INDEPENDENT RENEWABLE ENERGY MICROGRID DESIGN FOR AFRICA

by

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DECLARATION

I, **Taina Zandile Matshotyana**, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

07 November 2024

Signed **Date**

ABSTRACT

Around 761 million people in Africa have no access to modern energy, affecting people living in rural areas the most. Rural communities are areas where the extension of the national electricity grid is a technically difficult, costly, and inefficient solution because of remoteness and sparse population density. Kenya ranks number 8 on the list of Africa's largest economies, with more than 60% of its population living in rural areas. Nearly 43 million people do not have clean cooking energy, and approximately 55% of Kenya's population has no access to electricity. With the lack of electricity access, the people who find themselves in remote areas have no choice but to use traditional methods of cooking, such as biomass. Electricity availability is crucial for both economic and human development.

Renewable Microgrids can be designed to cater for the needs of such communities using available renewable resources in the villages. In this study, the renewable energy microgrid was designed using HOMER Pro. Geographic information was collected to assess the available natural resources a village has that will be used in the design, and the population information collected assisted in knowing the electricity demand. The loading of the studied villages was taken from the findings of previous studies of villages in Kenya. A simulation was done, and the suitable system configurations that could supply the demand of each of the villages were selected. This study designed a renewable microgrid which provided economic energy to Mumbiri, South Korr, Kitulu, Mkwiro, and Sasimwani villages in Kenya.

The study showed that a PV solar system, when combined with an energy storage, converter and an MPPT, could supply sufficient electricity for Mumbiri and Kitulu Village. As for South Korr and Mkwiro Village, the study concluded that because of the area's vast wind potential, the combination of the system included a wind turbine, batteries, and a converter. Sasimwani Village has large forests, and the study revealed that that resource could be used to fuel the generator. The findings suggested that available renewable energy resources in the selected locations could provide electricity without any capacity shortages. Therefore, the implementation of renewable energy microgrids could assist in achieving rural electrification.

Keywords: *Renewable energy, microgrids, rural electrification*

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ABBREVIATIONS AND ACRONYMS

AC	Alternating current
BESS	Battery Energy Storage System
BOS	Balance of System
°C	Degree Celsius
CAES	Compressed air energy storage
CAPEX	Capital costs
CO2	Carbon Dioxide
COE	Cost of energy
DC	Direct Current
EES	Electrical Energy Storage (EES)
EPII	Engineering fee, Permitting, Inspection, and Interconnection
EUR	Euro
FF	Fossil Fuels
GACC	Global Alliance Clean Cookstove
GDP	Gross Domestic Product
GHG	Green gas houses
GIS	Geographic Information System
IEA	International Energy Agency
KES	Kenya Shilling
KFS	Kenya Forest Services
kWh	Kilowatt hour
kWp	Kilowatt peak
LCA	Life cycle assessment
LCO	Li-Cobalt
LCOE	Levelised Cost of Electricity
LFP	Li-Phosphate
LFYP	Lithium-iron-yttrium phosphate
LMO	Li-Manganese
LPG	Liquified Petroleum Gas
LV	Low Voltage
MW	Mega Watt
MG	Microgrid
MPPT	Maximum Power Point Tracker
MTF	Multi-Tier Framework
NASA	National Aeronautics and Space Administration
NCA	Lithium Nickel-Cobalt Aluminium
NiCd	Nickel-cadmium
NiMH	Nickel-metal hybrid
NMC	Lithium-Nickel Manganese-Cobalt
NPC	Net present cost
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Pacific Island Countries
PIC	Operational costs
PV	Photovoltaic
P_2H_2P	Power to hydrogen power
RBF	redox flow batteries
REA	Rural Electrification Authority
RES	Renewable Energy Systems
RE_RU_KE	Renewables for the Rural electrification of Kenya
REP	Rural Electrification Programme
Rse	Series resistance
Rsh	Shunt resistance

SDG7	Sustainable Development Goal 7
SMES	Superconducting magnetic energy storage
SSA	Sub-Saharan Africa
SWERA	Solar and Wind Resources Assessment
SWT	Small Wind Turbine
UN	United Nations
USD	United States Dollar
V	Volt
VRA	Valve regulated lead-acid.
$	United States Dollar
CSP	Concentrated Solar Power

Conversions as of 04 August 2022:
1 USD = 0.98 Euro

Conversion as of 01 July 2024
1 USD = IDR. 61151

Chapter 1 : Introduction

1.1. Background

Despite Africa having great potential in renewable energy, Kenya, together with most parts of the continent, experience a lack of access to modern energy **(IEA, 2019, p.14)**. Kenya specifically has 23% of its population having no access to electricity **(Cowling, 2024)**. The majority of this population lives in rural areas where the extension of the national electricity grid is a technically difficult, very costly, and inefficient solution because of remoteness and sparse population density. In 2021, South Africa had already tapped into its natural resources with an installed capacity of 500 MW from Concentrated Solar Power (CSP) plants, 2212 MW from solar photovoltaics, 3343 MW from onshore wind plants, and 50 MW from other resources. It is projected that by 2031, South Africa will have an installed capacity of 600 MW from CSP, 8288 MW from Solar PV, and 17 742 MW from Onshore **(Mehta, R. et al., 2023, p. 2)**. On the other hand, Kenya has targeted to reach 100% renewable energy generation by 2030, and this will be achieved mostly from geothermal and wind resources **(Kihara, M. et al., 2024, p. 1)**. Access to energy for the population of Kenya may improve sustainable growth and economic development in the country. Thus, the promotion of independent renewable energy is critical and requires immediate action.

By delaying action towards providing electricity to these communities, delays improving their lives, and the continued impacts are.

Social

- Without power, rural people are cut off from vital information like government initiatives, health campaigns, and weather alerts. They also have restricted access to telecommunication devices like phones, radios, and the internet.
- Lack of lighting in the home raises safety concerns, particularly for women and children who may be more vulnerable to violence and accidents after dark.

Educational

- After dark, students in remote places without electricity are unable to study. The alternative is frequently to use candles or paraffin lamps, which produce inadequate light, increase the risk of respiratory problems, and increase household expenses.
- Poor study environments and limited resource availability can demotivate students, which raises the dropout rate, particularly for female students.

Economic

- Women and girls are frequently left to take on the task of gathering firewood or alternative energy sources, spending time away from activities that bring income to themselves and participating in economic activities that benefit the Country as a whole.

Therefore, in addressing the lack of energy access for villages in Kenya, studies conducted by other researchers showed that there is potential for the deployment of renewable microgrids. For example, in the study by (Muchiri, K. et al., 2023, pp. 5-9) which the synergy between wind and solar resources was explored, it was found that wind speeds ranged from 2.5 m/s to 4.9 m/s, and this meant that the area had good wind potential. A good solar resource is found mostly in the western regions of Kenya, while biomass was found (Kinyanjui, M. J. et al., 2014, pp. 621-624) to be an average of 236 megagrams per Hectare, this indicates a good potential for renewable energy in Kenya. However, these studies were not from the selected locations where my research is aimed at looking at.

Independent renewable microgrids are a practical substitute for traditional grid extensions. Microgrids are small energy systems that can be connected to the main grid or run independently. As defined by (Johannsen, R. et al., 2020, p. 113), microgrids are electricity grids that are at capacities between 1-10 kW and which are located in remote areas. Microgrids can provide electricity to different customers in close vicinity while operating independently from the national grid. They have various benefits for electrifying rural areas:

- Decentralisation: By lowering transmission losses and boosting dependability, microgrids can offer customised energy solutions that are customised to meet the demands of communities.
- Scalability: They can be extended as necessary and scaled to meet local communities' energy needs.
- Resilience: Microgrids improve energy security and resilience, especially in places where the main grid is isolated or at risk of outages.

Although microgrids present a promising option, there are several obstacles to their implementation in Kenya's rural areas:

- Technical: Developing dependable and effective microgrids that combine storage technologies and a variety of renewable energy sources.
- Economic: Rural communities have high initial capital expenses and fewer financing options.
- Regulatory: Microgrid adoption has been restricted by complicated regulatory frameworks and insufficient legislative assistance.
- Social: Ensuring community involvement and tackling sociocultural elements that affect how well-received and sustainable new energy solutions are.

Research aimed at creating detailed and long-lasting models for independent renewable energy microgrid designs that are suited to Kenya's rural communities is desperately needed, even though there are these obstacles. My research will focus on designing the five selected locations which currently do not have electricity access.

1.2. Problem statement

Kenya is the eighth-largest economy in Africa, with over 60% of its people residing in rural areas. Due to their challenging geographic locations, power distribution in these areas is more expensive and difficult to implement. Because of this, the community gets its energy from biomass via traditional means to satisfy their energy needs. Approximately more than half of Kenyans lack access to electricity, and nearly 43 million people lack clean cooking energy. Climate change is a major threat to sustainable growth and economic development in Sub-Sahara Africa. Lack of access to electrical energy stems from a lack of electrical energy supporting policies, lack of financial means and know-how, the geographical nature of rural settlement and non-uniform distribution of energy resources.

1.3. Aim and Objectives

1.3.1. Aim

To develop microgrid designs for five villages in Kenya based on their available renewable energy resources. The villages currently do not have electricity access. The village community should be able to live better and more sustainably while lowering their current and future carbon footprints because of the designed microgrid. Most of this project's technical research will be devoted to the design and optimisation of the solar microgrid, which may be implemented profitably in a community with projected energy consumption and load distribution.

1.3.2. Objectives

The objectives of the research are as follows:

I. Review mainstream literature to understand the availability of renewable energy resources in the selected locations.

II. Review the relevant mainstream literature to understand Independent renewable energy microgrid design.
III. Model and design the microgrid system using Homer Pro.
IV. Conduct a techno-economic analysis of the microgrid designs and select a suitable and lowest net present value for the chosen locations.

1.4. Limitations

- This is a theoretical study based on information gathered through a literature review and some information generated from the Homer Pro software.
- Practical experiments will not be conducted except for the usage of the Homer Pro software.
- The results of the study will only be limited to the selected locations.

1.5. Thesis Outline

This thesis's format is intended to methodically address the research goals and offer a complete understanding of how a microgrid for renewable energy is designed.

- Chapter 1: In this first chapter, you will find the introduction of the paper, explaining the background, problem statement, aim and objectives, and limitations.
- Chapter 2: An outline of the Literature Review on Kenya's solar PV potential, systems cost, installation, load profile, energy policies in the country, rural electrification, renewable options, and stakeholders is discussed in this chapter.
- Chapter 3: More literature is covered here on renewable microgrids and energy storage potential.
- Chapter 4: This chapter looks at microgrid modelling and design using Homer Pro.
- Chapter 5: This chapter presents results and discussion.
- Chapter 6: Lastly, the conclusion and recommendation are contained in this chapter.

Chapter 2 : Literature Review

2.1. Overview

According to the UN, a person who had access to electricity and modern energy services and improved end-use devices at an affordable price was considered to have access to energy (IEA, 2019, p.36). In the case of Kenya, population growth and industrialisation were putting pressure on the insufficient electrical energy supply. As of 2019, 36% of Kenya's population had no access to basic electrical energy services (World Bank, 2019, p.25). The GDP growth rate assumption in Kenya between 2000 – 2018 was 4.8%, the Stated Policy Scenario assumption was 5.9%, and the Africa Case was 9% between 2018 – 2040 (IEA, 2019, p 25). Those percentages found in the Stated Policy Scenario referred to the assessment of current Sub-Saharan Africa policies, future ambitious policies and known technologies that would influence the electrical energy sector in future. The value found for the Africa Case was derived from assessing a country's policies on how they would grow the economy. The population assumption in 2018 was 51 Million, and in 2040, the population was assumed to be 79 million people, the average annual growth rate between 2018 – 2040 was 2% (IEA, 2019, p 25). These changes necessitate continuous updating of policies to suit the needs of the growing Kenya.

A study by Lee and Kenneth (2016, pp. 26-35) stated that the challenges to universal electricity access for Kenya's rural population were the policies and interactions of institutions. This study found that half of the rural population without access to electricity was within 200 m of the current grid connection point.

The Africa Energy Outlook (2019, p. 79) reported that if Kenya improved on efficiency and stopped using traditional forms of bioenergy like wood, animal waste, etc, it could supply an economy six times bigger than the current using electrical energy consumption, roughly twice the current consumption. Bioenergy accounts for two-thirds of Kenya's energy. However, this statement doesn't specify the degree of efficiency improvement required to achieve the six-fold economic growth. Also, the feasibility and timeline of such a massive infrastructure upgrade are not addressed.

Greenhouse gas emissions from the use of wood fuels contributed about 1.9 - 2.3% of global CO^2 emissions. The average annual increase in clean cooking access rate in Kenya between 2010 -2017 was about 2% percentage points. Kenya was in the top 20 countries with the highest population without clean cooking access. Goal 7 on sustainable development (SDG7) becomes important as it facilitates access for all to clean, safe, accessible, reliable and modern energy services to improve the lives and health of people around the world (World Bank, 2019, pp.16-17). Kenya's adoption of clean cooking options had the potential to help sustainability. However, the transition was not happening at a fast enough pace. Even with the growth of the large economy, clean cooking services, including electricity, LPG, solar and ethanol stoves, were available to only 13% of the population (World Bank, 2019, p.52). However, this report focuses on the environmental and health effects of wood fuels and does not consider the cultural aspects that necessitate the use of wood fuels. These cultural norms form part of their way of life.

Almost 42 million people in Kenya still use traditional methods of cooking, with 30% - 40% of people using enhanced biomass stoves, and the rest depend on open fires to cook (Oloo, F. et al., 2015, pp. 17-29).

Clean cooking has become a top priority globally, with international initiatives being seen to assist with the drive. The Global Alliance Clean Cookstove (GACC) has been actively involved in supporting 100 million households by 2020 for clean and effective cookstoves. Since the

GACC was launched in 2010, about 53 million safe and effective cookware have been distributed globally. Kenya's Government was also doing its part to promote clean cooking. The government has placed policies, and more stoves and fuels are available on the market for consumers. (Karanja, A. & Gasparatos, A. 2019, pp. 289-291). However, lack of awareness, affordability, and interest in paying for clean cooking affected the progress of clean cooking. In addition, free access to traditional fuels, cultural norms, and technical barriers influenced the low levels of clean cooking (World Bank, 2019, p.7).

The use of biomass dominated total electrical energy use in Kenya, approximately 68% of biomass electrical energy was used nationally and 98% was domestically used in rural communities. 45 % of Kenya's electrical energy comes from biomass resources, while 7% comes from woodlands and forests across the country. This type of electrical energy use has affected the environment negatively, resulting in deforestation, depletion of biodiversity, land degradation and greenhouse gas emissions (Karanja, A. & Gasparatos, A. 2019, p. 286). This paper lacks specifics as to which regions in Kenya are experiencing deforestation to design an alternative to biofuel for those specific regions to prevent the overuse of biomass.

The industry of charcoal contributes to the economy of Kenya by approximately KES 32 billion (US$ 45 million) annually. As a result, charcoal production has been allowed in Kenya, and Kenya Forest Services (KFS) has managed the relevant regulations and permits. However, there was an overlap of mandates between government agencies relating to the charcoal value chain, which complicated the management and regulation of the wood fuel sector (Karanja, A. & Gasparatos, A. 2019, p. 286).

There was a significant gap in domestic supply and demand, which created a deficit in annual wood supply. This wood supply shortage was estimated at 10.3Mm of wood in 2010. The supply and demand for biomass electrical energy were projected to grow by 20% and 21.6% in 2032, causing the fuelwood and coal shortfall to reach 18.3% and 19.1%, respectively (Karanja, A. & Gasparatos, A. 2019, p. 286).

Welfle, Chingaira and Kassenov (2020, p. 2) presented that more than 75% of biochemicals in Kenya are made from 'traditional biomass' such as charcoal and firewood, and up to 80% of Kenyan households rely on firewood for cooking and heating. This has led to deforestation in some regions and, in extreme cases, exhaustion of the firewood. Consequently, a biomass resource modelling (BRM) tool was used to study how different types of biological resources can be sustainably produced/accumulated/harvested in Kenya to provide alternative fuels for bioenergy systems. Secondly, the life cycle assessment (LCA) analyses were used to evaluate the GHG savings that can be achieved when sustainable bioenergy feedstock is produced as an alternative feedstock (Welfle, A. et al., 2020, p. 2). This analysis concluded that Kenya has large potential bioenergy opportunities through the country's agricultural activities and that Kenya has sufficient land to grow crops for use in bioenergy. Bioenergy generated from briquettes produces less GHG compared to fossil fuels and traditional biomass. This information on the availability of bioenergy assists this research in identifying the available renewable resources in Kenya that can be used as alternative energy.

2.1.1. Cost of Domestic Electricity in Kenya

(Energy & Petroleum Regulatory Authority, 2022, p. 12), as of April 2023, the Energy & Petroleum Regulatory Authority (EPRA) of Kenya approved the retail electricity tariff review for the 2022/23 – 2025/26 tariff period. The approved tariff is displayed in Table 2-1 below.

Table 2-1: Domestic Electricity Tariff Control Period (2022/23-2025/26)

Customer	Energy Limit kWh/month	Unit	2022/23	2023/24	2024/25	2025/26
Domestic Lifeline	0-30	$/kWh	0.0831	0.0832	0.0832	0.0826
Domestic Ordinary 1	31-100	$/kWh	0.1108	0.1127	0.1125	0.1122
Domestic Ordinary 2	>100	$/kWh	0.1426	0.1399	0.1297	0.1262

Kenya has categorised the domestic customers into different classes: Domestic Lifeline: 0-30 kWh, Domestic Ordinary 1: 31-100kWh and Domestic Ordinary 2: >100 kWh. Domestic Ordinary 2 customers pay more than the other categories. The tariffs provided in Table 2-1 are of good contribution as they are the current tariffs which can be used to compare with the cost of electricity after the design of the microgrids.

2.1.2. Installation

By selecting the best possible combination of PV array, wind turbine (40 kW-80 kW) and battery storage or a given place, the device design was cost-optimised. Naturally, electrical energy output (solar irradiation, wind), production and consumption differences in occurrence were location-dependent. Hence, in some places, a provided PV device with battery storage could be oversized and, in others, under-dimensioned. To avoid this, RE_RU_KE used the combination to ensure there was always a power supply in the area for at least 95% of the time (Moner-Girona, M. et al., 2018, p. 1156).

Restrepo, D., Restrepo-Cuestas, B., and Trejos, A. (2018, p. 129) designed two hybrid microgrids in the Pacific Island Countries. The two microgrid designs included PV, wind, storage, and an inverter. However, one design included a diesel generator, while the other did not. A real building located in Medellin was used to obtain the load profiles using the Fluke 435 power analyser, the profiles were then entered into the Homer software, which used the data as a source to estimate the rest of the information for one year (Restrepo, D. et al., 2018, p. 129). The characteristics of the two microgrids are shown in Table 2-2:

Table 2-2: Components of Microgrid 1 and Microgrid 2 (Restrepo, D. et al., 2018, pp. 132-133).

