.10 demonstrates the change in LCOE when the cost of equity is increased from 20% to 30%. There is a slight difference in the LCOE of these technologies as the rates increases, with PV plus genset backup technology having the lowest. The equity value is much lower compared to the debt value. Hence, while the LCOE still increases, there is a slight variation in the LCOE.

Table 4.11 Varied Corporate Tax Shield on Debt against Discount and LCOE

	PV+BATTERY		PV+SUPERCAPACITOR		PV+GENSET		PV ONLY	
CORPORATE TAX SHIELD	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE
5	5.65	14.24	6.48	17.12	6.32	34.71	5.92	10.8
10	5.18	13.71	6.06	16.57	5.89	34.4	5.46	10.42
15	4.7	13.18	5.64	16.04	5.46	34.1	5	10.04
20	4.22	12.66	5.22	15.51	5.03	33.8	4.54	9.67
25	3.74	12.16	4.8	14.99	4.06	33.52	4.08	9.31
30	3.26	11.67	4.38	14.47	4.17	33.23	3.62	8.95

Table 4.12 Varied Corporate Tax Shield on Equity against Discount and LCOE

	PV+BATTERY		PV+SUPERCAPACITOR		PV+GENSET		PV ONLY	
CORPORATE TAX SHIELD	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE	DISCOUNT	LCOE
5	5.93	14.55	6.6	17.28	6.47	34.77	6.14	10.93
10	5.72	14.32	6.3	16.89	6.19	34.57	5.91	10.73
15	5.52	14.09	6	16.5	5.91	34.37	5.67	10.54
20	5.32	13.86	5.7	16.11	5.63	34.17	5.44	10.34
25	5.11	13.64	5.4	15.73	5.35	33.98	5.2	10.15
30	4.91	13.41	5.1	15.36	5.06	33.79	4.97	9.95

The tax shield is mostly always 30%. Table 4.11 and 4.12 demonstrate how the tax shield affects the overall discount rate and LCOE when its conceptualized on either debt or equity. Various percentages of tax shield were conceptualized from 5% to 30%. When the corporate tax shield is associated with equity instead of debt, the percentage variation in the LCOE rises from 2% to 15% as the tax shield increases. The cost of equity is always higher than debt, therefore, even if it reduces due to the tax shield, the LCOE will still be higher due to the increased discount rate.

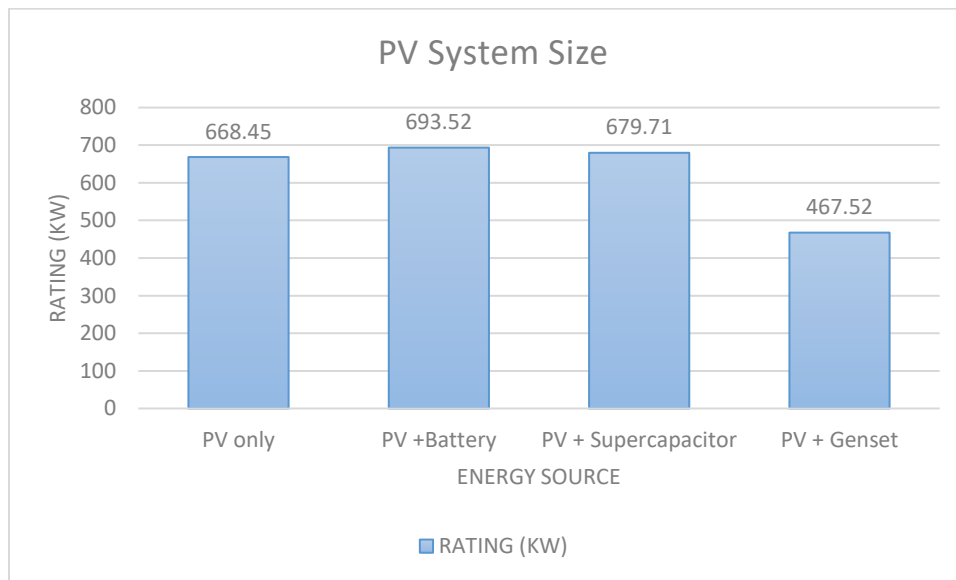


Figure 4.7 PV System size considering each Energy Technology

From figure 4.7, the PV system sizing considering each technology is presented. The PV with genset back up has the lowest PV capacity at 467.52 KW. This is because, the diesel generator generates its own energy from fuel to supplement the solar PV output and meet demand requirements. This is the opposite for battery and supercapacitor back up technologies as they get their energy for storage from the PV output resulting in a higher PV array capacity. However, the PV with supercapacitor back up PV array capacity is slightly lower than that with battery backup because of its higher efficiency.

4.5 Model Validation using the HOMER Simulation tool

The results of the developed model were tested and validated using the homer simulation tool. The PV modules and battery are connected directly to the DC bus-bar, together with an AC-DC converter. The generator on the AC side of the converter acts as a backup system to supply power to the load when the PV system is unavailable. The daily energy consumption for Mashuru area, that is 2923.9 kWh, was input into the system and computed a peak load value of 492.18 kw. In the developed model, the battery or supercapacitor and diesel generator were designed to supplement the PV output separately to meet the demand. All the results from HOMER are in appendix XIII to XXI.