Components	Description	Cost	Microgrid 1	Microgrid 2
			Required	Required
PV System	Kyocera 320-Watt panels	$ 584,90 per panel	√ 504 PV panels	√ 391 PV panels
Wind System	1.5-kW 2.2-m/s turbines	$ 1 464,26 per turbine	√ 59 Wind turbines	√ 3 Wind turbines
Diesel Generator	Kholer 30 kW-h plant	$ 69 184,20	√	
Storage System	Discover 2VRE-6200TF-U	$ 1 081,38 per battery	√ 152 Batteries	√ 79 Batteries
Inverter	Leonics S-219Cp 5kW	$ 1 385,60 per inverter	√ 9 Inverters	√ 7 Inverters
Connection to conventional grid	Grid	$ 174 478,73		√
Total System Cost			**$ 635 302,02**	**$ 504 412,34**

Based on the above Table 2-2, all shared components of the two microgrids have the same cost. The total system cost of MG1 is higher than the total costs of MG2, and MG2 requires a smaller number of components compared to MG1, therefore, economically and technically, it is beneficial to implement MG2.

Chapter 3 : Kenya renewable resource potential, systems cost, installation, load profile.

3.1.1. Renewable Resource Potential

3.1.1.1. Solar PV potential

Kenya has a vast potential in solar electrical energy resources, with insolation averaging 4-6 kWh/m² daily and up to 3500 hours of sunlight all year round (Samu, R. et al., 2019, p. 298). Kenya Power and Lighting Company and Solar and Wind Resources Assessment (SWERA) reported that annually, solar PV generated power was more than consumed electricity from its grid (Samu et al., 2019, p. 298). According to Samu, Poyrazoglu and Fahrioglu (2019, p. 298) , the use of solar resources for electrical energy generation was not harnessed in Kenya despite the country's large availability of the resource.

A study by Oloo, Olang and Strobi (2015, pp. 19-28) assessed the potential of solar PV in Kenya considering the atmospheric transmissivity and topography factors which influence global solar radiation. Monthly transmissivity factors were modelled from a cloud cover combination, altitude effect and diffuse ratios. The influence of topography was factored in by applying the analysis of hemispherical viewshed to establish the amount of surface radiation according to the orientation of the surface. The spatial databases from different themes were integrated using a GIS concept. The results were that 70% of the land of Kenya had a potential of getting 5 kWh/m²/day annually (Oloo, F. et al., 2015, p 28). Figure 3-1 indicates the potential for solar PV in the country.

Currently, in Kenya, small-scale stand-alone PV systems provide 99% of off-grid electrification (Moner-Girona, M. et al., 2019, p. 129).

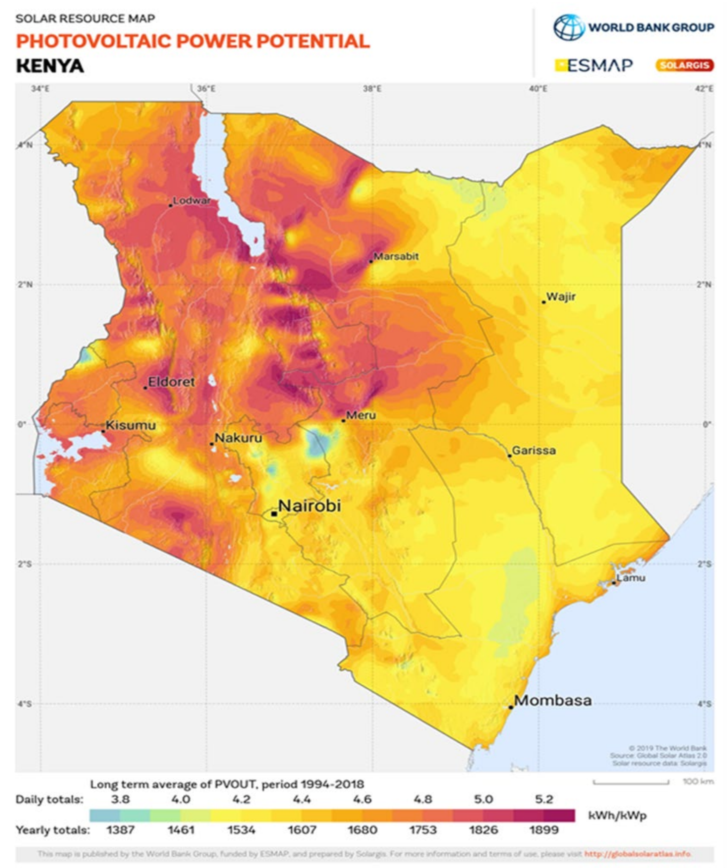


Figure 3-1: Solar resource map for Kenya (World Bank, 2020)

Kenya has good solar radiation with the best potential between the Northern and Western parts of the country, as indicated in the above figure.

3.1.1.2. Wind resource potential

(Muchiri, K. et al., 2023, pp. 5-9) Conducted a study to explore the synergy between wind and solar resources when integrated into a microgrid design in Machakos County, Kenya. The researchers utilised an onsite experiment employing a cup anemometer for measuring wind speed, a wind vane for wind direction, and temperature sensors for ambient temperature. The recorded monthly average wind speeds ranged from 2.5 m/s to 4.9 m/s under standard temperature and pressure conditions.

Located in the northern part of Kenya, Marsabit County is home to the Lake Turkana Wind Power project, featuring 365 wind turbines. Each turbine has a capacity of 850kW, collectively providing a substantial contribution to the country's energy landscape. The project's output is significant, capable of supplying 17% of the total installed capacity in Kenya (Lake Turkana Wind Power, 2022).

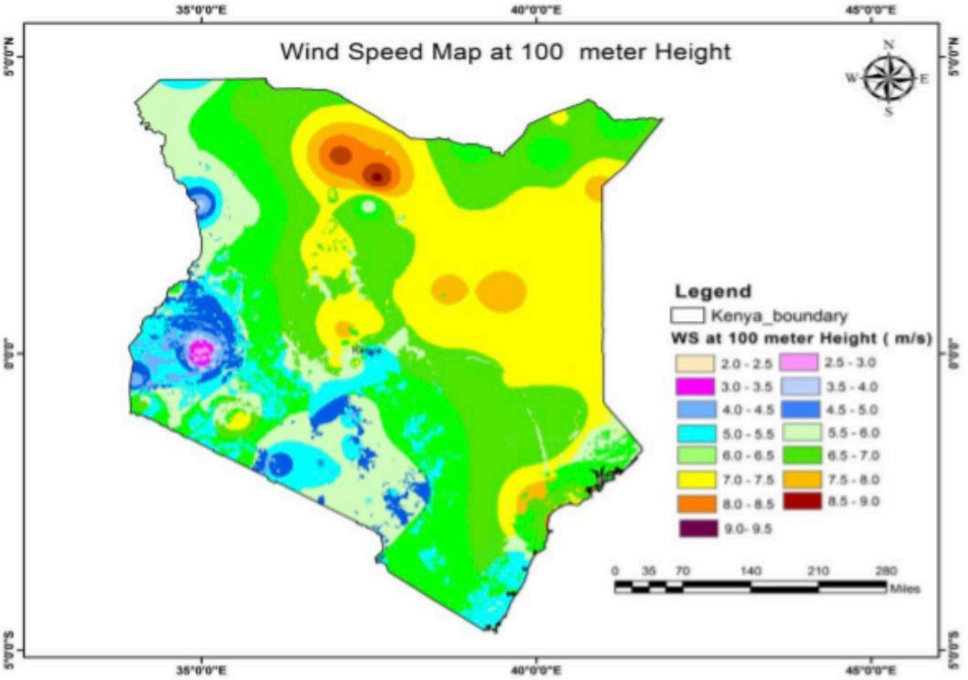


Figure 3-2: Wind Speed Map for Kenya (Energy & Petroleum Regulatory Authority, 2024)

With 73% of the country experiencing wind speeds of 6 m/s or greater at 100 metres above ground level, Kenya has favourable wind speeds. In this case, wind speeds range from 7.5 to 8.5 m/s for 28228 sq. km and from 8.5 to 9.5 m/s for 2825 sq. km. The Lake Turkana Wind Project, being in the northwest of Kenya, is in a good place, as seen in the above figure, which confirms the wind availability in the area. Lake Turkana has wind speeds ranging from 6.5 – 1 m/s at 100-meter height.

3.1.1.3. Biomass resource potential

A study by (Kinyanjui, M. J. et al., 2014, pp. 621-624) recorded an average of 236 megagrams per Hectare of natural forest in the Mau Forest Ecosystem (MFE). This biomass amount was estimated using an integration of 26 allometric equations.

A more recent study (Fumba, M. R. 2019, p 23) researching the status of the conservation of the Maasai Mau forest in Narok County indicated that in the whole of East Africa, the Mau Forests Complex is one of the largest natural forests. There are five main reserves which the forest is subdivided into, namely, Eastern Mau, Western Mau, South-western Mau, Trans-Mara and Olpusimoru, which cover 66,000 ha, 22,700 ha, 84,000 ha, 34,400 ha and 17,200 ha respectively. An area of 46,000 has been found in the forest; however, it is not yet gazetted.

3.1.2. System cost

The costs of renewable microgrids, and microgrids in general, have decreased steadily over the past years. Due to the decrease in costs, the adoption of the technology has been increasing as an alternative to traditional electrical energy approaches (IRENA, 2016, p.24). The costs depend on the number of electrical energy sources, local factors (location, availability to financing, type of technology adopted, governing environment, dependability requirements and electricity demand) and international market conditions (IRENA, 2016, p.24).

According to Abdelsalam, R.A. et al. (2023, pp. 3-4), who were proposing a hybrid AC/DC microgrid, found the equipment costs shown in Table 3-1 for their proposed microgrid. In Egypt, diesel fuel costs $0.361/Litre.

Table 3-1: Microgrid Components Cost (Abdelsalam, R.A. et al., 2023, p. 3)

Component	Initial Capital Cost ($/kW)	O&M Cost
Photovoltaics System	833	$10/kW/year
Wind System	1355	$44.5/kW/year
Diesel Generator	600	$0.005/kWh
Electrolyser	1200	$10/kWh
Fuel Cell	2500	$0.02/h
Hydrogen Tank	1000	$10/kWh

Table 3-1 displays the microgrid component's initial capital cost as well as O&M costs.

Table 3-2 shows the levelized costs of energy (LCOE) found for microgrid generation from different sources in Sub-Saharan Africa (IRENA, 2016:24). These costs are, however, too broad and don’t give details of each component and all costs associated with a system.

Table 3-2: LCOE ranges for 25 kWp solar PV, Solar PV-diesel and 100% solar PV microgrid (IRENA, 2016, p. 24).

Different microgrid sources	LCOE
25 kWp solar PV microgrid	USD 0.43/kWh – USD 0.63/kWh
Solar PV-diesel microgrid	USD 0.46/kWh – USD 0.74/kWh
100% solar PV microgrid	USD 0.467/kWh and USD 0.714/kWh

For a more detailed system cost, research conducted by Gerber, D. L., *et al.* (Gerber, D. L. et al., 2023, pp 10-11) will be looked at where costs of distributed storage in AC and DC microgrids have been analysed. The distributed cost and centralised costs were compared to see the most cost-effective option. For this paper, the centralised costs analysis will be presented in Table 3-3 as it contains all involved costs, and they will be compared with other literature.

Table 3-3: Total Cost/kWh Breakdown

	AC-Central 13 kWh 6.5 kW	AC-Central 25 kWh 12.5 kW	DC-Central 13 kWh 6.5 kW	DC-Central 25 kWh 12.5 kW
Battery	$221	$221	$221	$221
Power Electronics	$141	$118	$113	$94
Electrical BOS	$71	$37	$71	$37
Supply Chain	$22	$19	$20	$18
Sales Tax	$26	$23	$25	$21
Install Labour	$84	$51	$84	$51
EPII	$136	$71	$136	$71
Sales and Marketing	$231	$178	$221	$169
Overhead	$126	$97	$121	$92
Profit	$180	$139	$172	$132
Total	$1,238	$954	$1,183	$906

The 13 kWh and 25 kWh are the battery banks installed on both AC and DC centralised systems. The price of the battery is $221 per kWh, and the power electronics is a kW capacity sized at 50% of the battery kWh capacity, Supply chain is made of 5% of the equipment subtotal. Sales tax is 6.1% of the equipment subtotal. EPII stands for Engineering Fee, Permitting, Inspection, and Interconnections. Sales and marketing costs are derived from 33% of the direct cost subtotal. The overhead is costed at 18% of the direct cost subtotal, and lastly, 17% if the sum of all the project costs will be profits. More detailed costs are provided in this paper; however, the paper only deals with a battery system and does not provide costs for renewable power generation sources like solar, wind, biomass, and hydropower.

Table 3-4 below shows the component costs of a PV/Diesel with Hydro Pumped Storage Microgrid for Mentawai Island in Indonesia (Syafii et al., 2021, p 2). The below cost table includes more components like solar and a diesel generator, and it also gives costs for a different type of storage.

Table 3-4: Components costs for PV/Diesel with Hydro Pumped Storage Microgrid

PV System	
Description	**Cost ($)**
Sharp ND-250QCS 1kW	611.51
Installation	61.15
O&M Cost ($/hour)	12.23
Diesel Generator	
Description	**Cost ($)**
Generic medium genset 1 kW	275.18
Replacement Cost	152.88
O&M Cost ($/hour)	30.58
Inverter	
Description	**Cost ($)**
Solar Inverter Sinecxel 30 kW	3057.55
O&M Cost ($/hour)	0.0
Replacement Cost	3057.55
Hydro Pumped Storage	
Description	**Cost ($)**
Hydro Turbine Generator/Motor and control system	1834.53
Water Dam 300 m³ and pipe installation	4280.58
Replacement Cost	3057.55
O&M Cost ($/hour)	30.58

The pumped storage carries the highest costs in the entire microgrid system, with a total cost of $9,203.24. Batteries could have been a cheaper option and simpler to install. The table above has excluded the fuel costs. As a result, these costs are not a comprehensive reflection of the expected costs of the system. Fuel takes up a significant amount of funds from the total budget, as it is important to include it when costing a project.

A design study of a hybrid microgrid was conducted in the Pacific Islands. The paper analysed two different cases of microgrids (MG) that have the same load requirements: Microgrid 1, which is composed of a PV system, wind turbine, diesel generator and storage system, and Microgrid 2, comprised of a PV cell, a wind turbine and a storage system connected to the conventional grid. Both MG's used the Kyocera 320-Watt PV panels, each panel costing $ 584,90, and they also used the same wind system costing $1 464,26 (Restrepo, D. et al., 2018, p. 130). However, the researcher did not investigate and present the costs of the battery system. The study mentions connecting to the grids, and the costs of the connection have also not been presented.

A study by Moner-Girona M. *et al.* (2018, pp. 1148-1154) included a hardware and non-hardware ('soft') cost classification for PV/hybrid microgrid components. The results were based on the progress of bottom-up data collection and analysis of PV/hybrid microgrids implemented in different rural SSA communities. The methodology used was the dissemination of a detailed survey to microgrid installers currently in business. The survey gathered up-to-date data and evaluated the current PV/hybrid rural microgrid costs installed between 2009 and 2015. The PV/hybrid microgrids had battery storage, backup of diesel storage, and distribution grid low voltage (LV). Components affecting the comprehensive costs of the PV/hybrid microgrids were grouped into different factors and are shown in Table 3-5.

Table 3-5: Rural PV/hybrid microgrids cost factor groups (Moner-Girona, M. et al., 2018, p. 1153).

#	Factor group	Components	Cost Unit	
1	PV array	PV modules	EUR/kWp	Only silicon PV panel technology is considered
		PV mounting structure		
2	BOS	PV cabling	EUR/kWp	
		PV earthing	EUR/kWp	
		Charge controller	EUR/kWp	
		DC protections board	EUR/kWp	
		Inverter	EUR/kW (AC)	Battery inverter and grid-tied inverter (AC bus)[a]
		AC protections	EUR/kW (AC)	General board and surge discharge protections
		AC cabling	EUR/kW (AC)	Inverters AC cabling, AC cabling to main switchboard

3	Storage and Monitoring	Battery bank and battery rack	EUR/kWh	Only lead-acid batteries considered as benchmark. Capacity differentiation, from 1 to 3 days of autonomy.
		DC battery protections	EUR/kWh	
		DC battery cabling	EUR/kWh	The Depth of Discharge (DOD) designed at 70%.
		Control and battery room	EUR/kWh	Main building for batteries, control equipment and others
		Monitoring board and Software	EUR/kW (AC)	Plant measuring operating conditions and monitoring equipment. Data gathering capacities can vary
4	Distribution and Metering and End-users	Street lighting (poles, lights...)	EUR/# connections	LV or MV
		Distribution lines (including cabling and connection boxes)	EUR/# connections	In some mini-grids, there is a distribution grid in place but need refurbishment, usually where a genset is already used to provide the electricity.
		Earthing lines and electronic protections	EUR/# connections	
		End user indoor wiring	EUR/# connections	
		End user metering and protections	EUR/# connections	Metering equipment (equipment installed depends on business model): Fee for service, pre-paid, flat rate, etc.
		End-user devices and household internal devices	EUR/# connections	Includes sockets, light bulbs, radio, TV, refrigerator, etc. Considering energy efficient appliances
5	Back-up generation	Diesel generator and cabling	EUR/kVA	Usually already available on-site, might need refurbishment or replacement
6	Soft costs	Installation, civil works and material	Lump sum	Labour installation: Buildings, land clearing and preparation, fences, etc
		System design and project management	Lump sum	Management, commissioning and engineering
		Capacity building	Lump sum	Strengthening skills, competencies and abilities of community
		Permitting fees, taxes and financing	Lump sum	Administrative and financial aspects
		Transport	Accessibility factor [EUR/km]	Shipping and land transportation
	Other equipment (for O&M)	Spare parts and storage	kWp	Some mini-grids are contracted with a minimum stock of materials

The cost shares of each factor group for PV/hybrid were compared. The capital costs share was 14% on average for PV modules and mounting structure, BOS (balance of system) was 14%, 6% for storage and monitoring, distribution metering and end-user devices costs was 21%, diesel gen-sets had a share of 3% and 27% for soft costs (Moner-Girona, M. et al., 2018, p. 1154). This researcher made a more detailed presentation of how costs were allocated.

3.1.3. Load profiles for rural areas in Africa

There is a challenge with the scarce availability of data and modelling complexity, which makes it difficult to compute load profiles correctly without collecting data on-site (Dominguez, C. et al., 2021, p. 1). To all of this, publicly available data was used. They generated the load profiles by applying machine learning approaches to first identify which cluster (This is the occupant behavioural model, which takes into consideration the daily activities of household (HH) members to determine behavioural patterns, which are then grouped into distinct groups (clusters)) the village belongs to. Secondly, to define the type of lamps they use, and thirdly, to estimate the number of lights they own, both indoor and outdoor. The average monthly radiance values were retrieved from the satellite image with approximate geographic coordinates for each household to account for the night-time lighting, while the streetlight access for each village was acquired from the Energy Sector Management Assistance Program's Multi-Tier Framework (MTF) Survey conducted in Kenya (ESMAP) (Dominguez, C. et al., 2021, p. 2). As a result, this research developed a system for classifying rural houses based on occupant behaviour and forecasting their specific lighting equipment ownership, including the type of lamp used and the amount owned for indoor and outdoor use. This allowed them to determine their prospective electrical energy consumption for lighting only (Dominguez, C. et al., 2021, pp. 3-5). The simulated lighting load profiles are presented in Figure 3-3 below.

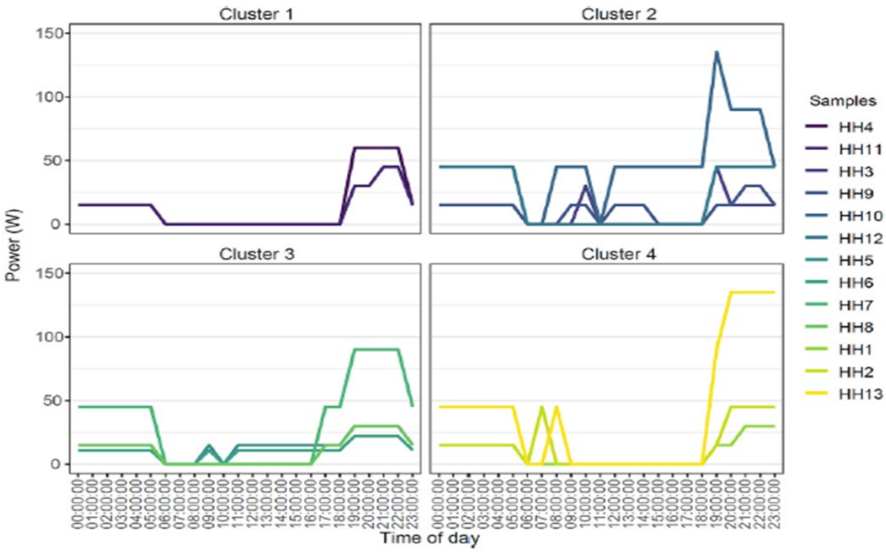


Figure 3-3: Results from the simulated lighting load profiles for households (HH) in each cluster (Dominguez, C. et al., 2021, p. 11).

A study was conducted (Blodgett, C. et al., 2017, p. 88) to compare predicted and actual electricity consumption in eight rural Kenyan mini-grids. The predicted electricity use was gathered by doing a survey of customers on their usage of electricity and what appliances they hope to acquire once they have electricity. Then, the study used the average daily consumption per customer from the mini-grid considering one year to find the actual electricity consumption, the results are tabled below in Table 3-6.

Table 3-6. Individual daily load consumption for Rural Kenya Villages

Time	Power (kW) 1HH	Time	Power (kW) 1HH	Time	Power (kW) 1HH
0:00	0.017	8:00	0.034	16:00	0.048
1:00	0.012	9:00	0.031	17:00	0.036
2:00	0.013	10:00	0.049	18:00	0.068
3:00	0.008	11:00	0.062	19:00	0.049
4:00	0.003	12:00	0.066	20:00	0.052
5:00	0.004	13:00	0.051	21:00	0.040
6:00	0.006	14:00	0.058	22:00	0.030
7:00	0.031	15:00	0.053	23:00	0.021

From Table 3-6 above, it can be seen that the peak is at 18:00 with a demand of 0.068 kW per household.

3.1.4. Energy Policies

Kenya has a long history of policies, approaches, and initiatives like electricity from biomass (Karanja, A. & Gasparatos, A. 2019, p. 287).

Kenya had a vision to explore alternative energy sources to add to the current energy mix in the country. In the Energy Act of 2019, the Government promoted the exploration of new technologies of renewable energy, which include biogas, biodiesel, biomass (usually in the form of fuelwood, charcoal), bioethanol, solar, wind, tidal, hydropower, and more Kenya Ministry of Energy Kenya.

The current energy mix in Kenya is shown below in Figure 3-4.

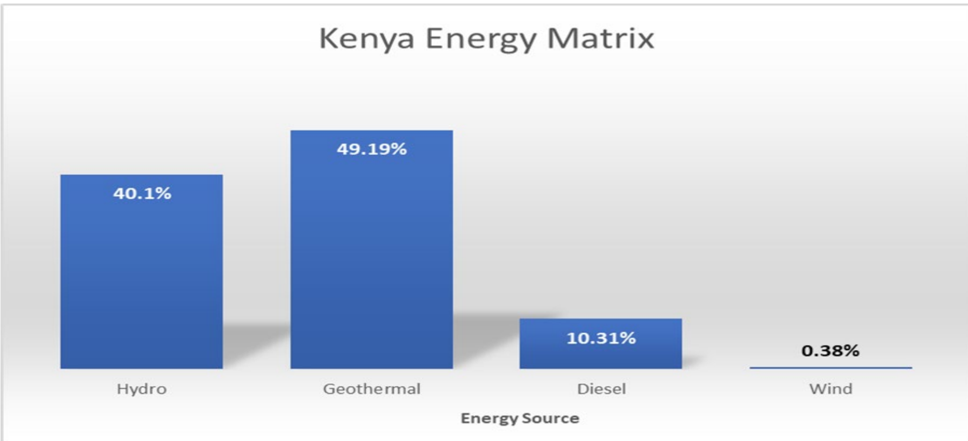


Figure 3-4: Current Energy matrix in Kenya (Government of Kenya, 2019).

The Energy Act No. 12 of 2006 amended and simplified energy laws and provided provisions for defining the regulatory body, its mandate, and its function. The act also placed initiatives to encourage renewable electrical energy technologies (Karanja, A. & Gasparatos, A. 2019, p. 287).

The 2004 Sessional Paper No. 4 set out the overall basis of Kenya's energy policy for achieving economic development.

Kenya has a **Vision 2030** plan, which identifies the opportunity to both diversify Kenya's energy mix and industrialise the agriculture sector through greater use of grown energy crops and agricultural wastes and residues for bioenergy (Welfle, A. et al., 2020, p. 2).

3.1.5. Rural Electrification

The policy aimed to speed up rural electrification through grid extension and off-grid projects and to achieve this, the government had a goal which is demonstrated in Figure 3-5. The policy took into account the criteria for economic productivity and demonstrated the efficient use of power for development and job creation (Kenya Ministry of Energy, 2004, p. 38).

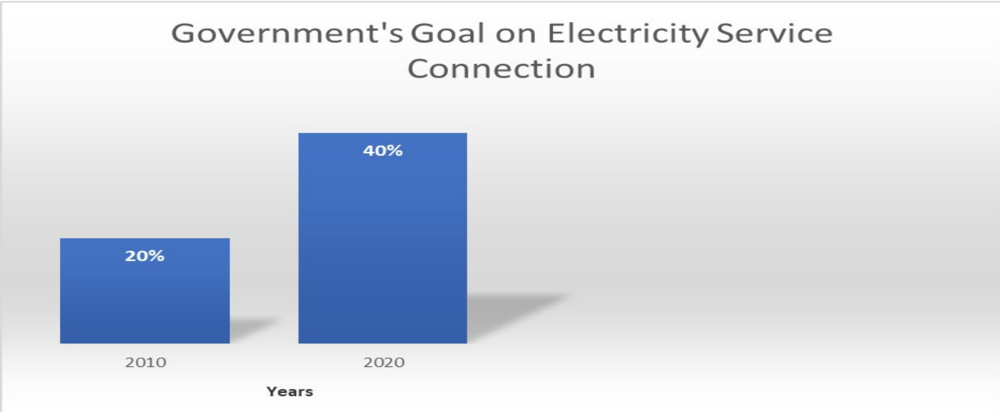


Figure 3-5: Government's goal on electricity service connection (Kenya Ministry of Energy, 2004, p. 38).

The Government's goal was to provide electricity services to 20% of the rural population by 2010, rising to at least 40 % by 2020 (Kenya Ministry of Energy, 2004, p. 38).

To achieve the above goals, the Government was to establish the Rural Electrification Authority (REA) agency, which would manage the Rural Electrification Programme (REP), including the creation of a rolling REP Master Plan outlining the least costly electrification solutions for the target areas (Kenya Ministry of Energy, 2004, p. 38).

Because grid extensions might not be economically feasible and provide cheaper supply options for all rural communities in Kenya, small hydro and/or hybrid off-grid systems with renewable electrical energy and oil-fired components would be developed through the REP Master Plan (Kenya Ministry of Energy, 2004, p. 38).

Rural Electrification activities would be funded by the Government together with the communities on a cost-sharing basis through REA. The REA would administer the distribution of funds based on a fair formula which reflected the criteria for economic, financial and social development (Kenya Ministry of Energy, 2004, p. 38).

To encourage rural electrification through private schemes, the Government planned to create an easily workable regulatory framework, including cost-reflective tariff frameworks for small power. Companies. The policy would allow independent power distributors (IPDs) to enter the electrical energy market serving particularly areas remote from the grid (Kenya Ministry of Energy, 2004, p. 38).

3.1.6. Renewable options

To encourage the adoption of renewable sources for electrical energy, the Government planned to (Kenya Ministry of Energy, 2004, p. 44).

i. Conduct pre-feasibility and feasibility studies on solar insolation, small hydro, and wind.
ii. Draw up and impose standards and codes of practice on renewable technologies to protect consumer interests.

iii. Enable duty-free import of renewable electrical energy hardware to promote extensive use.

In the National Energy Policy 2018, the Government of Kenya had the following policies and strategies on renewables, and they are presented in Tables 3-7 to Table 3-15:

Table 3-7: Kenya policies and strategies on Geothermal (Ministry of Energy, 2018, p. 26)

Geothermal	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. The Government shall continue to support and fund geothermal resource assessment and development so as to manage the geothermal exploration risk and attract investors.	✓	✓	✓
2. Promote research, development and capacity building for geothermal development by providing fiscal and other incentives.	✓	✓	✓
3. Streamline licensing and allocation of geothermal blocks with incentives and sanctions in order to accelerate geothermal development.	✓	✓	✓
4. The government to package incentives through attractive pricing to promote and encourage direct uses of geothermal resources such as utilization of heat, water, gases and minerals.	✓	✓	✓
5. The government to enforce compliance with the regulatory requirement to utilize the best available technologies that optimise the resource and conserve the reservoir	✓	✓	✓
6. Promote early geothermal generation through implementation of efficient modular geothermal technologies.	✓	✓	✓

The above table provides short-term (2018-2022), medium (2018-2026) and long-term (2018-2030) goals to achieve the set policies and strategies which will promote the use of Geothermal energy in Kenya.

Table 3-8: Kenya policies and strategies on Hydropower (Ministry of Energy, 2018, p. 29)

Hydropower	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. The government to develop a hydro risk mitigation mechanism to address risks such as prolonged droughts so as to cushion generators, transmitters, distributors and consumers against effects of adverse hydrology.	✓	✓	✓
2. The government to establish a coordinated approach for the management of water reservoirs.	✓	✓	✓
3. Develop a framework for coordination for use of water resource against various interests.	✓	✓	✓
4. The government to finance conservation of hydro power water catchment areas.	✓	✓	✓
5. The Government shall implement hydro power projects as multi-purpose projects.	✓	✓	✓
6. The government to invest in increased storage capacity for hydro power reservoirs.	✓	✓	✓
7. The government to finance pre-feasibility studies for identification of potential hydropower sites.	✓	✓	✓

Table 3-8 above makes mention of the goal for the management of water reservoirs by forming a coordinated approach.

Below is Table 3-9 with policies and strategies on small hydropower.

Table 3-9: Kenya policies and strategies on Small Hydros (Ministry of Energy, 2018, p. 30)

Small Hydros	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Finance conservation of hydro power water catchment areas.	✓	✓	✓
2. Provide incentives for Public Private Partnerships in small hydros.	✓	✓	✓
3. Invest in hydrological data collection, management and dissemination	✓	✓	✓
4. Promote development of capacity and knowledge on usage of appropriate technologies.	✓	✓	✓
5. Formulate and enforce standards, legal and regulatory regimes for small hydros	✓	✓	✓

Because technology has evolved, Kenya has put a strategy to promote capacity and knowledge of these technologies.

(Welfle, A. et al., 2020, p. 2), Kenya has a **Vision 2030** plan which identifies the opportunity to allow energy mix and the use of bioenergy. To achieve that, the country has placed the following targets described in Tables 3-10 to Table 3-12 below.

Table 3-10: Kenya policies and strategies on Biomass (Ministry of Energy, 2018, p. 32)

Biomass	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. The government to undertake a comprehensive base line study on biomass energy resources and potential, and establish status of tree cover in the country.	✓	✓	✓
2. The government to develop, update and disseminate information on biomass energy resources.	✓	✓	✓
3. Formulate and implement a national strategy for coordinating subsistence and commercial biomass production.	✓	✓	✓
4. Promote efficient conversion and cleaner utilization of biomass energy.	✓	✓	✓
5. Promote the use of biomass briquettes as alternatives to woodfuel.	✓	✓	✓
6. Provide incentives for private sector participation in conversion of waste to energy initiatives to reduce overreliance on Biomass energy	✓	✓	✓
7. Undertake public sensitization and awareness programmes to enhance participation in the management, protection and conservation of the environment as provided for in Article 69 (d) of the Constitution.	✓	✓	✓
8. Promote alternative sources of energy and technologies such as LPG, biogas and solar as substitutes for biomass.	✓	✓	✓
9. Collaborate with other relevant ministries and stakeholders to promote sustainable afforestation programmes.	✓	✓	✓
10. Collaborate with other stakeholders to ensure efficient use of land resource for biomass, food production and other human needs.	✓	✓	✓
11. Undertake and promote Research, Development and Dissemination (RD&D) of biomass energy technologies.	✓	✓	✓

As shown in the above table, the goal is to reduce the overreliance on biomass energy by providing incentives to institutions that come up with alternative energy, and this will reduce the increasing deforestation.

Table 3-11: Kenya policies and strategies on Biofuels (Ministry of Energy, 2018, p. 33)

Biofuels	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Undertake RD&D on biofuel feed-stock.	✓	✓	✓
2. Review the existing legal, fiscal, regulatory and institutional framework.	✓	✓	✓
3. Provide incentives for biofuel production projects and consumption.	✓	✓	✓
4. Collaborate with other stakeholders to ensure efficient use of land resource for biofuel feed-stock, food production and other human needs.	✓	✓	✓
5. Create stakeholder awareness and sensitization on the importance and viability of biofuel production and consumption.	✓	✓	✓
6. Implement the bioethanol pilot program.	✓	✓	✓
7. Initiate and implement biodiesel blend pilot program.	✓	✓	✓

Table 3-12: Kenya policies and strategies on Biogas (Ministry of Energy, 2018, p. 34)

Biogas	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Develop and implement public awareness programs on the benefits and potential of biogas technology.	✓	✓	✓
2. Undertake and promote RD&D of biogas energy technologies	✓	✓	✓
3. Provide appropriate fiscal incentives for local manufacture of biogas plant and equipment, large scale production, storage and distribution.	✓	✓	✓
4. The government to initiate capacity building programs on biogas technology in learning institutions.	✓	✓	✓
5. The government to develop and enforce legal and regulatory requirements on biogas.	✓	✓	✓
6. Support domestic and community based biogas plants among urban, rural population and institutions.	✓	✓	✓
7. Promote the use of biogas as an alternative to woodfuel and kerosene for domestic and commercial energy needs.	✓	✓	✓
8. Roll out biogas initiatives to supply the remaining public institutions including prisons, schools and hospitals as well as biogas bottling plants across the country.	✓	✓	✓

The solar energy short, medium, and long-term goals are provided in Table 3-13.

Table 3-13: Kenya policies and strategies on Solar (Ministry of Energy, 2018, p. 36)

Solar Energy	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Undertake awareness programs to promote the use of solar energy	✓	✓	✓
2. Enforce regulations on standards.	✓	✓	✓
3. Regular review of standards for solar energy technologies and equipment.	✓	✓	✓
4. Provide incentives to promote the local production and use of efficient solar systems.	✓	✓	✓
5. Enforce regulations on building codes on water heating and lightning.	✓	✓	✓
6. Provide a framework for connection of electricity generated from solar energy to national and isolated grids, through direct sale or net metering.	✓	✓	✓
7. Enhance penalties for theft and vandalism of solar systems.	✓	✓	✓
8. Support hybrid power generation systems involving solar and other energy sources to manage the effects caused by the intermittent nature and availability of solar energy.	✓	✓	✓
9. Roll out installation of solar PV systems in all the remaining public facilities in the off grid areas.	✓	✓	✓
10. Procure and distribute solar lanterns to light up rural, peri-urban and urban areas.	✓	✓	✓
11. Undertake RD&D on solar technologies.	✓	✓	✓

Solar energy is the most used renewable energy option, and the Government aims to install solar PV systems in off-grid locations.

Table 3-14 shows Kenya's goals for Wind energy up to 2030.

Table 3-14: Kenya policies and strategies on Wind Energy (Ministry of Energy, 2018, p. 38)

Wind Energy	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Develop institutional capacity for wide spread use of wind energy.	✓	✓	✓
2. Continually review and enforce regulations and standards for wind energy technology.	✓	✓	✓
3. Collect and compile wind energy data and update the wind atlas.	✓	✓	✓
4. Provide incentives for wind energy development.	✓	✓	✓
5. Support hybrid power generation systems involving wind and other energy sources.	✓	✓	✓
6. Provide a framework for connection of electricity generated from wind energy to national and isolated grids, through direct sale or net metering.		✓	✓
7. Plan and invest in transmission lines to facilitate evacuation of power from areas with high wind potential to major load centres.	✓	✓	✓
8. Undertake Research Development and Dissemination (RD&D).	✓	✓	✓

The above table presents long-term goals for wind energy up to the year 2030, which aligns with the research (Kihara, M. et al., 2024, p. 1). The researcher states that wind energy generation combined with geothermal energy will help Kenya to achieve 100% renewable energy by 2030.

Table 3-15 provides policies and strategies for Municipal Waste energy.

Table 3-15: Kenya policies and strategies on Municipal Waste (Ministry of Energy, 2018, p. 39)

Municipal Waste	Short Term 2018-2022	Medium Term 2018-2026	Long Term 2018-2030
1. Develop and implement legal and regulatory framework for exploitation of municipal waste.	✓	✓	✓
2. Develop and implement a framework for collaboration to manage and exploit the municipal waste.	✓	✓	✓
3. Develop programs for data collection and dissemination on the potential of municipal waste.	✓	✓	✓
4. Provide incentives for conversion of municipal waste to energy.	✓	✓	✓
5. Undertake pilot programmes for the generation of electricity using municipal and industrial solid waste.	✓	✓	✓
6. Provide integrated solid waste management plan and roadmaps	✓	✓	✓

One of the set goals, as described in the above table, is to include municipal waste into the energy mix by taking the initiative to start a pilot project to use municipal waste to generate electricity.