The average daily load was set to 2923.9kWh/day as calculated in the research area, with peak month set to January. The model inputs, that is, generator cost in \$/Kw, fuel cost in \$/liter, PV Capital cost in \$/kw, battery cost in \$/kWh were set . The values were calculated using an exchange rate of KES 160 for 1 dollar. Battery size used for the LCOE computation were obtained from the results from the developed model and was taken as 924kWh. Therefore, a 1MWh battery was selected in homer.

Table 4.13 Conversion Table of Component Costs from KES to USD

Inputs	KES	USD
PV Capital Costs per kW	171,245	1070.28
Genset Capital Cost per kW	50000	312.5
Fuel Cost per liter	205	1.28
Battery Cost per kWh	14000	87.5

Validation was done by varying the discount rate used while calculating the LCOE and observing the change in final result of the LCOE as the discount rate changes. It was varied from 3.26% to 12.18%. As observed from the developed model, the LCOE increases with an increase in discount rate. Table 4.14 shows how the LCOE varied, for the PV with Battery backup, using the discount rates in table 4.6, and the LCOE computed using the homer simulation tool. An exchange rate of 160KES/USD was used.

Table 4.14 LCOE of Developed Model Vs Homer Simulation Tool for a PV+Battery Technology

PV+BATTERY					
Developed Model			Homer Simulation tool		Percentage Variation
	KES/KWH	USD/KWH	USD/KWH		
LCOE 1	12.09	0.0756	0.165		118.36
LCOE 2	23.12	0.1445	0.256		77.16

The trend in the discount rate is similar in both tools, however, the PV system size remains the same for each technology considered in homer. This is because homer does not consider a PV only option but an already established PV system size to be backed up by battery or generator or both at the same time. The variation in the LCOE can be attributed to errors in the computed value of battery autonomy using the homer simulation tool. The diesel generator is modelled to meet the demand when PV is unavailable in homer. Moreover, the generator is auto sized by the model depending on the demand to be supplied, hence this affects total fuel cost and generator capacity. This explains its very high LCOE.

The PV and inverter total energy output was about 1000MWh. This value is similar to the demand used in the developed model. The slight differences can be attributed to system efficiencies and hours of operation of the PV system.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

This study proposed an optimization model for renewable energy systems consisting of photovoltaics, and battery, supercapacitor, and a diesel generator which act as back up.

- 1) The average LCOE for diesel water pumping energy systems for farms in Mashuru area was 35.64KES/kWh. The highest LCOE of a diesel water pumping energy system is 115.8KES/kWh while the lowest LCOE is 19.7 KES/kWh. This work therefore concludes that consumers within the same environment, of same characteristics in undeserved regions have different costs of maintaining energy utilities.
- 2) The difference in LCOE between solar water pumping systems using either supercapacitors or batteries is 24 %, whereas the two have a 40 % cost difference. This study therefore concludes that the charge-discharge cycles of a battery give it a capex advantage over a supercapacitor.
- 3) The total capital costs of a solar water pumping energy system backed by a battery was 131.69 million KES while one backed by a generator was 95.3 million KES. However, the LCOE between the two technologies has a 184% variation. This study concludes that fuel costs give the PV plus genset backup technology an opex disadvantage.
- 4) There was about 70% variation in the LCOE of modelled energy technologies when the cost of debt doubled as the rates increases except for the PV plus genset backup. Moreover, when the cost of debt is doubled, the discounted production costs reduced by about 75% compared to the others. For example, the discounted replacement costs for PV plus battery backup technology reduced by only 14%. The study concludes that variation in cost of debt affects the opex of genset 5 times more that either battery or supercapacitor.
- 5) When the corporate tax shield was associated with equity instead of debt, the percentage variation in the LCOE rose from 2% to 15% as the tax shield increased. This relationship emphasizes the significance of the discount rate in the economic assessment of energy projects and the determination of their levelized costs.

5.2 Recommendation

Applying the methodology used in the present study, a proposal for future work involves;

- 1) The possibility of grid connection to underserved regions, while considering terrain constraints and grid intensification and densification costs, while keeping in mind that the grid is a public resource and may be highly subsidized.

- 2) This work focussed on a small, remote community. There is need to study and focus on a much larger remote area.
- 3) Another recommendation for future work includes the consideration of derating and capacitor factors while sizing the PV system and state of charge and depth of discharge values while determining battery capacity, which would lead to more accurate computation results.

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APPENDICES

Appendix I: LCOE for farm A

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	1,663.51		1	3,321,595.74		1	116,887.72
2	1,576.78		2	3,148,431.98		2	110,794.05
3	1,494.58		3	2,984,295.71		3	105,018.05
4	1,416.67		4	2,828,716.32		4	99,543.18
5	1,342.81		5	2,681,247.69		5	94,353.72
6	1,272.81		6	2,541,467.01		6	89,434.81
7	1,206.45		7	2,408,973.47		7	84,772.33
8	1,143.56		8	2,283,387.17		8	80,352.92
9	1,083.94		9	2,164,348.03		9	76,163.91
10	1,027.43		10	2,051,514.72		10	72,193.28
11	973.87		11	1,944,563.72		11	68,429.65
12	923.10		12	1,843,188.36		12	64,862.22
Sum of O&M PVs	15,125.50		Sum of FUEL PVs	30,201,729.90		Sum of Et PVs	1,062,805.84
Capital Cost	117,000.00						
Sum of PV O&M, Fuel plus Ct	30,333,855.40					Sum of Et PVS	1,062,805.84
	LCOE	28.54				KES/kWh	

Appendix II: LCOE for farm B

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	1,947.87		1	3,321,595.74		1	169,487.19
2	1,846.32		2	3,148,431.98		2	160,651.37
3	1,750.07		3	2,984,295.71		3	152,276.18
4	1,658.83		4	2,828,716.32		4	144,337.61
5	1,572.35		5	2,681,247.69		5	136,812.90
6	1,490.38		6	2,541,467.01		6	129,680.47
7	1,412.68		7	2,408,973.47		7	122,919.88
8	1,339.04		8	2,283,387.17		8	116,511.74
9	1,269.23		9	2,164,348.03		9	110,437.66
10	1,203.06		10	2,051,514.72		10	104,680.25
11	1,140.34		11	1,944,563.72		11	99,222.99

	12	1,080.89		12	1,843,188.36		12	94,050.22
Sum of O&M PVs		17,711.05		Sum of FUEL PVs	30,201,729.90		Sum of Et PVs	1,541,068.46
Capital Cost		137,000.00						
Sum of PV O&M, Fuel plus Ct		30,356,440.96					Sum of Et PVS	1,541,068.46
		LCOE	19.70				KES/kWh	

Appendix III: LCOE for farm C

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,658.77		1	4,529,448.73		1	116,887.72
2	2,520.16		2	4,293,316.33		2	110,794.05
3	2,388.78		3	4,069,494.15		3	105,018.05
4	2,264.24		4	3,857,340.43		4	99,543.18
5	2,146.20		5	3,656,246.85		5	94,353.72
6	2,034.31		6	3,465,636.83		6	89,434.81
7	1,928.26		7	3,284,963.82		7	84,772.33
8	1,827.73		8	3,113,709.78		8	80,352.92
9	1,732.45		9	2,951,383.68		9	76,163.91
10	1,642.13		10	2,797,520.07		10	72,193.28
11	1,556.52		11	2,651,677.79		11	68,429.65
12	1,475.38		12	2,513,438.67		12	64,862.22
Sum of O&M PVs	24,174.94		Sum of FUEL PVs	41,184,177.14		Sum of Et PVs	1,062,805.84
Capital Cost	187,000.00						
Sum of PV O&M, Fuel plus Ct	41,395,352.08					Sum of Et PVS	1,062,805.84
		LCOE	38.95				KES/kWh

Appendix IV: LCOE for farm D

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,164.83		1	4,042,813.74		1	68,943.94
2	2,051.98		2	3,832,050.94		2	65,349.71
3	1,945.00		3	3,632,275.77		3	61,942.85
4	1,843.60		4	3,442,915.43		4	58,713.60

5	1,747.49		5	3,263,426.94		5	55,652.71
6	1,656.39		6	3,093,295.68		6	52,751.38
7	1,570.04		7	2,932,033.82		7	50,001.31
8	1,488.19		8	2,779,178.98		8	47,394.60
9	1,410.60		9	2,634,292.87		9	44,923.80
10	1,337.06		10	2,496,960.07		10	42,581.80
11	1,267.36		11	2,366,786.79		11	40,361.89
12	1,201.29		12	2,243,399.80		12	38,257.72
Sum of O&M PVs	19,683.83		Sum of FUEL PVs	36,759,430.84		Sum of Et PVs	626,875.31
Capital Cost	152,260.00						
Sum of PV O&M, Fuel plus Ct	36,931,374.67					Sum of Et PVS	626,875.31
	LCOE	58.91				KES/kWh	

Appendix V: LCOE for farm E

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	1,706.16		1	3,623,558.98		1	116,887.72
2	1,617.21		2	3,434,653.07		2	110,794.05
3	1,532.90		3	3,255,595.32		3	105,018.05
4	1,452.99		4	3,085,872.34		4	99,543.18
5	1,377.24		5	2,924,997.48		5	94,353.72
6	1,305.44		6	2,772,509.46		6	89,434.81
7	1,237.39		7	2,627,971.05		7	84,772.33
8	1,172.88		8	2,490,967.82		8	80,352.92
9	1,111.73		9	2,361,106.94		9	76,163.91
10	1,053.78		10	2,238,016.06		10	72,193.28
11	998.84		11	2,121,342.24		11	68,429.65
12	946.77		12	2,010,750.93		12	64,862.22
Sum of O&M PVs	15,513.33		Sum of FUEL PVs	32,947,341.71		Sum of Et PVs	1,062,805.84
Capital Cost	120,000.00						
Sum of PV O&M, Fuel plus Ct	33,082,855.05					Sum of Et PVS	1,062,805.84
	LCOE	31.13				KES/kWh	