3.1.7. Stakeholders

The value chain of clean bioenergy stoves in Kenya includes various phases, which are (a) extraction of raw materials, (b) processing and assembly of stoves, (c) distribution of stoves and sale, and (d) use of stoves. The Kenyan sustainable bioenergy stove value chain involved several stakeholders due to the variety of cooker technologies and designs. Besides those directly involved in manufacturing and selling clean bioenergy stoves, several other stakeholders were interested in clean bioenergy cooking. These included government departments, Nongovernmental organisations, research organisations, funders, and international organisations.

Given the unusual participation of these stakeholders in the actual distribution of cookstoves, their role made a positive contribution to the adoption of renewable bioenergy stoves (Karanja, A. & Gasparatos, A. 2019, pp. 294-300).

Chapter 4 : Renewable Microgrids and Energy Storage Potential

4.1. Renewable microgrids in Kenya

Microgrids have been widely developed in Kenya for rural electrification, mainly as systems that combine photovoltaic modules (PV), a diesel generator and battery power. In these installations, (small) wind turbines have been largely ignored and are practically non-existent in Kenya microgrids despite potential complementary with PV due to specific temporal output profiles of PV and wind power.

The introduction of wind resources in the microgrids would be beneficial because wind was available at night while solar irradiation was available in a specific pattern and approximately 10 hours every day. Figure 4-1. illustrates the wind speed and solar irradiation profile for average daily resources.

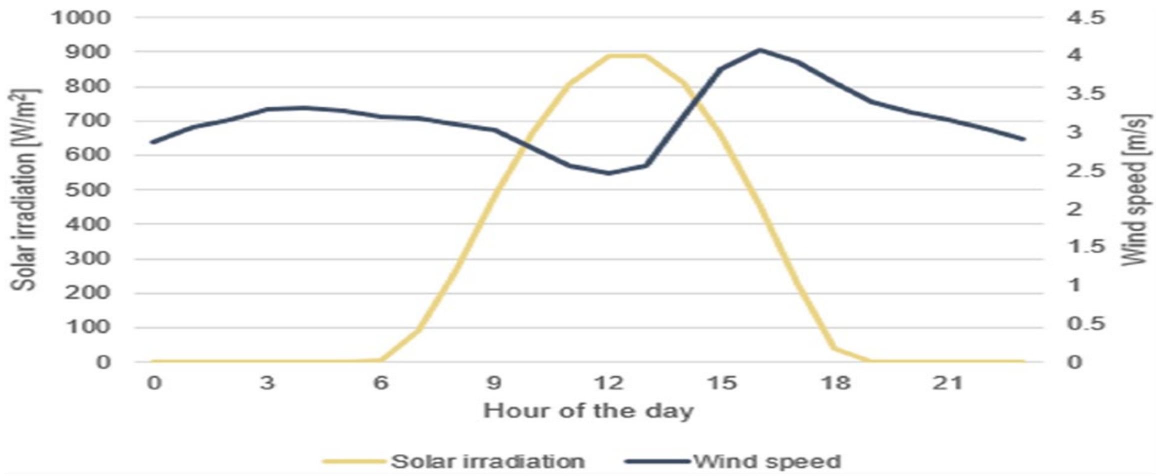


Figure 4-1: Wind speed and solar irradiation profile for average daily resource for Island in Homabay County. 2017 ERA5 data at 10m hub height (Johannsen, R. et al., 2020, p. 112).

As presented in Figure 4-1, the wind speeds range from 3 m/s to 9 m/s, and maximum solar irradiation is around 890 W/m², these values indicate a potential success in developing microgrids using these natural resources. Because of the differences in the times when the wind and solar resources are available and output from PV and small wind turbines (SWTs), the combination of the two resources could be exploited and create PV/wind hybrid microgrids in Kenya (Johannsen, R. et al., 2020, p. 113). In addition, there is a potential for the SWT equipment to be manufactured locally, which can boost the economy and development of the country.

However, the study on the Ringiti base scenario revealed the opposite, where installing a SWT with an average wind speed of 3.18m/s per annum was of little benefit (Johannsen, R. et al., 2020, p. 120). It was then evident that PV/wind hybrid microgrids could only be installed and work efficiently in areas with wind speeds of 4.5m/s and higher, this solution was not practical everywhere in Kenya.

4.2. Electrical energy storage potential and options for Kenya

An evaluation of the system costs over its 20-year target lifetime was conducted for eight PV systems which were specified for rural South Africa. The system contained different available batteries: 4 lithium-iron-yttrium phosphate (LFYP), 3 Valve-Regulated Lead-Acid (VRLA), and 1 Advanced Hybrid Ion Battery (AHIB). To determine the best batteries in terms of techno-economic efficiency, lifetime costs were compared to the value of electricity produced (Charles,R. G. et al., 2019, p. 1209). The paper concluded that the current best choice of battery for rural sustainable small-scale (50 kWh/month) domestic PV in South Africa is the VRLA batteries (Charles, R. G. et al., 2019, p. 1209).

4.2.1. Hydrogen Storage

Dawood, Shafiullah and Anda (2020, p. 2) used hydrogen as an electrical energy carrier due to its longer storage periods and ease of storage capacity expansion. The system was called power to hydrogen to power(X) (X means different applications depending on the hydrogen utilising pathway or end-use). Three main components are comprised in this system: the electrolyser, hydrogen storage and fuel cell, as presented in Figure 4-2.

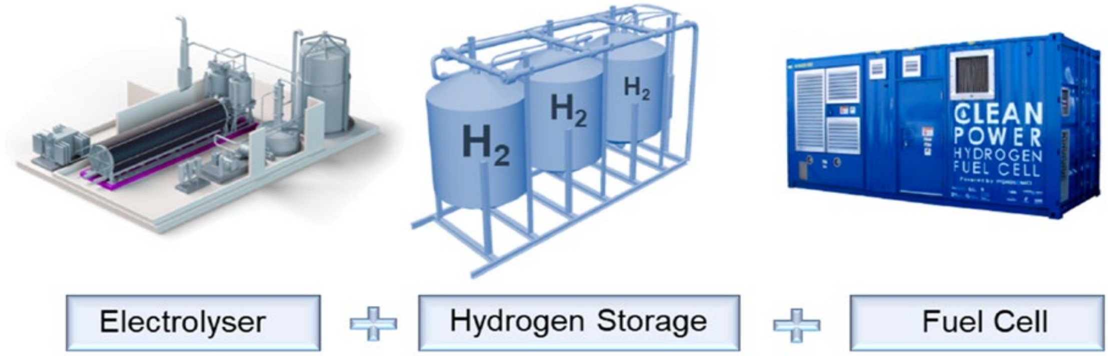


Figure 4-2: Power to hydrogen power (P2H2P) system components (Dawood, F. et al., 2020, p. 4).

Power to hydrogen to power (P2H2P) is a unique concept that could be a promising solution for storing intermittent renewables and generating power when needed (Dawood, F. et al., 2020, p. 4).

4.2.2. Batteries

Batteries are one of the most common electrical energy storage devices used in microgrids, and other devices commonly used are fuel cells, super-capacitors and flywheels (Selim Ustun, T. et al., 2011, p. 4031).

According to Rai, (2015, pp. 174-175) batteries are important to microgrids because they:

i. Maintain power balance despite changes in load and other transients,
ii. Enable distributed generation systems to function as units that can be routed and provide crossing capability,
iii. Enable a transition between grid-connected or island-based microgrid operations by providing initial power,
iv. Ensure uninterrupted power supply,
v. Improve power quality and increase the stability of the micro-network.

According to Rai, (2015, pp. 174-175) there are four forms in which electrical energy may be stored:

- Chemicals (battery and fuel cell),
- Electrical (super or ultra-capacitors and superconducting magnetic energy storage (SMES)),

- Mechanical (flywheels, compressed air energy storage (CAES) systems and pumped hydro),
- Thermal (superheated oil or molten salts).

4.2.3. Secondary batteries

The oldest electrical energy storage is the secondary, which can also be called rechargeable batteries. They are electrochemical devices that can produce electrical energy, and the electrochemical reactions enable chemical energy to be produced to generate electrical energy. The batteries can be recharged by applying a voltage to their electrodes because these electrochemical reactions are reversible (Ibrahim, H. et al., 2008, pp. 1232-1236). Below in Figure 4-3, we show how batteries are commonly used for grid electrical energy storage applications.

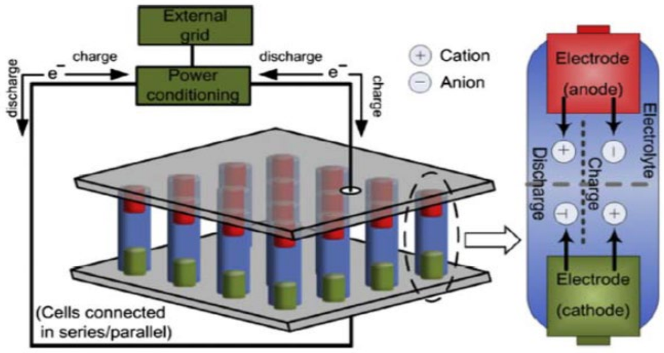


Figure 4-3: Schematic diagram for a battery system operation (Akinyele, D. et al., 2017, p. 5).

In a battery storage system, there are electrochemical cells which are wired in series. Each electrochemical cell comprises an anode, a cathode and an electrolyte (Bipongo, C. N. 2021:33). The electrochemical cell can function in either scenario—convert electrical energy into chemical energy or generate electrical energy through electrochemical reactions (Akinyele, D et al., 2017, p. 5).

Due to their easy design and manufacture, batteries are the most used form of storage system (Bipongo, 2021:34). Among the different kinds of batteries in the market, lead-acid batteries, nickel-based batteries, lithium-ion batteries, and redox batteries are the most well-known (Achkari, O. 2021, pp. 69-79).

- **Lead Acid Battery:** With a 2V per cell and an energy density of between 30 and 50 Wh/kg, this type of battery is mostly used for emergency power supplies and for starting cars (Azzollini, I. A. et al. 2018). The cost per cycle is about US $ 0.10, and the benefits of the lead acid battery are (Bipongo, C. N. 2021, p. 32):

  i. Cheap,
  ii. Low self-discharge,
  iii. High tolerance at the temperature of charging and discharging.

The disadvantages are:

  i. Low energy density,
  ii. Limited lifespan,
  iii. Slow charge.

- **Nickel-Based Battery**: This battery includes two technologies, which are a nickel-metal hybrid (NiMH) battery and a nickel-cadmium (NiCd) battery. These batteries can support less load due to their good memory (Vazquez, S. et al., 2010, p. 3882). The cost per cycle of this battery is approximately US $ 0.12. Other characteristics include a maximum discharge rate of 10 °C, a rapid charge time of 1 to 2 hours, and a slow discharge period of 15 hours. The disadvantage of the battery is that it requires complex recycling. Nickel-metal hybrid batteries and lithium-ion batteries have gradually replaced the nickel-cadmium (NiCd) battery (Bipongo, C. N. 2021, p. 34).

- **NaS Battery:** Liquid sodium and liquid sulphur make up this battery technology. Only positively charged sodium ions can travel through the electrolyte, and these ions will react with sulphur to form sodium polysulphides, as shown in Equation 4-1.

$$2Na + 4S = Na^2S^4 \qquad \textbf{(4-1)}$$

The operation system of this battery is reversible. In the discharge mode, the positive sodium ions in the battery's external circuit circulate in the electrolyte to generate a voltage of about 2V. The sodium polysulphides are induced to return the positive sodium ions across the electrolyte during the charge operation, resulting in a recombination of electrons and the formation of elemental sodium. The battery should be maintained at a temperature of about 300 °C to enable this process. The advantage of this battery is its efficiency (about 89%) and a higher pulse power capacity that is six times greater than its continuous rate (30s) (Bipongo, C. N. 2021, p. 34).

- **Lithium-ion Battery:** The Lithium-ion battery is commonly used in devices like laptops, mobile phones, and other portable electronic devices. These batteries are used in many applications because of their energy density capacity. The lithium-ion battery has advantages that include (Bipongo, C. N. 2021, p. 35);
  i. High energy density
  ii. Long lifetime
  iii. Low self-discharge rate.

Because of these aspects, this battery is classified as the best battery for electric vehicles.

The disadvantages include.

i. High cost and a protection exigency for limiting the voltage and current.

Li-ion batteries can be found in 5 diverse types depending on cathode materials. These types include Li-Cobalt (LCO), Li-Manganese (LMO), Li-Phosphate (LFP), Lithium-Nickel Manganese-Cobalt (NMC), Lithium Nickel-Cobalt Aluminium (NCA) and Li-Titanite batteries (LTO). In comparison to other technologies, lithium-ion batteries are regarded as a more reliable electrical energy storage solution for micro-grid applications because of their fast response characteristics, high power density and electrical energy, and good scalability (from 1kW to 100MW) in diverse applications (Bipongo, C. N. 2021, p. 35).

Lai, C. S. et al. (2019, p. 2) presented the usage of lithium-ion battery/storage for solar and biogas hybrid energy systems and examined the financing of electrical energy storage (EES). The charging of the EES could be from the PV/biogas hybrid power plant. Degradation affected the efficiency of the electrochemical storage systems significantly. It affected storage and power capacities and, therefore, the storage capacity to meet electrical demands (Birkl, C.R. et al., 2017, p. 373). Owing to operating and environmental conditions, the lithium-ion cells degrade. The degradation could be categorised as cycling-induced deterioration and ageing according to the calendar (Lai, C.S. et al., 2019, p. 3).

According to Clemens, K. (2022) , the price of lithium-ion battery costs $1,200 per kWh. However, today, thanks to the continuous development of cheaper and more powerful lithium-ion batteries for use in electric vehicles, the costs have dropped to between $150 - $200 per kWh.

- **Metal-air Battery**: These batteries are generally known as the cheapest technology and are characterised as the most conventional technology. Their disadvantage is the difficulty and inefficiency of recharging them electrically. Rechargeable metal-air batteries have an efficiency life of only about 50% and just a few hundred cycles when improved. These batteries' anodes are made of high-energy-density metals. The electrolytes are generally constituted of a good conductor of OH- ions like KOH (Bipongo, C. N. 2021, p. 36).

- **Redox Flow Battery:** The redox flow battery (RFB) is a recent technology. It comprises a cell voltage of 1.15V to 1.55V. The design of these batteries allows them to manage intense electrical energy applications that need many deep charging/discharging cycles (over 10,000 cycles). Redox flow batteries offer a single capability to separate power from electrical energy and can react swiftly to changes in load or input (Bipongo, C. N. 2021, p. 36).

The amount and concentration of the reactants, as well as the size of the reagent reservoir, can be used to define energy, whereas the size of the reactor allows for the determination of this battery's output power. Because of this, the RFB can generate a large power ranging to energy ratios. The advantage of this battery is that the discharge of the battery is safer compared to other batteries due to the reactants being stored in separate tanks. As a result of all these factors, the redox flow battery is comparatively well suited for large electrical energy storage systems with numerous deep discharge cycles. The disadvantages of the RFB are that they have a medium power density (25 to 35 W/kg), a lower energy density, and a more complex system in comparison to ordinary batteries. However, these batteries are a high price, similar to Li-ion batteries (about $500/kWh) (Bipongo, C. N. 2021, p. 36).

Chapter 5 . Modelling and Design using Homer Pro

Renewable Microgrids energy systems are considered as the possible ways of electrifying communities where it would be high costs to connect to the main grid due to their location. The selected suitable designs are intended to provide cost-effective electrical energy to households in each of the villages of Mumbiri, South Korr, Kitulu, Mkwiro, and Sasimwani Village, which are in Kenya, and the Villages will be referred to as Village A, B, C, D and Village E respectively. Family members in each household were approximately four (04) family members in the 2015/16 Kenya Integrated Household Budget Survey (KIHBS) (Kenya Integrated Household Budget Survey, 2018, p. 30).

The method of investigation that will be used is HOMER Pro Energy Modelling. A study was conducted (Blodgett, C. et al., 2017, p. 88) to compare predicted and actual electricity consumption in eight rural Kenyan mini-grids. The electrical load findings from this study will be used in this design as the studied locations are in the same country as the locations aimed to be designed for. The maximum customer consumptions will be used to ensure to cover all possible demands. A simulation will be done, and the suitable system configurations that can supply the demand of each of the villages will be selected.

5.1. Design procedure and methodology

This paper will follow the design procedure of Microgrid as illustrated in Figure 5-1.

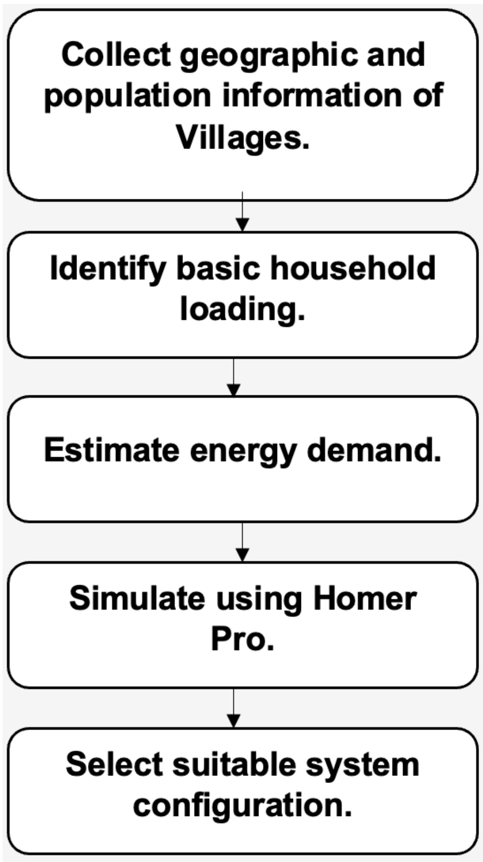


Figure 5-1: Design process of the proposed Microgrid system.

An analytical approach is used for this proposed design because it is the commonly used tool for Microgrid design. In this method, a simulated Microgrid system is represented as a computational model with a feasibility index for each model. Technical, meteorological, and economic inputs are used to calculate the index, which the designer can assess the performance of different Microgrid systems (Prakash, S. S. et al., 2018, p. 248).

5.2. Mathematical modelling of main components used in microgrid design.

This study examines the photovoltaic (PV) system, energy storage (battery), inverter, wind turbine, and biomass generator as components of the microgrid. A collection of mathematical formulas is used to simulate each component, capturing its operating properties under various loads and environmental conditions.