Appendix VI: LCOE for farm F

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,104.27		1	3,321,595.74		1	116,887.72
2	1,994.56		2	3,148,431.98		2	110,794.05
3	1,890.58		3	2,984,295.71		3	105,018.05
4	1,792.02		4	2,828,716.32		4	99,543.18
5	1,698.60		5	2,681,247.69		5	94,353.72
6	1,610.05		6	2,541,467.01		6	89,434.81
7	1,526.11		7	2,408,973.47		7	84,772.33
8	1,446.55		8	2,283,387.17		8	80,352.92
9	1,371.14		9	2,164,348.03		9	76,163.91
10	1,299.66		10	2,051,514.72		10	72,193.28
11	1,231.90		11	1,944,563.72		11	68,429.65
12	1,167.68		12	1,843,188.36		12	64,862.22
Sum of O&M PVs	19,133.11		Sum of FUEL PVs	30,201,729.90		Sum of Et PVs	1,062,805.84
Capital Cost	148,000.00						
Sum of PV O&M, Fuel plus Ct	30,368,863.01					Sum of Et PVS	1,062,805.84
	LCOE	28.57				KES/kWh	

Appendix VII: LCOE for farm G

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,872.04		1	4,529,448.73		1	45,586.21
2	2,722.31		2	4,293,316.33		2	43,209.68
3	2,580.39		3	4,069,494.15		3	40,957.04
4	2,445.87		4	3,857,340.43		4	38,821.84
5	2,318.36		5	3,656,246.85		5	36,797.95
6	2,197.49		6	3,465,636.83		6	34,879.58
7	2,082.93		7	3,284,963.82		7	33,061.21
8	1,974.34		8	3,113,709.78		8	31,337.64
9	1,871.42		9	2,951,383.68		9	29,703.92
10	1,773.85		10	2,797,520.07		10	28,155.38
11	1,681.38		11	2,651,677.79		11	26,687.56

	12	1,593.72		12	2,513,438.67		12	25,296.27
Sum of O&M PVs		26,114.11		Sum of FUEL PVs	41,184,177.14		Sum of Et PVs	414,494.28
Capital Cost		202,000.00						
Sum of PV O&M, Fuel plus Ct		41,412,291.25					Sum of Et PVS	414,494.28
		LCOE	99.91				KES/kWh	

Appendix VIII: LCOE for farm H

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,061.61		1	3,321,595.74		1	116,887.72
2	1,954.13		2	3,148,431.98		2	110,794.05
3	1,852.26		3	2,984,295.71		3	105,018.05
4	1,755.70		4	2,828,716.32		4	99,543.18
5	1,664.17		5	2,681,247.69		5	94,353.72
6	1,577.41		6	2,541,467.01		6	89,434.81
7	1,495.18		7	2,408,973.47		7	84,772.33
8	1,417.23		8	2,283,387.17		8	80,352.92
9	1,343.34		9	2,164,348.03		9	76,163.91
10	1,273.31		10	2,051,514.72		10	72,193.28
11	1,206.93		11	1,944,563.72		11	68,429.65
12	1,144.01		12	1,843,188.36		12	64,862.22
Sum of O&M PVs	18,745.28		Sum of FUEL PVs	30,201,729.90		Sum of Et PVs	1,062,805.84
Capital Cost	145,000.00						
Sum of PV O&M, Fuel plus Ct	30,365,475.18					Sum of Et PVS	1,062,805.84
		LCOE	28.57			KES/kWh	

Appendix IX: LCOE for farm I

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	2,218.01		1	3,019,632.49		1	26,243.18

2	2,102.38		2	2,862,210.89		2	24,875.05
3	1,992.78		3	2,712,996.10		3	23,578.25
4	1,888.89		4	2,571,560.29		4	22,349.05
5	1,790.41		5	2,437,497.90		5	21,183.93
6	1,697.08		6	2,310,424.55		6	20,079.56
7	1,608.60		7	2,189,975.88		7	19,032.76
8	1,524.74		8	2,075,806.52		8	18,040.53
9	1,445.25		9	1,967,589.12		9	17,100.03
10	1,369.91		10	1,865,013.38		10	16,208.55
11	1,298.49		11	1,767,785.20		11	15,363.56
12	1,230.80		12	1,675,625.78		12	14,562.62
Sum of O&M PVs	20,167.33		Sum of FUEL PVs	27,456,118.09		Sum of Et PVs	238,617.05
Capital Cost	156,000.00						
Sum of PV O&M, Fuel plus Ct	27,632,285.43					Sum of Et PVS	238,617.05
	LCOE	115.80				KES/kWh	

Appendix X: LCOE for farm J

LCOE							
Year	PV O&M		Year	PV Fuel		Year	PV Et
1	3,383.89		1	2,821,235.15		1	116,887.72
2	3,207.48		2	2,674,156.54		2	110,794.05
3	3,040.26		3	2,534,745.53		3	105,018.05
4	2,881.76		4	2,402,602.40		4	99,543.18
5	2,731.53		5	2,277,348.25		5	94,353.72
6	2,589.13		6	2,158,623.93		6	89,434.81
7	2,454.15		7	2,046,089.03		7	84,772.33
8	2,326.21		8	1,939,420.89		8	80,352.92
9	2,204.94		9	1,838,313.64		9	76,163.91
10	2,089.99		10	1,742,477.38		10	72,193.28
11	1,981.03		11	1,651,637.33		11	68,429.65
12	1,877.75		12	1,565,533.01		12	64,862.22
Sum of O&M PVs	30,768.11		Sum of FUEL PVs	25,652,183.06		Sum of Et PVs	1,062,805.84

Capital Cost	238,000.00					
Sum of PV O&M, Fuel plus Ct	25,920,951.17				Sum of Et PVS	1,062,805.84
	LCOE	24.39			KES/kWh	

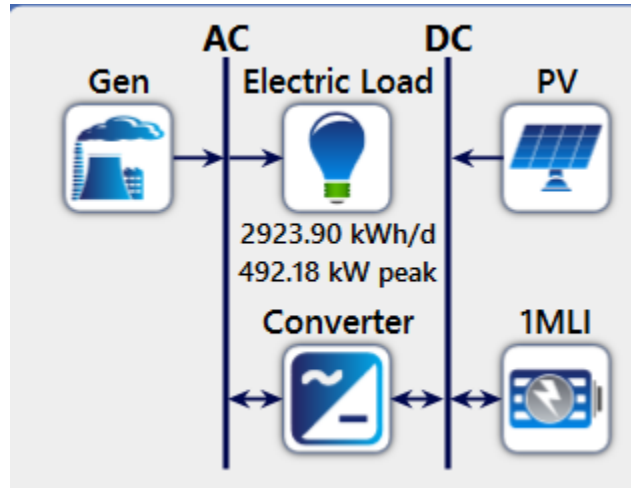
Appendix XI: Average LCOE for all the 10 farms

LCOE						
Year	PV O&M		Year	PV Fuel		Year
						PV Et
1	22,780.95		1	35,852,521.14		1,011,586.26
2	21,593.32		2	33,983,432.36		958,849.53
3	20,467.60		3	32,211,784.23		908,862.12
4	19,400.57		4	30,532,496.90		861,480.68
5	18,389.16		5	28,940,755.35		816,569.36
6	17,430.49		6	27,431,995.59		773,999.40
7	16,521.79		7	26,001,891.56		733,648.72
8	15,660.46		8	24,646,342.71		695,401.63
9	14,844.04		9	23,361,462.28		659,148.46
10	14,070.18		10	22,143,566.15		624,785.27
11	13,336.66		11	20,989,162.22		592,213.53
12	12,641.39		12	19,894,940.50		561,339.84
Sum of O&M PVs	207,136.60		Sum of FUEL PVs	325,990,350.98		Sum of Et PVs
						9,197,884.78
Capital Cost	1,602,260.00					
Sum of PV O&M, Fuel plus Ct	327,799,747.58				Sum of Et PVS	9,197,884.78
	LCOE	35.64			KES/kWh	

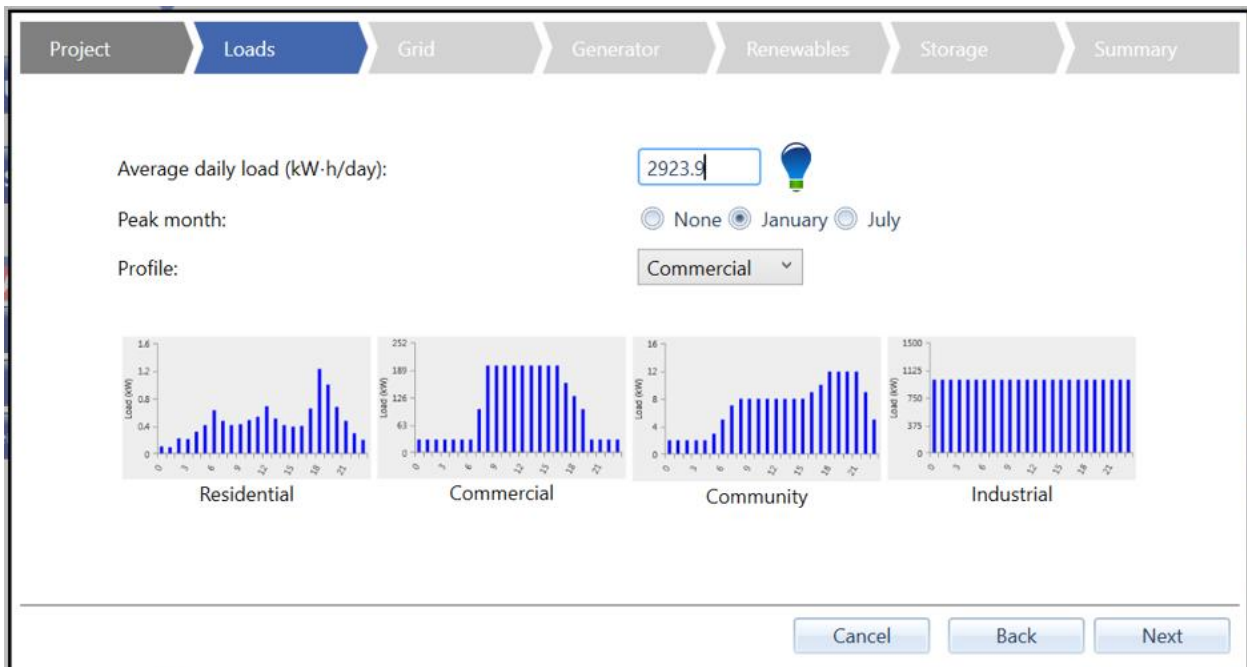
Appendix XII: Average hourly profiles per year for Mashuru from Global Solar Atlas