5.2.1. Wind Energy Mathematical Modelling

To anticipate turbine output and maximise its integration into power systems, wind power modelling is crucial. It offers information on energy generation, system stability, and viability from an economic standpoint. This study evaluates the contribution of turbines to the energy mix of a microgrid through wind power modelling. This wind energy model is characterised by the variation of wind speed and wind velocity with gusts (Gunasekaran, M. et al., 2018, pp. 7-8).

$$W_V = V_w + V_g + V_{wr} \qquad \textbf{(5-1)}$$

With, V_w is the base wind velocity (m/s), V_g being the gust wind velocity (m/s), and V_{wr} is the ramp wind component.

The gust speed is as follows:

$$V_{wg} = \left\{ \begin{array}{c} 0 t < T_1 \\ C_2 \left\{ 1 - cos\pi \left[\frac{t - T_1}{T_2 - T_1} \right] T_1 \leq t \leq T_2 \right\} \\ 0 t \geq T_2 \end{array} \right\} \qquad \textbf{(5-2)}$$

$$V_w = \left\{ \begin{array}{c} 0 s < T_3 \\ C_3 = \left\{ \left[\frac{t - T_1}{T_2 - T_1} \right] T_3 \leq s \leq T_4 \right\} \\ 0 s \geq T_4 \end{array} \right\} \qquad \textbf{(5-3)}$$

With, C_2 being the maximum gust value, C_3 = maximum wind speed due to ramp, and T_3 and T_4 are the ramp start and stop times, respectively.

Wind power is calculated as follows:

$$P_w = \frac{dW_w}{dt} \qquad \textbf{(5-4)}$$

The energy drawn by the wind turbine is calculated using the below formula 5-5:

$$\left. \begin{array}{l} W_w = V_a \times \frac{1}{2} \rho \left({V_1}^2 - {V_3}^2 \right) \\ P_W = d \frac{V_a \frac{1}{2} \rho \left({V_1}^2 - {V_3}^2 \right)}{dt} \end{array} \right\} \qquad \textbf{(5-5)}$$

With, W_w being the energy drawn by the wind turbine and ρ is the air density.

The maximum wind turbine power output is given below:

$$P_M = \frac{16}{27} A_R \frac{3}{2} V^3 \quad \textbf{(5-6)}$$

The value for V_1 and V_2 is substituted to get Equation 5-7.

$$V_2 = \frac{2}{3} V_1 \quad \textbf{(5-7)}$$
$$V_3 = \frac{1}{3} V_1$$

The output power that the turbine captures is represented by the wind turbine model [33–36]. The characteristic curve for wind speed vs. power is displayed in Figure 5-2. One can determine the wind power (Pw) in each region by.

$$P_W = \frac{1}{2} \rho A W_V{}^3 \quad \textbf{(5-8)}$$

$$P_M = P_W C_P \quad \textbf{(5-9)}$$

$$C_P = \frac{1}{2}[\delta - 0.22\beta^2 - 5.6]e^{-0.17\delta} \quad \textbf{(5-10)}$$

β = Blade pitch angle in degrees, δ = Turbine tip speed ratio, and C_P = Power coefficient.

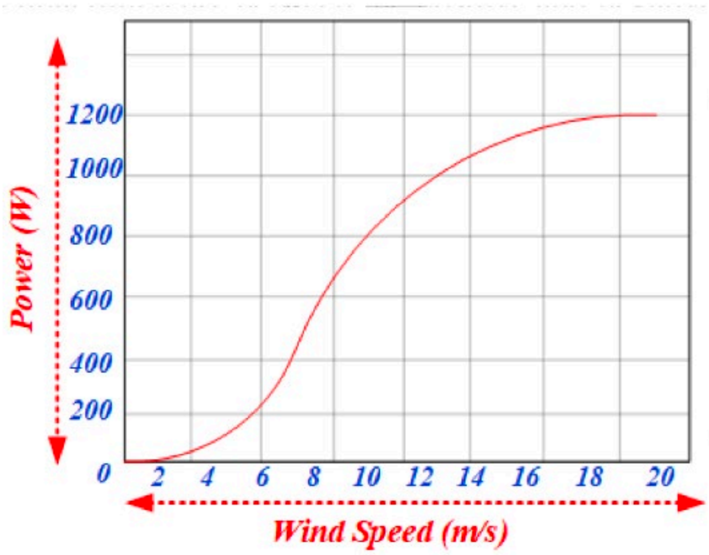


Figure 5-2: Wind system characteristic curve (wind speed vs. power) (Gunasekaran, M. et al., 2018, p. 8).

Wind-generated power is articulated as follows:

$$p_G = V_G I_G \quad \textbf{(5-11)}$$

5.2.2. Solar Power Mathematical Modelling

The goal of modelling is to understand a system's characteristics; in the case of solar power, two parameters are specifically considered: ambient temperature and irradiance. Study reports have demonstrated that a PV model may be complex, depending on the systems.

The PV module's output power is determined by the solar irradiation and the area of the PV module. Formula 5-12 below determines the PV model's output. (Gunasekaran, M. et al., 2018, p. 5)

$$P_{solar} = \eta_g i_r A \quad \textbf{(5-12)}$$

With, η_g being the generation efficiency, i_r is the solar irradiation (W/m²), A is the area (m²), and Equation 5-13 is used to calculate the PV efficiency.

$$\eta_{ce} = \eta_{ref}\eta_{ce}[1 - \beta(T_{ceLL} - T_{cellref})] \quad \textbf{(5-13)}$$

With, η_{ce}being the power conditioning efficiency, β is the temperature co-efficient C ((0.004-0.006)/C), η_{ref} is the reference module efficiency, $T_{cellref}$ is the reference cell temperature, and the temperature is calculated using Equation. 5-14.

$$T_c = T_a + \left[\frac{NOCT - 20}{800}\right] G_t \quad \textbf{(5-14)}$$

With, T_a being the temperature in C, $NOCT$ is the nominal operating cell temperature in C, G_t is the solar radiation in the titled module (W/m²).

Equation 5-15 Below is used to calculate the total radiation in the solar cell considering normal and partial solar radiation.

$$T_l = I_D R_D + (I_b + I_d) R_r \quad \textbf{(5-15)}$$

5.2.3. PV system Mathematical Modelling

The PV cell operates by converting light energy into electricity using the photovoltaic effect. The connection of multiple PV cells in series and parallel make up a PV module. Figure 5-3 shows how one PV cell is configured into one diode representation. In this model, the circuit parameters include the diode current I_d, the output current I, output voltage V, parallel resistance R_p, and series resistance R_s, and the solar irradiance is described by a current source (Gunasekaran, M. et al., 2018, pp. 5-7).

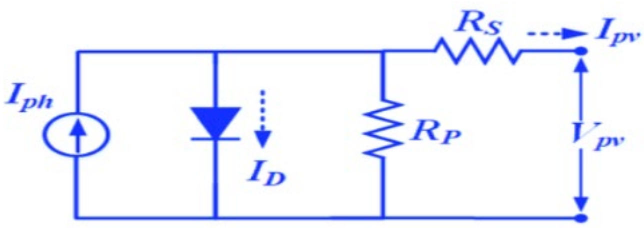


Figure 5-3: A single diode model of a PV cell **(Gunasekaran, M. et al., 2018, p. 6)**

$$I = N_p\left[I_{ph} - I_{rs}\left(\frac{\exp q(V + IR_s)}{AKTN_s}\right) - 1\right] \quad \textbf{(5-16)}$$

$$I_{RS} = I_{rr} - \left[\frac{1}{T_K} - \frac{1}{T}\right] \quad \textbf{(5-17)}$$

With, N_p and N_s being the number of cell connected in parallel and series, K Is the Boltzmen constant, A being the diode ideality factor, IR_s is the reserve saturation current of cell at T, T_r is the refered cell temperature, and I_{rr} is the reserve saturation current at T_r.

$$I_{ph} = \left[I_{scr} + K_i(T - T_r)\frac{S}{100}\right] \quad \textbf{(5-18)}$$

With, I_{scr} being the short circuit current at a reference temperature of the cell. K_i is the co-efficient of the short circuit temperature, S is the solar irradiation in (W/m²). Equation 5-19 below is used to calculate the characteristics of I-V, while the shunt resistance is parallel to the ideal shunt diode.

$$\mathrm{I} = I_{ph} - I_D \quad \textbf{(5-19)}$$

The characteristics of the PV array are described by the below Equation 5-20:

$$\mathrm{I} = I_{ph} - I_o\left[exp\frac{q(V + IR_s)}{ATK} - 1\right] - \frac{V + R_s I}{R_{sh}} \quad \textbf{(5-20)}$$

With, I_{ph} being the radiance current (A), I_D is the diode current (A), I is the cell current (A), R_s is the series resistance (Ω) I_o is the inverse saturation current (A), R_{sh} is the shunt resistance (Ω), V is the cell voltage, and Equation 5-21 below is used to express the output current of the PV cell using a single diode.

$$\mathrm{I} = I_{PV} - I_{D1} - \frac{V + R_s I}{R_{sh}} \quad \textbf{(5-21)}$$

The PV module maximum power and open circuit voltage is obtained by the simplified PV system. The fill factor is used to calculate the voltage and power with series resistance values (R_s).

$$\left.\begin{array}{r} FF = FF_o\left[1 - \frac{\frac{R_s}{V_{OC}}}{I_{SC}}\right] \\ FF_o = \frac{V_{OC} - In(V_{OC} + 0.72)}{1 + V_{VOC}} \end{array}\right\} \quad \textbf{(5-22)}$$

$$\left.\begin{array}{r} P_{max} = FF \times V_{OC} \times I_{OC} \\ P_{max} = \frac{V_{OC} - In(V_{OC} + 0.72)}{1 + V_{OC}} \times (1 - \frac{I_{SC} \times R_S}{V_{OC}}) \times \frac{V_{OCO}}{1 + \beta In\frac{G_O}{G}} \times (\frac{T_O}{T})^{\delta} \times I_{SO}(\frac{G}{G_O})^{\propto} \end{array}\right\} \quad \textbf{(5-23)}$$

With, FF being the fill factor of the ideal PV module without resistive effects and V_{OC} is the normalised value of the open circuit voltage to thermal voltage.

The PV modules bring about the power conversion in the PV system. Figure 5-4 shows the PV temperature and characteristic curve (power & V, I curve) at standard test conditions, which showcases the efficiency of the PV. To achieve the required PV power, several PV cells are interconnected in series and parallel. PV modules are scaled up to get the voltage and current and are expressed as follows:

$$I_A = \frac{N_p}{I_M} \\ V_A = N_s \times V_M \\ P_A = FF \times V_A \times I_A \quad (5\text{-}24)$$

With, I_A and V_A being the cell voltage and current, I_M and V_M are the PV module voltage and current, and P_A are the PV array power and module power.

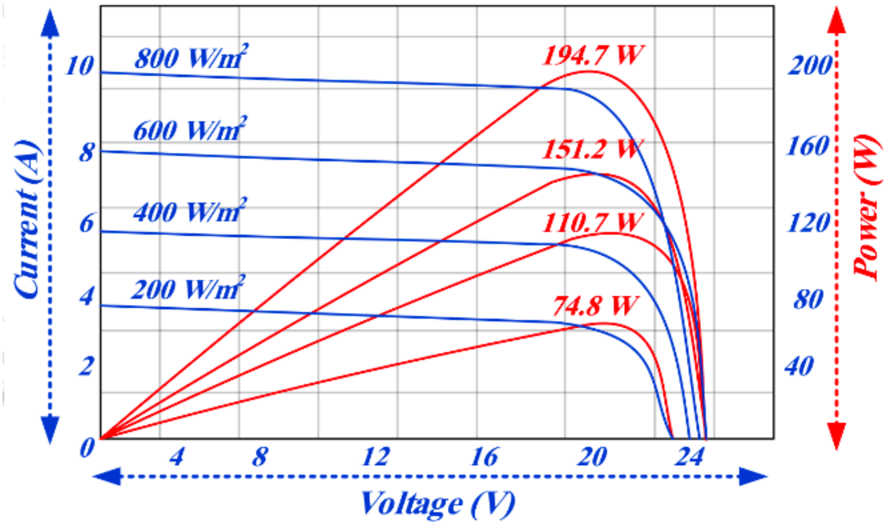


Figure 5-4: Solar cell characteristics curve (voltage vs. current power) (Gunasekaran, M. et al., 2018, p. 7)

5.2.4. Battery mathematical modelling

The parameters V and I are the main factors when it comes to modelling the battery. The current results from the battery's terminal voltage change, while the generation of the current results from the transfer of electrons from one electrode to another. The positive and negative electrode potential differences determine the open circuit voltage at the battery. The charging/discharging of the battery is described as follows:

$$V_{discharge} = E_o - V_{op}{}^{+} - V_{op} - IR_{pol} \quad (5\text{-}25)$$

$$V_{charge} = E_o + V_{op}{}^{+} + V_{op} + IR_{pol} \quad (5\text{-}26)$$

$$V_{battery} = E_o - K\left[\frac{Q}{Q - it}\right]i - R_o i \quad (5\text{-}27)$$

$$V_{battery} = E_o - \left(\frac{K}{S_{OC}}\right)i - R_o i \quad (5\text{-}28)$$

$$V_{discharge} = E_o - K_{dr}\frac{Q}{Q - it}i_1 - R_o i - Kd_v\frac{Q}{Q - it}it + e(t) \quad (5\text{-}29)$$

$$V_{charge} = E_o - Kc_r\frac{Q}{it + \lambda Q}i_1 - R_o i - Kc_v\frac{Q}{Q - it}it + e(t) \quad (5\text{-}30)$$

$$e(t) = Bi[e(t) + Au(t)] \quad (5\text{-}31)$$

$$V_{discharge} = E_o - K_{dr}\frac{1}{S_{OC}}i - R_o i - K_v(\frac{1}{S_{OC}} - 1) + e(t) \quad (5\text{-}32)$$

There is an option to write Equation 5-27 differently and use the state of charge because of the polarisation of ohmic voltage. The shepherd relation model is used to modify Equation 5-29 And Equation 5-30. E_o is the open circuit of a battery (V), while K represents the polarisation coefficient (Ω), Q is the battery capacity (A/h), and R represents the internal resistance. Equations 5-29 and 5-30 have limitations, which include, firstly, ageing of the battery and self-discharge, secondly, battery capacity does not rely on the amplitude of the current, and thirdly, consideration of temperature coefficient. The SoC condition is analysed frequently and is calculated with threshold capacity using Equation 5-33:

$$Soc = Soc_{in} - \int_0^t (i - \max(i_g, i_d)) \frac{d\tau}{Q} \quad \textbf{(5-33)}$$

The total power of the DC microgrid architecture is calculated by adding up all the power from the different energy sources.

$$P_{net} = P_{PV} + P_{Wind} + P_{Biom} + P_{Battery} \quad \textbf{(5-34)}$$

5.3. Mathematical Formulation of Optimisation Objective Functions

5.3.1. Optimisation Objective Function

Following is the mathematical expression for the NPC, which is what is aimed at optimising the system. The NPC represents the lifetime cost of the system, including capital, operational, and maintenance costs.

In this microgrid system, it is hoped to optimise the NPC, which is the representation of the system's total lifespan cost, which includes maintenance, operation, and capital expenses. Equation 5-35 below presents the objective function:

$$\text{Minimise: } C_{NPC} = C_{cap} + \sum_{t-1}^{T} \frac{C_{op} + C_{maint}}{(1+r)^t} \quad \textbf{(5-35)}$$

With, C_{NPC} being the total net present cost, C_{cap} is the initial capital cost, C_{op} is the operating cost, C_{maint} is the maintenance cost, r is the discount rate, T is the total time horizon for analysis (years).

5.3.2. Constraints

Energy demand:

The limitations or specifications that the system needs to adhere to are called constraints. These can include making sure the system can handle a given load, storage capacity, and minimum percentage of renewable energy. The constraint for this system is described by the following Equation 5-36.

$$E_{gen} \geq E_{load} \quad \textbf{(5-36)}$$

This guarantees that, always, the system's energy generation must equal or exceed the energy needed for the load.

Renewable fraction:

100% of the energy generated must come from renewable energy.

$$E_{renewable} = 100\% \quad \textbf{(5-37)}$$

5.4. Energy Management Strategy

The energy management system is a technique used to monitor and improve the system's performance. For a variety of power grid applications, the EMS is typically used to schedule programs and manage power generation. Nonetheless, EMS might be taken into consideration as an additional method of microgrid electrical load control.

Three renewable energy sources are included in the suggested DC microgrid architecture, together with a storage device to continually provide the demand. The microgrid is designed to meet household loads and streetlights. The household loads will be taken as a priority load in the system. The following formula is used to determine the load demands and net power generation:

$$P_G = P_{pv} + P_{Wind} + P_{Biom} \quad \textbf{(5-38)}$$

$$P_L = P_{HH} + P_{SL} \quad \textbf{(5-39)}$$

With, P_G being the power generation, P_{pv} is the power produced from PV, P_{Wind} is the power produced from wind, P_{Biom} is the power produced from biomass, P_L is the load demands, P_{HH} is the household loads, P_{SL} is the streetlight loads.

When there is an excess of power generated, the battery bank will charge; when the power generation is insufficient to meet the demands of the load, it will discharge. The power generation will meet the load demands under four scenarios and with the assistance of the battery bank, according to the developed architecture. Figure 5-5 shows the generated flow chart architecture.

First, the following scenarios will be used to quantify the load demand and power generation from various sources:

Scenario 1: When the overall load demands are equal to the power generation.

According to this scenario, electricity generation from solar, wind, and biomass sources supplies the loads continuously without any shortage.

Scenario 2: When the overall load demands are exceeded by the power generation.

In this scenario, the power generation exceeds the load demands; therefore, excess production is used to charge the batteries, and the power generation directly feeds power to the entire load demands. While the power generation provides the loads, the battery's SoC is measured. The requirement is that the battery will be charged until its SoC reaches the maximum value, and the extra power will be given to the auxiliary load if it has a minimum value which is less than 100%.

$$SoC_{min} < SoC_{battery} < SoC_{max} = 20\% < SoC_{battery} < 100\% \quad \textbf{(5-40)}$$

$$P_G > P_L = \text{Charging} \quad \textbf{(5-41)}$$

Scenario 3: When the power generation is exceeded by the overall power demand.

In this case, the battery bank will assist in supplying the loads. The energy generation and load differential are measured and computed by the EMS. Simultaneously, the battery bank's SoC will be measured. When there is sufficient power in the battery to meet the demands of the load, the battery is discharged until its SoC drops to its lowest point.

$$P_G < P_L = \text{Discharging} \quad \textbf{(5-42)}$$

$$P_L = P_G + P_{battery} \quad \textbf{(5-43)}$$

$$SoC_{battery} < 20\% = \text{Disconnect} \quad \textbf{(5-44)}$$

Scenario 4: When the battery's state of charge (SoC) is less than 20%, and the generation power is also less than the load demands.