Time (hrs)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	2	2	1	2	6	1	0	0	4	19	17	12
6 - 7	217	185	139	84	93	71	58	53	106	152	127	195
7 - 8	417	389	290	186	184	159	137	129	212	271	226	346
8 - 9	557	550	485	317	297	235	231	225	347	438	347	468
9 - 10	650	663	601	446	379	308	301	304	445	525	451	568
10 - 11	692	717	647	520	401	324	319	336	495	572	512	611
11 - 12	694	705	650	531	396	297	301	333	500	557	526	597
12 - 13	651	657	622	523	368	282	275	329	507	531	516	562
13 - 14	611	599	586	483	355	280	276	329	490	477	499	552
14 - 15	566	549	555	432	320	268	262	303	424	414	467	522
15 - 16	516	501	485	365	269	230	237	269	359	346	411	477
16 - 17	419	407	354	244	190	157	157	193	244	232	263	326
17 - 18	76	99	45	14	15	10	13	18	19	10	8	21
18 - 19	0	0	0	0	0	0	0	0	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0
Total	6068	6023	5460	4147	3273	2622	2567	2821	4152	4544	4370	5257

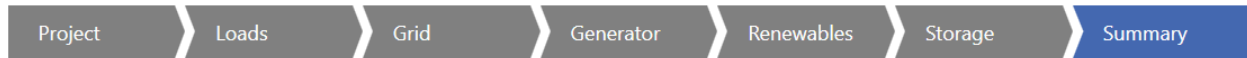
Appendix XIII: Schematic on the PV-Battery-Converter-Generator design from HOMER based on daily energy consumption



Appendix XIV: Load Profile from HOMER



Appendix XV: Model Inputs in HOMER



Project

Discount rate: 3.26 %

Load Information

Average daily load: 2923.9 kW·h/day

Peak month: January

Profile: Commercial

Grid Information

No grid is included in this system

Generator Information

I might want a generator

Generator cost: 312.5 \$/kW

Fuel cost: 1.28 \$/liter

Renewables Information

A PV is included in this system

PV capital cost: 1070.28 \$/kW

No wind turbine is included in this system

Storage Information

A battery is included in this system

Battery type: Generic 1MWh Li-Ion

Battery cost: 80850 \$/battery

Include Sensitivity Cases

Appendix XVI: LCOE calculation using a discount rate of 3.26%

NominalDiscountRate (%)	Diesel Fuel Price (\$/L)	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)
1.63	0.640	854	550	2	388	LF	\$2.90M	\$0.133	\$75,145	\$1.36M
3.26	0.640	854	550	2	388	LF	\$2.64M	\$0.146	\$75,190	\$1.36M
6.52	0.640	854	550	2	388	LF	\$2.27M	\$0.175	\$74,593	\$1.36M
1.63	1.28	854		5	388	CC	\$3.23M	\$0.152	\$87,964	\$1.43M
3.26	1.28	854		5	388	CC	\$2.92M	\$0.165	\$87,985	\$1.43M

Export... Export Details... Optimization Results Double click on a system to see its Simulation Details.

Architecture							Cost				System	
	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)	
	854		5	388	CC	\$2.92M	\$0.165	\$87,985	\$1.43M	100	0	
	854	550	2	388	LF	\$2.94M	\$0.163	\$93,334	\$1.36M	91.3	28,350	
	854	550		388	CC	\$13.6M	\$0.753	\$732,908	\$1.20M	0	372,923	

Appendix XVII: LCOE calculation using a discount rate of 5.49%

NominalDiscountRate (%)	Diesel Fuel Price (\$/L)		PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)
2.75	0.640		854	550	2	388	LF	\$2.71M	\$0.142	\$75,204	\$1.36M
5.49	0.640		854	550	2	388	LF	\$2.37M	\$0.165	\$74,866	\$1.36M
11.0	1.28		854	550	2	388	LF	\$2.13M	\$0.237	\$90,956	\$1.36M
2.75	1.28		854		5	388	CC	\$3.01M	\$0.161	\$88,023	\$1.43M
5.49	1.28		854		5	388	CC	\$2.61M	\$0.186	\$87,390	\$1.43M

Optimization Results												
Double click on a system to see its Simulation Details.												
Architecture							Cost			System		
		PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)
		854		5	388	CC	\$2.61M	\$0.186	\$87,390	\$1.43M	100	0
		854	550	2	388	LF	\$2.61M	\$0.182	\$93,010	\$1.36M	91.3	28,350
		854	550		388	CC	\$11.0M	\$0.771	\$733,242	\$1.20M	0	372,923

Appendix XVIII: LCOE calculation using a discount rate of 7.72%

NominalDiscountRate (%)	Diesel Fuel Price (\$/L)		PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)
15.4	1.28		854	550	2	388	LF	\$1.92M	\$0.286	\$88,697	\$1.36M
3.86	1.28		854		5	388	CC	\$2.83M	\$0.171	\$87,891	\$1.43M
7.72	1.28		854	550	2	388	LF	\$2.37M	\$0.203	\$92,341	\$1.36M
15.4	2.56		854		5	388	CC	\$1.93M	\$0.294	\$79,367	\$1.43M
3.86	2.56		854		5	388	CC	\$2.83M	\$0.171	\$87,891	\$1.43M

Optimization Results												
Double click on a system to see its Simulation Details.												
Architecture							Cost			System		
		PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)
		854	550	2	388	LF	\$2.37M	\$0.203	\$92,341	\$1.36M	91.3	28,350
		854		5	388	CC	\$2.38M	\$0.208	\$86,197	\$1.43M	100	0
		1.00	550		388	CC	\$9.12M	\$0.782	\$807,723	\$289,345	0	441,355

Appendix XIX: LCOE calculation using a discount rate of 9.95%

NominalDiscountRate (%)	Diesel Fuel Price (\$/L)	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)
4.97	0.640	854	550	2	388	LF	\$2.42M	\$0.161	\$74,975	\$1.36M
9.95	0.640	854	550	2	388	LF	\$2.03M	\$0.209	\$73,287	\$1.36M
19.9	1.28	854	550	2	388	LF	\$1.79M	\$0.338	\$86,393	\$1.36M
4.97	1.28	854		5	388	CC	\$2.67M	\$0.181	\$87,585	\$1.43M
9.95	1.28	854	550	2	388	LF	\$2.20M	\$0.226	\$91,431	\$1.36M

Optimization Results											
Architecture							Cost			System	
	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)
	854	550	2	388	LF	\$2.20M	\$0.226	\$91,431	\$1.36M	91.3	28,350
	854		5	388	CC	\$2.21M	\$0.232	\$84,549	\$1.43M	100	0
	1.00	550		388	CC	\$7.65M	\$0.786	\$807,416	\$289,345	0	441,355

Appendix XX: LCOE calculation using a discount rate of 12.2%

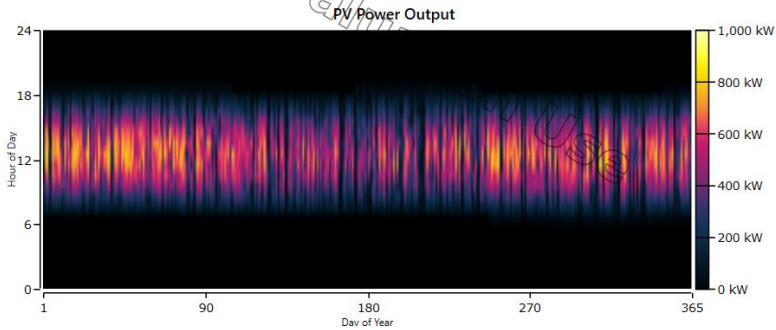
NominalDiscountRate (%)	Diesel Fuel Price (\$/L)	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)
12.2	1.28	854	550	2	388	LF	\$2.06M	\$0.250	\$90,372	\$1.36M
24.4	1.28	854	550	2	388	LF	\$1.71M	\$0.392	\$84,242	\$1.36M
6.09	1.28	854		5	388	CC	\$2.54M	\$0.192	\$87,121	\$1.43M
12.2	2.56	854		5	388	CC	\$2.07M	\$0.256	\$82,581	\$1.43M
24.4	2.56	854		5	388	CC	\$1.72M	\$0.403	\$70,220	\$1.43M

Optimization Results											
Architecture							Cost			System	
	PV (kW)	Gen (kW)	1MLI (#)	Converter (kW)	Dispatch	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)
	854	550	2	388	LF	\$2.06M	\$0.250	\$90,372	\$1.36M	91.3	28,350
	854		5	388	CC	\$2.07M	\$0.256	\$82,581	\$1.43M	100	0
	1.00	550		388	CC	\$6.54M	\$0.791	\$806,910	\$289,345	0	441,355

Appendix XXI: PV Output in kWh from Homer

Quantity	Value	Units
Rated Capacity	854	kW
Mean Output	158	kW
Mean Output	3,794	kWh/d
Capacity Factor	18.5	%
Total Production	1,384,778	kWh/yr

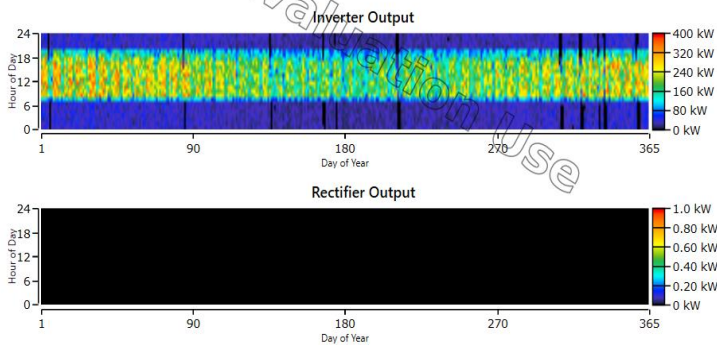
Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	828	kW
PV Penetration	130	%
Hours of Operation	4,321	hrs/yr
Levelized Cost	0.0489	\$/kWh
Clipped production	0	kWh