The battery will be disconnected from the system when the SoC falls below 20%. At that point, the household and streetlight loads will be powered by the renewable energy sources that are currently producing electricity. The available power generation will next be examined to see if it is sufficient to meet the two load needs, that will be done after the difference in power between the two load demands and the power generation has been computed. If the power generation is enough, the power generation will provide the two loads; if not, it will only supply the household load, which is the priority load. To determine if generated power can meet the demand for the priority load, the EMS will compute the difference between power generation and priority load. The available power generation will supply the priority load if the condition is accepted. On the other hand, if the criterion is not met, the difference between the streetlight load and the power generation will be measured to see if the available power generation is sufficient to meet the streetlight load. If the condition is accepted, the available power production from renewable sources will provide the demand for streetlight load; if not, the system will shut down, and the battery bank will receive the available power generation from renewable sources. The system will continuously monitor the power generation until the battery's SoC reaches 20% or the power generation becomes operational.

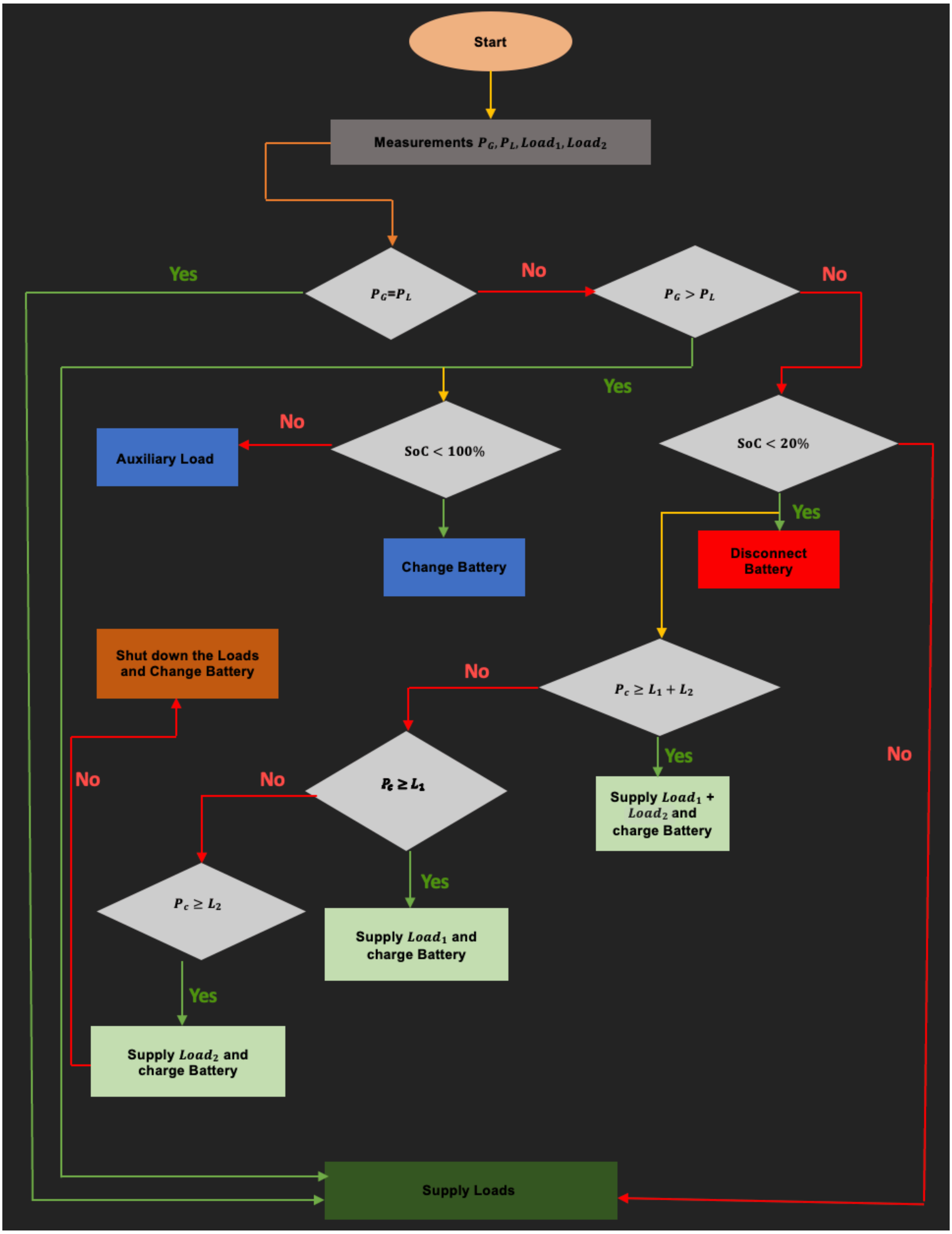


Figure 5-5: Energy Management System Flowchart

5.5. Load Location and modelling using Homer Pro

The villages are in remote areas across Kenya. Some of the villages are currently unelectrified, and some are under-electrified, so the load will be assumed based on literature and inserted on Homer Pro according to the size of the Village.

Fifteen appliances will be considered for household loads, and these are the appliances that a typical rural household owns or wishes to own in the future. The appliances are a phone charger, CFL, LED, TV, TV decoder, Radio, DVD player, Woofer, Music system, Hair dryer, Freezer, and Blow dryer. Desktop computer, Laptop computer, and a Fan.

5.5.1. Village A

Mumbiri is in Busia County, west of Kenya, near the border with Uganda. It is approximately 458km from Nairobi, the Capital City of Kenya. The proposed design for the microgrid system is considered for 60 households which are currently not electrified. As shown in Figure 5-6, Mumbiri Village is located at coordinates 0º26.6'N, 34º12.5'E, and it is close to Busia Town.

Solar energy is suitable for this location because, according to (World Bank, 2020), the photovoltaic power potential is high and is between 1753 kWh/kWp and 1826 kWh/kWp. Busia County has sugar factories, and the suppliers are surrounding local village farmers, within a radius of 5 km is Busia Sugar Industry, and Mumbiri residents are some of the suppliers. The factory crushes and processes 3000 tons of sugar cane daily (Busia Sugar Industry, 2024). Because of such farming, the village has the potential of biomass from the bagasse that comes from extracting juice from the sugar cane. Maize farming for food is also as large as sugar cane farming, by-products of maize plantation can be potentially used as biofuel in the microgrid.

The proposed system architecture is presented in Figure 5-6 below.

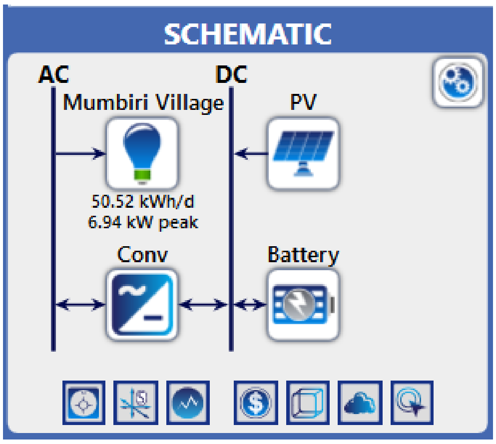


Figure 5-6: Schematic Diagram of Village A

The above figure shows the schematic diagram of the proposed microgrid design using Homer Pro. The main elements of the system, such as energy-producing sources, storage, and loads, as well as the energy flow between them, are shown in this diagram. At the same time, Figure 5-7 below illustrates the Village's geographical location.

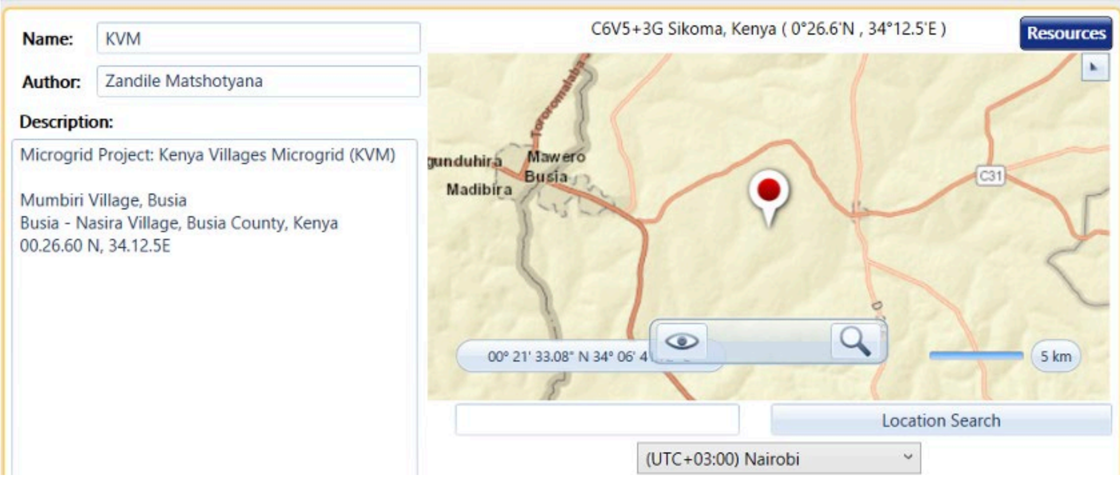


Figure 5-7: Study Case Village A

The electrical energy demand is provided in Table 5-1 and will be used in the proposed design simulation later. July will be considered as the peak month to get the estimation.

Table 5-1: Daily Load Data

Time	Power (kW)	Time	Power (kW)	Time	Power (kW)
0:00	1,02	8:00	2,04	16:00	2,88
1:00	0,72	9:00	1,86	17:00	2,16
2:00	0,78	10:00	2,94	18:00	4,08
3:00	0,48	11:00	3,72	19:00	2,94
4:00	0,18	12:00	3,96	20:00	3,12
5:00	0,24	13:00	3,06	21:00	2,4
6:00	0,36	14:00	3,48	22:00	1,8
7:00	1,86	15:00	3,18	23:00	1,26

From Table 5-1, daily load patterns can be seen. The average daily consumption per household from Blodgett's study was multiplied by 60 (the total number of households in Mumbiri Village) to obtain the load statistics. The peak load is around 18:00, with a power demand of 4.08 (kW). The daily load pattern modelled with HOMER Pro is illustrated in Figure 5-8.

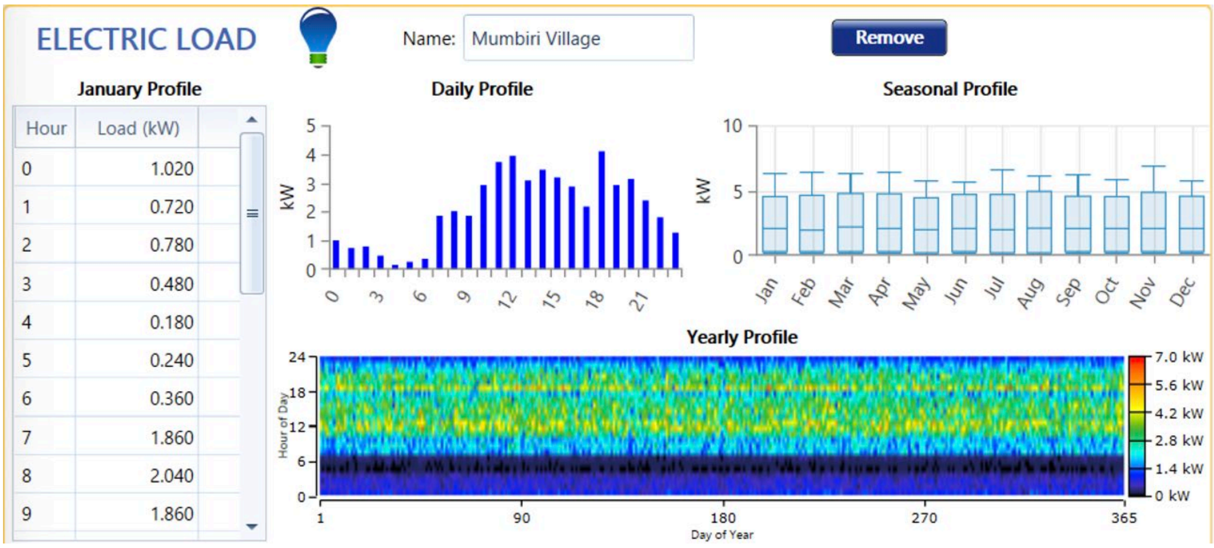


Figure 5-8: Load Patterns for Village A

Figure 5-8 provides the daily, seasonal, and yearly profiles. The village A 24-hour electrical demand is displayed in the load profile. The greatest demand occurs at noon and evening (at around noon with a demand of 3.96 kW and at 18:00 with a demand of 4.08 kW) when people are more likely to use appliances like lights, televisions, and refrigerators as they are back for lunch from their farming activities. Demand is lowest in the early hours of the morning when most people are still asleep, and that is, around 04:00, with only a demand of 0.18 kW.

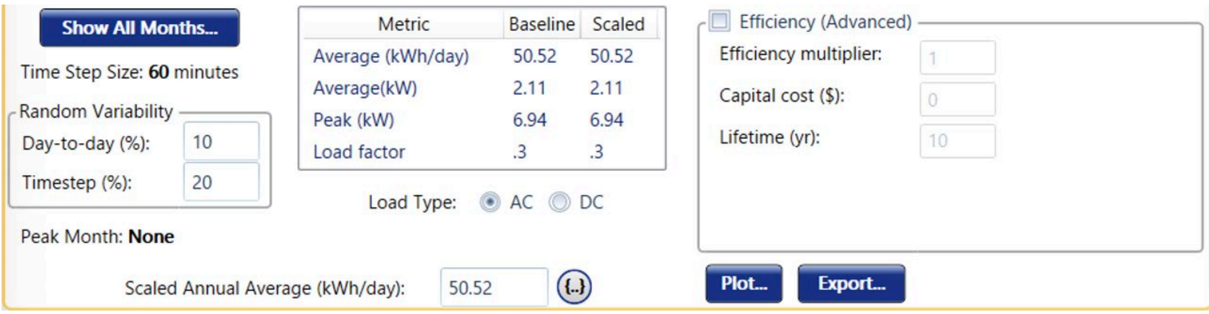


Figure 5-9: Electric Load for Village A

Figure 5-9 shows the electric load of the village. The baseline is an average of 50.52 (kWh/day) and a peak of 6.94 (kW). The load profile can be used to calculate the solar power system size for the community.

An energy-efficient solar power system that can be adjusted to suit peak demand will supply all the villagers' electrical requirements. A solar power system sized to match typical demand will be able to provide electricity to most villagers, while occasionally, the system may become overloaded.

5.5.2. Village B

South Korr Village is located North of Kenya in Turkana County, is the largest County in Kenya, and is home to Lake Turkana, the world's largest permanent desert lake and alkaline lake. The number of households is 278, with a population of 1886 people, and the percentage of households with electricity is 18% (Olsen & Westergaard-Kabelmann, 2018, p. 39).

Turkana County, being home to a large wind plant that is capable of supplying 17% of the total installed capacity in Kenya, evidently shows the availability of a wind resource (Lake Turkana Wind Power, 2022). The area has a biomass energy resource, and there are trees and bushes surrounding the area, which the community members are already using for traditional fuel use. Photovoltaic Power Potential is around 1826 kWh/kWp (World Bank, 2020), a wind-generated microgrid is suitable because it has been used before on a large scale. Below is the schematic diagram of the proposed system.

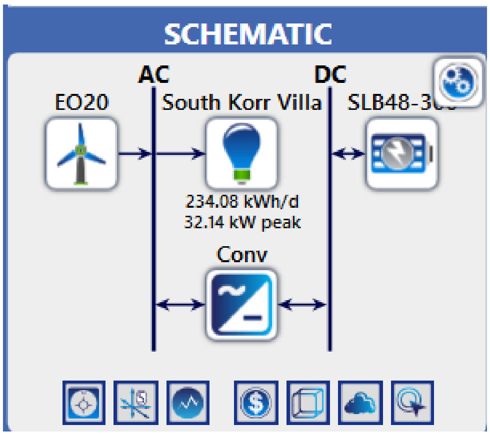


Figure 5-10: Schematic Diagram of Village B

The wind turbine is connected to the AC bus, as the diagram illustrates. Depending on the need, the energy generated by this renewable source is either stored in the battery system or delivered straight to the load. To power the load during times of low generation, the battery discharges.

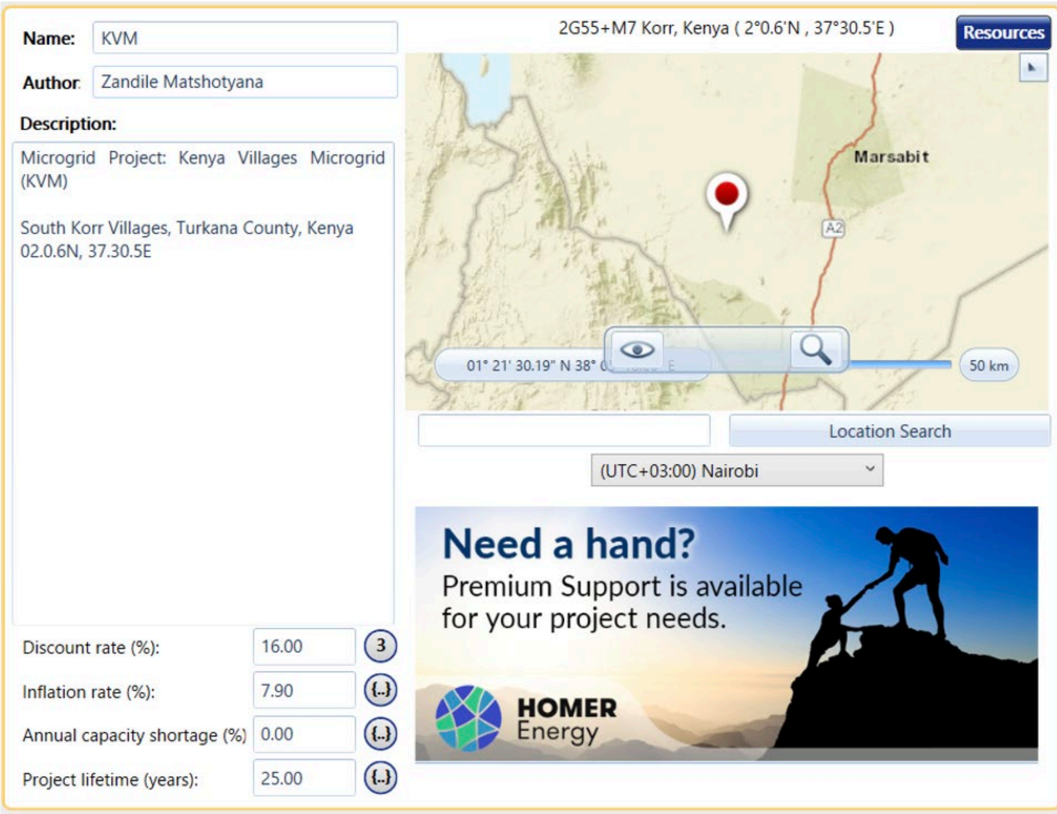


Figure 5-11: Study Case Village B

Figure 5-11 displays the overview information for Village B, and it shows the location on the map and the economics of the microgrid. The discount rate is 16%, the inflation rate is 7.9%, and the project lifetime is 25 years. This number is because the solar panels and controllers can last for around 25 years, especially when they are well taken care of.

The electrical demand for South Korr Village is shown in Table 5-2.

Table 5-2: Daily Load Data

Time	Power (kW)	Time	Power (kW)	Time	Power (kW)
0:00	4,726	8:00	9,452	16:00	13,344
1:00	3,336	9:00	8,618	17:00	10,008
2:00	3,614	10:00	13,622	18:00	18,904
3:00	2,224	11:00	17,236	19:00	13,622
4:00	0,834	12:00	18,348	20:00	14,456
5:00	1,112	13:00	14,178	21:00	11,12
6:00	1,668	14:00	16,124	22:00	8,34
7:00	8,618	15:00	14,734	23:00	5,838

The least power demand is around 4:00, with the peak load at around 18:00 by 0,834 kW and 18,904 kW, respectively. To find the load data, the average daily consumption per household taken from Blodgett's study has been used and multiplied by 278 (number of households in South Korr Village).

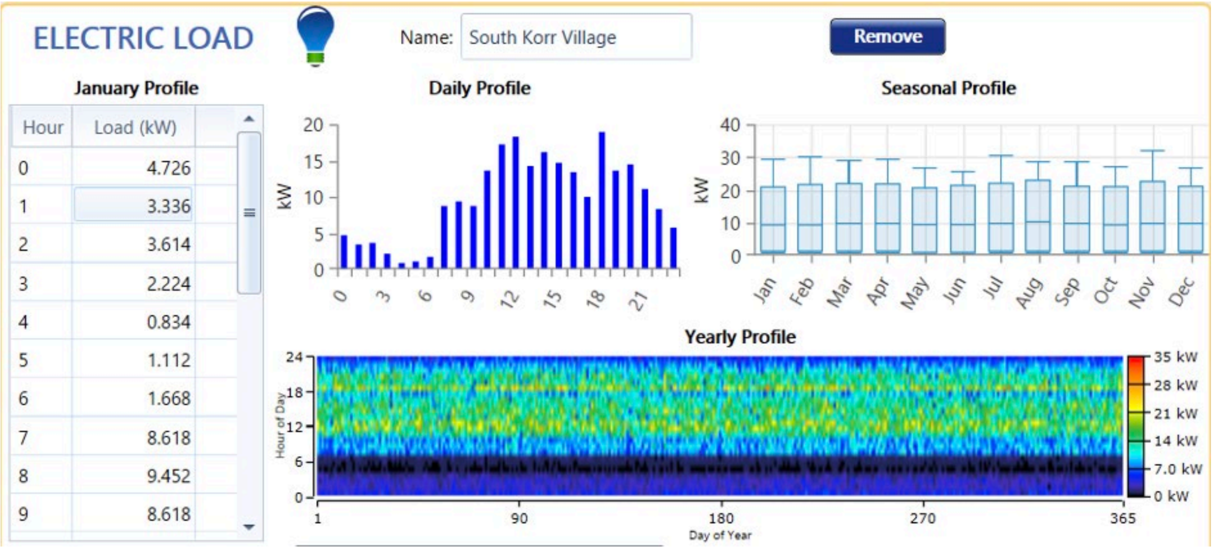


Figure 5-12: Load Patterns for Village B

Figure 5-12 shows the Homer Pro modelled load pattern for the village. The daily, seasonal, and yearly profiles are also provided. The seasonal profile shows the demand for each month of the year; it shows the fluctuation of the demand throughout the year. November month has the biggest demand, followed by July, with an energy demand of 32 kW and 30.5 kW, respectively. The average consumption and peak values are given in Figure 5-13.

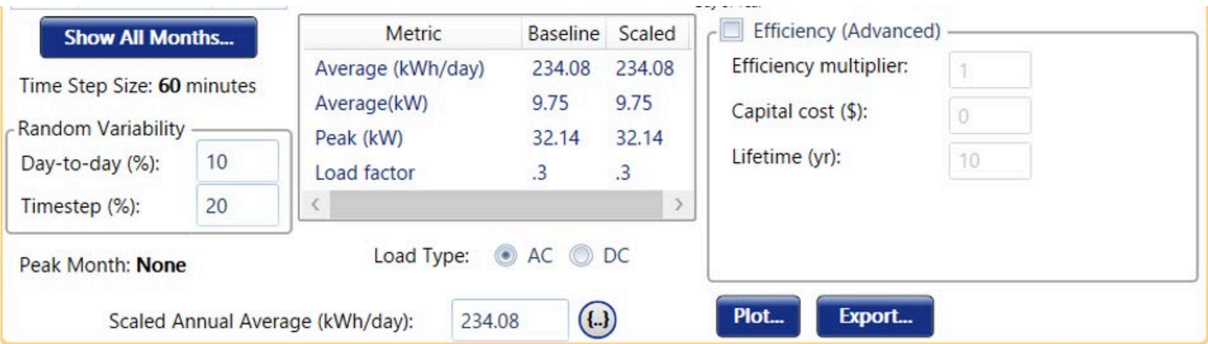


Figure 5-13: Electric Load for Village B

The average consumption is 234.08 kWh/day, and the peak is 32.14 kW. The weather patterns of Kenya consist of short rains and long rains; July is mostly dry, and November is the wettest.

The high demands are likely due to people having switched on TV and lights for longer periods because it is cold due to rain. The lowest demand is in June, with an average of 26 kW, this is when people are likely to spend more time outside due to a lot of sunlight.

Knowing the seasonal profile helps in optimising the sizing and configuration of renewable energy sources. This is because resources vary seasonally due to changes in weather conditions. As a result, the energy requirements are met even during periods of lower renewable resource availability.

5.5.3. Village C

Kitulu is a Village in Machakos County, Kenya. It is located approximately 70 km Southwest of Nairobi, the Capital City of Kenya. The number of residents of Kitulu Village is around 189 households.

Machakos County exhibits low wind speeds ranging from 0.5 m/s to 5 m/s, with an annual average wind speed of 3.5 m/s. Achieving optimal power generation from wind necessitates the meticulous design of the conversion system (Muchiri, K. et al., 2022, p. 1). This tells us that there is a potential for wind energy generation sufficient for the small size of the community intended to be designed for. Solar resource is the second available natural resource in this location, and it has a photovoltaic power potential yearly average of between 1680 kWh/kWp to 1753 kWh/kWp (World Bank, 2020). A combination of the two resources will be used to see if they can provide a sufficient power supply to the community.

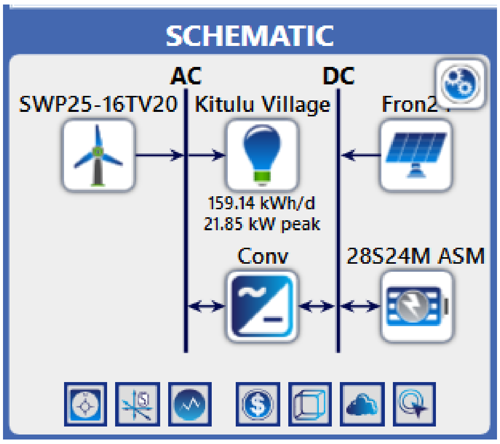


Figure 5-14: Schematic Diagram for Village C

The schematic diagrams for the proposed microgrid design are provided in the figure, showing a hybrid system consisting of wind, solar, battery and a converter. It is assumed that when the wind and solar energy resources are put together, they will be able to meet the energy demand of the community. The schematic diagram provides a visual understanding of how components interact in a microgrid. The movement of energy from generation sources to loads and the integration of storage devices and generators to provide a steady supply of power is easily seen from the schematic diagram.

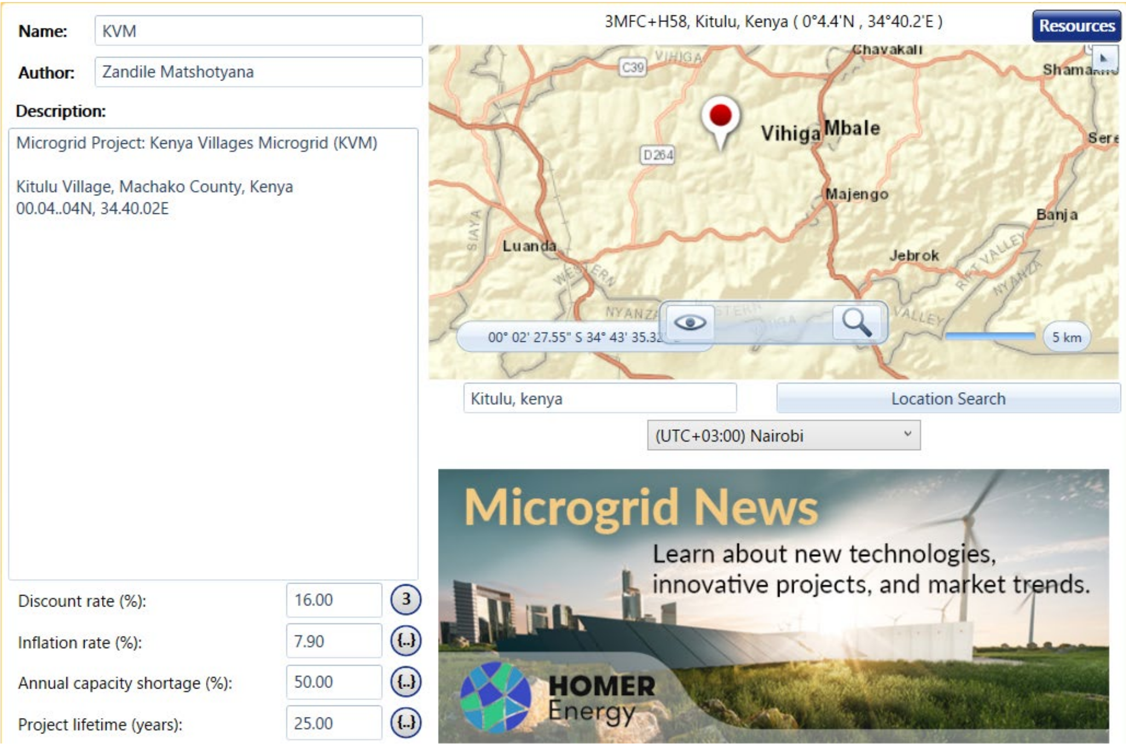


Figure 5-15: Study Case Village C

Overview information on the village that will be studied is shown above in Figure 5-15. The location has been pointed out on the map. Setting the location provides easy access to solar and temperature resources, which Homer Pro can download from the internet. This then allows Homer Pro to simulate possible combinations using real location circumstances.

The daily load data is provided below in Table 5-3. This is the load data that has been inserted on Homer Pro.

Table 5-3: Daily Load Data

Time	Power (kW)	Time	Power (kW)	Time	Power (kW)
0:00	3,213	8:00	6,426	16:00	9,072
1:00	2,268	9:00	5,859	17:00	6,804
2:00	2,457	10:00	9,261	18:00	12,852
3:00	1,512	11:00	11,718	19:00	9,261
4:00	0,567	12:00	12,474	20:00	9,828
5:00	0,756	13:00	9,639	21:00	7,56
6:00	1,134	14:00	10,962	22:00	5,67
7:00	5,859	15:00	10,017	23:00	3,969

The load data in the above figure was taken from Blodgett's study, where electricity use by Kenya villages was studied. That load data is multiplied by the number of households (189) in this village to give the load that will be inserted on Homer Pro as an electrical load.

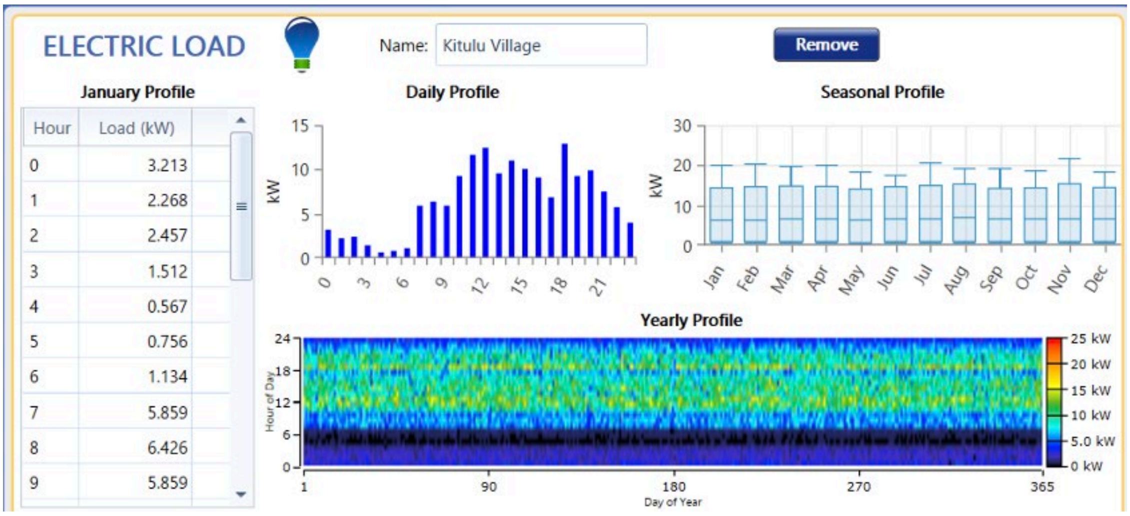


Figure 5-16: Load Patterns for Village C

Figure 5-16 illustrates the load pattern modelled by Homer Pro for the village. Daily, seasonal, and yearly profiles are included.

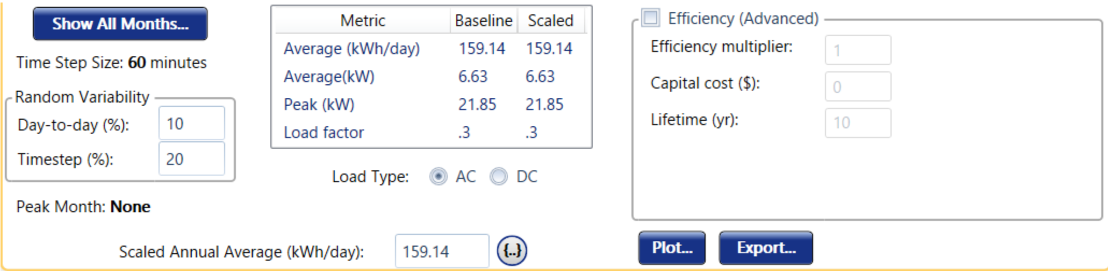


Figure 5-17: Electrical Load for Village C

The average consumption of Village C is 159.14 kWh/day, and the peak is 21.85 kW, as demonstrated in the above Figure 5-17.

5.5.4. Village D

Mkwiro is a Village inside the Wasini Island. The geographical location of Mkwiro is 4°40.0′S, 39°24.0′E. The village has no roads and no cars, and the people who stay there do mostly fish for a living. The number of households is 117.

Mkwiro village has a solar resource ranging between 1607 kWh/kWp to 1620 kWh/kWp per year, as shown in Figure 3-1, And wind speeds ranging between 5 m/s to 5.5 m/s at 100-meter height, as demonstrated in Figure 3-2. These are good wind speeds; therefore, the wind resource will be selected for this location.

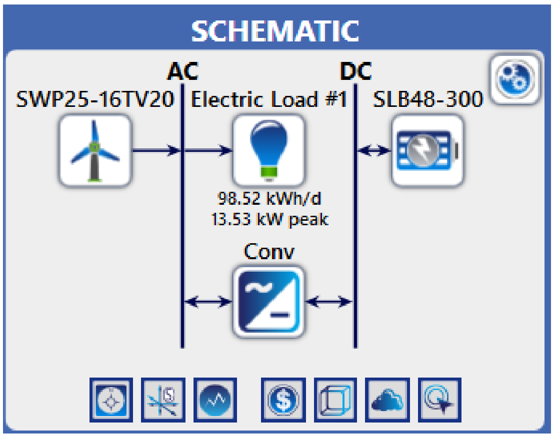


Figure 5-18: Schematic Diagram of Village D

The microgrid will operate independently, depending only on the wind renewable resource and storage, this is shown above in Figure 5-18.

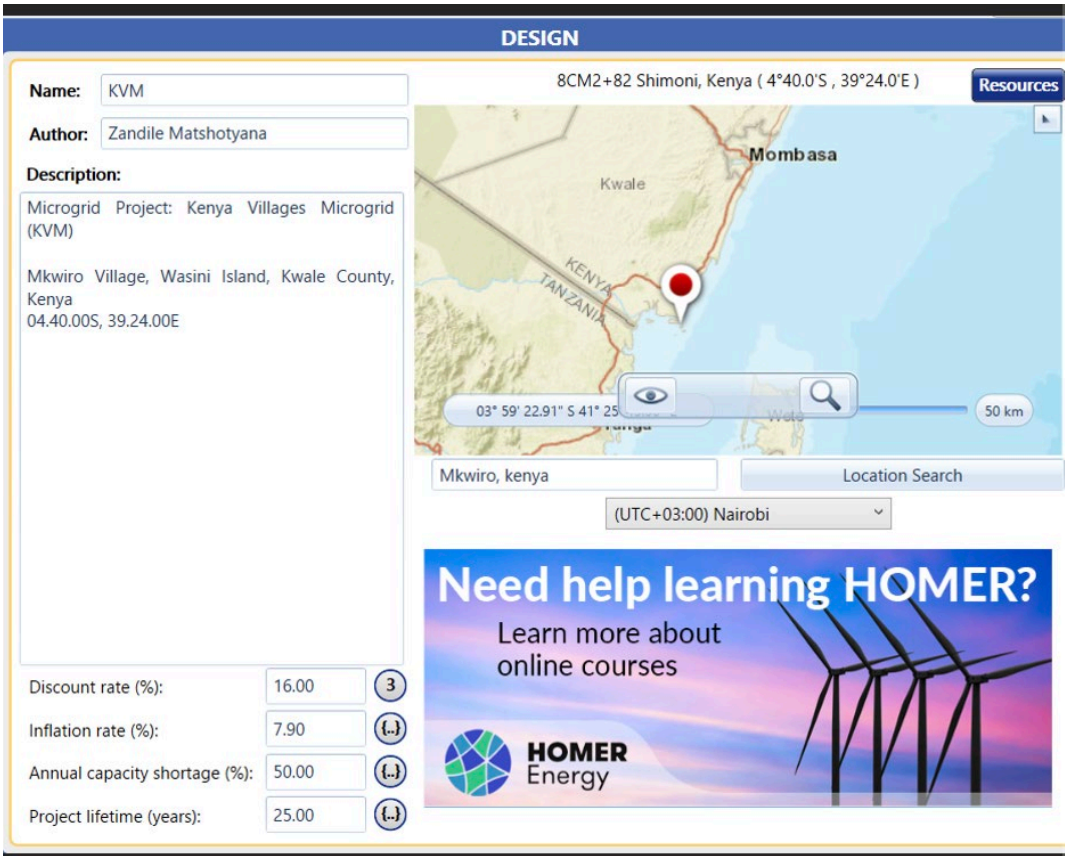


Figure 5-19: Study Case Village D

The project location is defined in Figure 5-19 with the project name, the author, and basic model inputs have been set.