Appendix XXII: Inverter Output in kWh in Homer

Quantity	Inverter	Rectifier	Units
Capacity	388	388	kW
Mean Output	119	0	kW
Minimum Output	0	0	kW
Maximum Output	388	0	kW
Capacity Factor	30.7	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	8,585	0	hrs/yr
Energy Out	1,044,548	0	kWh/yr
Energy In	1,099,525	0	kWh/yr
Losses	54,976	0	kWh/yr



Appendix XXIII: Questionnaire

Introduction

My name is Dorine Nabucha Mutekhele, currently pursuing a Master of Science program in Sustainable Energy Transitions at Strathmore University. My post-graduate thesis focuses on developing a model to optimize energy access in Mashuru. The objective of this study is to develop, test and validate a renewable energy model that will optimize accessibility in Mashuru. I hope to gain insights on the demand and energy consumption in Mashuru area and an approximation on expected daily energy usage. This questionnaire specifically targets farmers using diesel pumping energy systems for irrigation. The data gathered by this questionnaire will be handled with discretion.

General Information:

- 1) What is the size of your farm in hectares/acres?

- 2) How long have you been using diesel pumping systems for irrigation?

- 3) What crops do you primarily cultivate with the help of diesel pumps?

- 4) How many diesel pumps do you currently use on your farm?

Please provide;

- a) Pump model

- b) Pump power

- c) Pump head

- d) Pump flow rate

- e) Pump efficiency

- f) Engine model

- g) Engine power

- h) Capital costs for the diesel pumping energy system

Diesel Pumping System Usage:

1) How often do you use the diesel pumping system for irrigation?

2) What is the average number of hours per day that the diesel pump is operational?

3) Do you use the diesel pump during specific seasons, or is it used year-round?

4) How much diesel fuel (in liters/gallons) do you estimate using per month for irrigation?

Maintenance and Costs:

1) How often do you conduct maintenance on your diesel pumping system?

- Quarterly
 - Twice a year
 - Annually
 - Other:
-
-

2) What are the typical maintenance tasks you perform on the diesel pump?

3) Can you estimate the annual maintenance costs associated with the diesel pump?

- Yes
 - No
-

4) What are the main challenges or issues you face regarding the maintenance of the diesel pump?

- Economic challenges
 - Unavailability of technical expertise
 - Reduced yields during downtime for maintenance
 - Other:
-
-

Fuel Consumption and Efficiency:

1) Do you monitor fuel consumption for the diesel pumping system?

- Yes
- No

2) Have you noticed any changes in fuel efficiency over time?

- Yes
- No

3) What factors do you think affect the fuel efficiency of the diesel pump?

- Engine condition and maintenance
- Load demand
- Pump-engine sizing and design
- Other:

4) Are there any specific practices you follow to optimize fuel usage?

- Yes
 - No
-
-

Environmental and Sustainability:

1) Are you aware of the environmental impact of diesel usage on your farm?

- Yes
 - No
-
-

2) Have you considered alternative energy sources for irrigation, such as solar or wind power?

- Yes
 - No
-
-

3) What motivates you to explore more sustainable energy options for irrigation?

- Cost savings
 - Reduced vulnerability to changes in fuel price
 - Environmental impact
 - Other:
-
-

Knowledge and Awareness:

1) Are you aware of any government incentives or programs for energy-efficient farming practices?

- Yes
 - No
-
-

2) Would you be interested in attending workshops or training sessions on energy-efficient irrigation methods?

- Yes
- No

3) Do you have any concerns or hesitations about transitioning to alternative energy sources for irrigation?

- Yes
- No

Future Plans:

- 1) Are you considering any changes or upgrades to your irrigation system in the next 1-2 years?
- Yes
 - No

-
- 2) What are the main factors influencing your decision-making process regarding irrigation energy systems?

- Capital costs
 - Operational costs
 - System efficiency
 - Environmental impact
 - Reliability
 - Ease of maintenance
 - Other:
-
-

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13th September 2023

Ms Mutekhele Dorine Nabucha,
dorine.mutekhele@strathmore.edu

Dear Ms Mutekhele,

RE: Modeling and Optimization of Renewable Energy Accessibility in Underserved Regions: A Case of Mashuru

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU-masters** research proposal. Your application reference number is **SU-ISERC1850/23**. The approval period is from **13th September 2023 to 12th September 2024**.

This approval is subject to compliance with the following requirements:

- i. Only approved documents including (informed consents, study instruments, MTA) will be used.
- ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
- iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
- iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
- v. Clearance for the export of biological specimens must be obtained from relevant institutions.
- vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
- vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) <https://research-portal.nacosti.go.ke/> and obtain other clearances needed.

Yours sincerely,



Mr Ambrose Rachier,
Chairperson; SU-ISERC





REPUBLIC OF KENYA



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