Below is the daily load data of Mkwiro village assumed based on the literature.

Table 5-4: Daily Load Data

Time	Power (kW)	Time	Power (kW)	Time	Power (kW)
0:00	1,99	8:00	3,98	16:00	5,62
1:00	1,40	9:00	3,63	17:00	4,21
2:00	1,52	10:00	5,73	18:00	7,96
3:00	0,94	11:00	7,25	19:00	5,73
4:00	0,35	12:00	7,72	20:00	6,08
5:00	0,47	13:00	5,97	21:00	4,68
6:00	0,70	14:00	6,79	22:00	3,51
7:00	3,63	15:00	6,20	23:00	2,46

Table 5-4 above shows daily load data for a microgrid, showing energy consumption on an hourly basis. The lowest power demand is at 4:00 am with a power of 0.35 kW, and the highest is at 18:00 with a power of 7.96 kW.

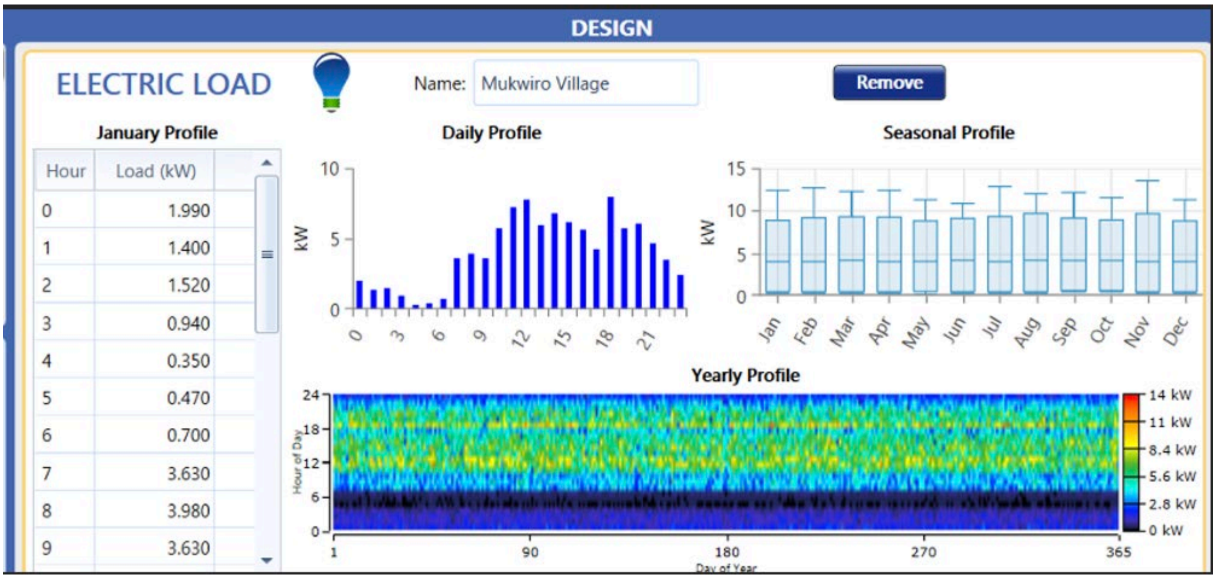


Figure 5-20: Load Patterns for Village D

In Figure 5-20, the load pattern for the village is depicted as modelled by Homer Pro. The figure includes daily, seasonal, and yearly profiles.

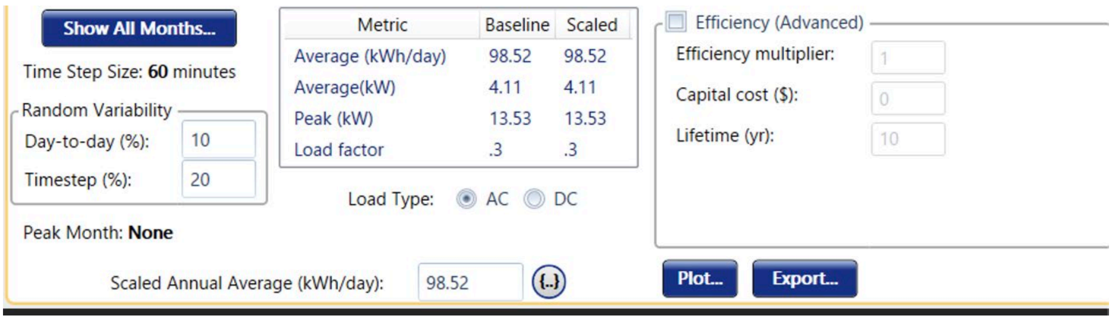


Figure 5-21: Electric Load for Village D

Figure 5-21 above showcases the average daily energy consumption of 98.5 kWh/day and an average peak power demand of 13.53 kW.

The baseline power consumption includes all the loads connected to the microgrid, such as appliances and all other electrical devices used by the community. The scaled average, on the other hand, means that the baseline has been adjusted down. This adjustment is done to suit the operational optimisations or system parameters like load profiles. Additionally, the adjustment represents possible modifications made to raise the system's overall efficiency or lower its energy consumption.

5.5.5. Village E

Sasimwani Village is home to the Ogiek people, where there are 700 households. The village is located on the edge of Maasai Mau Forest, which forms part of the larger Mau Forest ecosystem in Narok County. This village has a biomass natural resource from the large Mau Forest, which can be used to electrify the community. The forest has an average of 236 megagrams per Hectare of natural forest. Another natural resource available in this location is solar resources (1753 kWh/kWp to 1800 kWh/kWp per year).

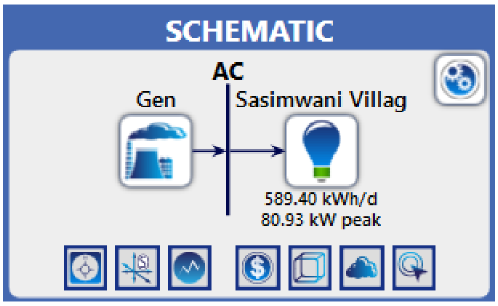


Figure 5-22: Schematic Diagram for Village E

The schematic diagram, as shown in the above Figure 5-22 above, gives a representation of the energy flow which is from the biogas generator to the load.

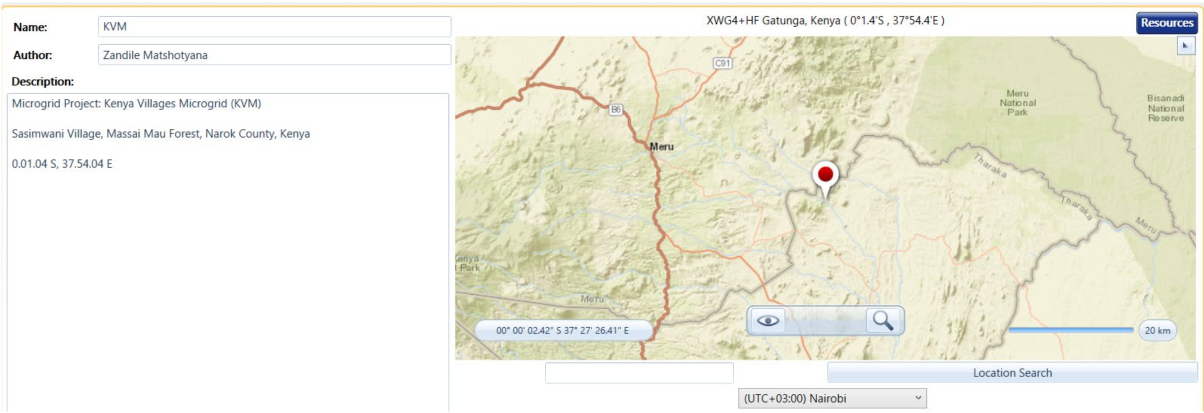


Figure 5-23: Study Case Village E

The village to be designed is demonstrated in Figure 5-23, showing the location on the map. Sasimwani Village microgrid design only includes a power generation unit which is fuelled by Biofuel. The name of this project is KVM, which stands for Kenya Villages Microgrids.

The following table represents the daily load data for Sasimwani Village, assumed based on existing literature. Figure 5-19 displays the daily load pattern for the Village.

Table 5-5: Daily Load Data

Time	Power (kW)	Time	Power (kW)	Time	Power (kW)
0:00	11,9	8:00	23,8	16:00	33,6
1:00	8,4	9:00	21,7	17:00	25,2
2:00	9,1	10:00	34,3	18:00	47,6
3:00	5,6	11:00	43,4	19:00	34,3
4:00	2,1	12:00	46,2	20:00	36,4
5:00	2,8	13:00	35,7	21:00	28
6:00	4,2	14:00	40,6	22:00	21
7:00	21,7	15:00	37,1	23:00	14,7

This table will inform Homer Pro of the load data of the area.

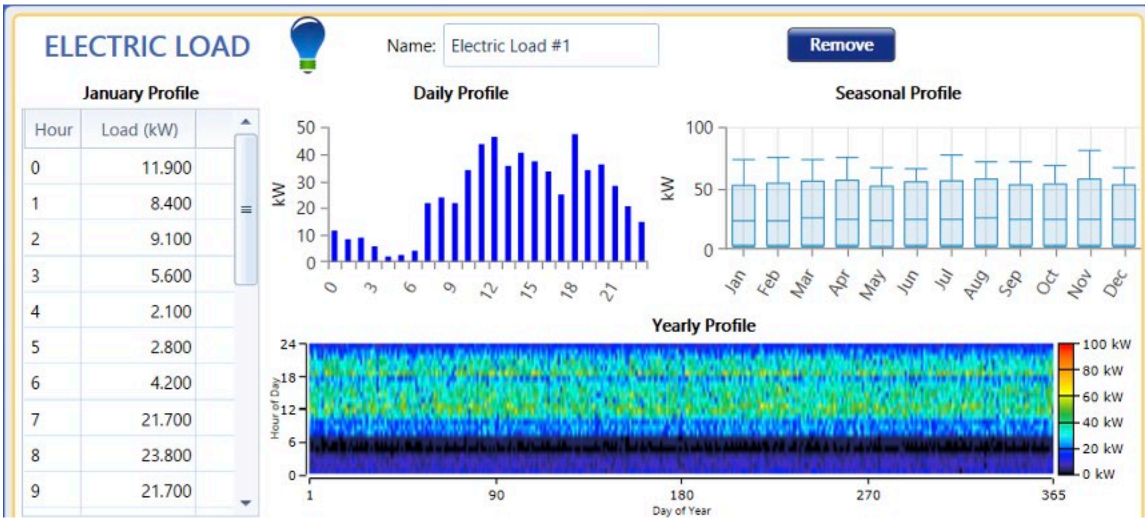


Figure 5-24: Load Patterns for Village E

As displayed in Figure 5-24 above, the electric load data has been modelled by Homer Pro, and the daily, seasonal, and yearly profiles can be seen.

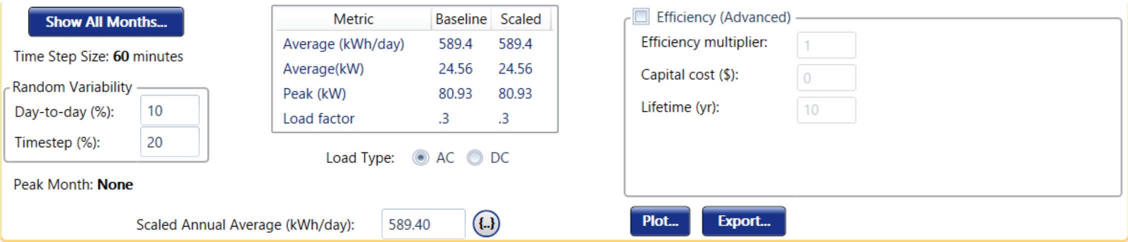


Figure 5-25: Electric Load for Village E

As shown in Figure 5-25 above, the baseline average is 589.4 kWh/day, with a peak at 80.93 kW. The electrical loads will use AC power, which is no different from the standard that is normally followed. Most domestic and commercial electrical appliances worldwide use AC, which is the common type of electrical power provided via utility networks.

5.6. Proposed system structure

This section will cover the proposed system structures for all the villages based on their available natural resources and their electrical demand.

5.6.1. Village A

Kenya has a vast potential in solar electrical energy resources, with insolation averaging 4-6 kWh/m² daily and up to 3500 hours of sunlight all year round (Samu, R. et al., 2019, p. 298). Mumbiri Village is part of the hot climate region. Therefore, a Solar microgrid is proposed, which will be comprised of a PV, Battery storage and a Converter, as shown in Table 5-6.

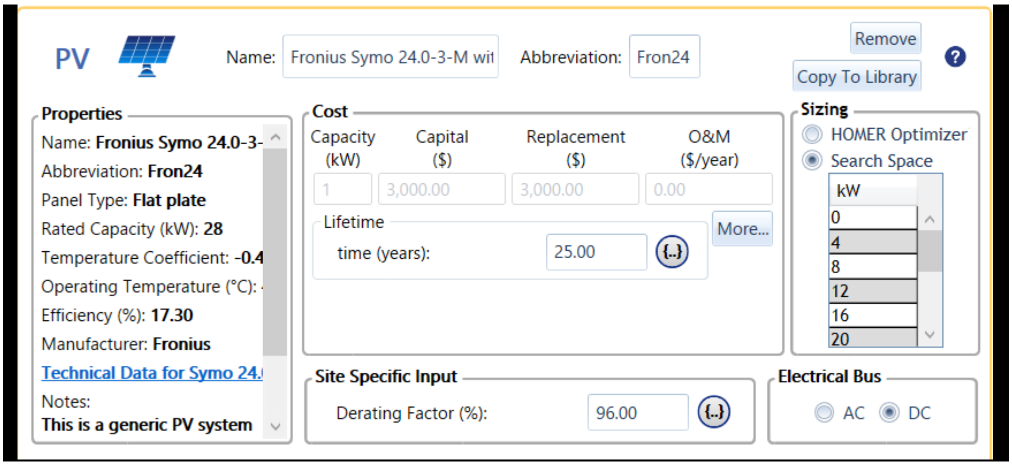
Table 5-6: Summary of system architecture

Component	Description
PV	28 kW Fronius Symo 24.0-3-M with generic flat plate
Storage	10.2 kWh Polarium SLB48-200-146-2
System converter	Generic large, free converter

Above is the summary of the proposed system architecture that will serve the electrical needs of the community.

5.6.1.1. Solar system modelling using Homer Pro

A generic flat plate PV has been selected so that Homer Pro can automatically size a suitable capacity. The modelling of PV is shown in Figure 5-26. overall, this figure shows how HOMER Pro makes studying and designing PV systems for microgrids context. A wide range of PV models, with their performance and prices, optimise the system to meet energy needs and financial goals. The solar system, being the only source of energy, is expected to produce an average of 50.52 kWh, and the efficiency is expected to be 17.30% throughout the year.



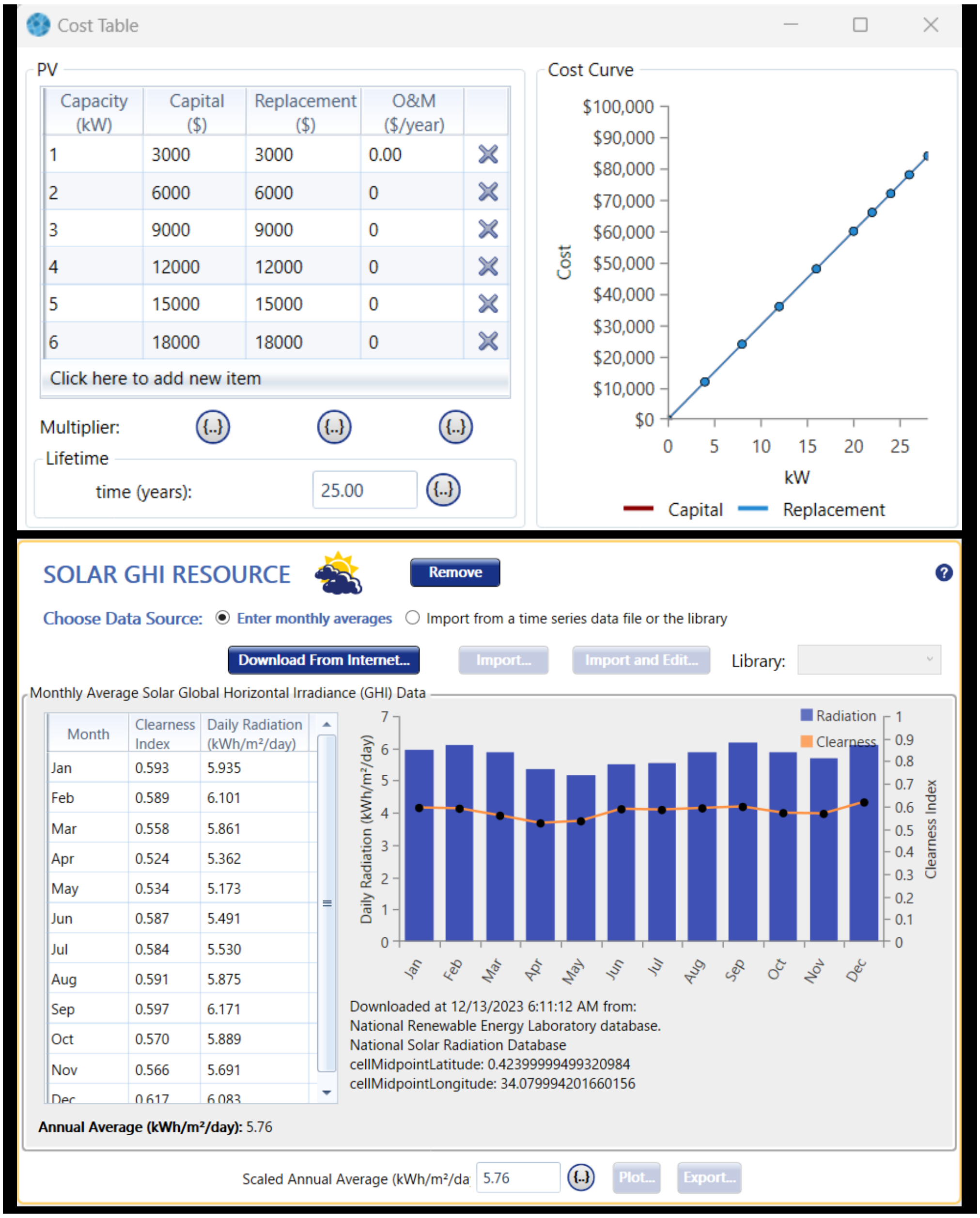
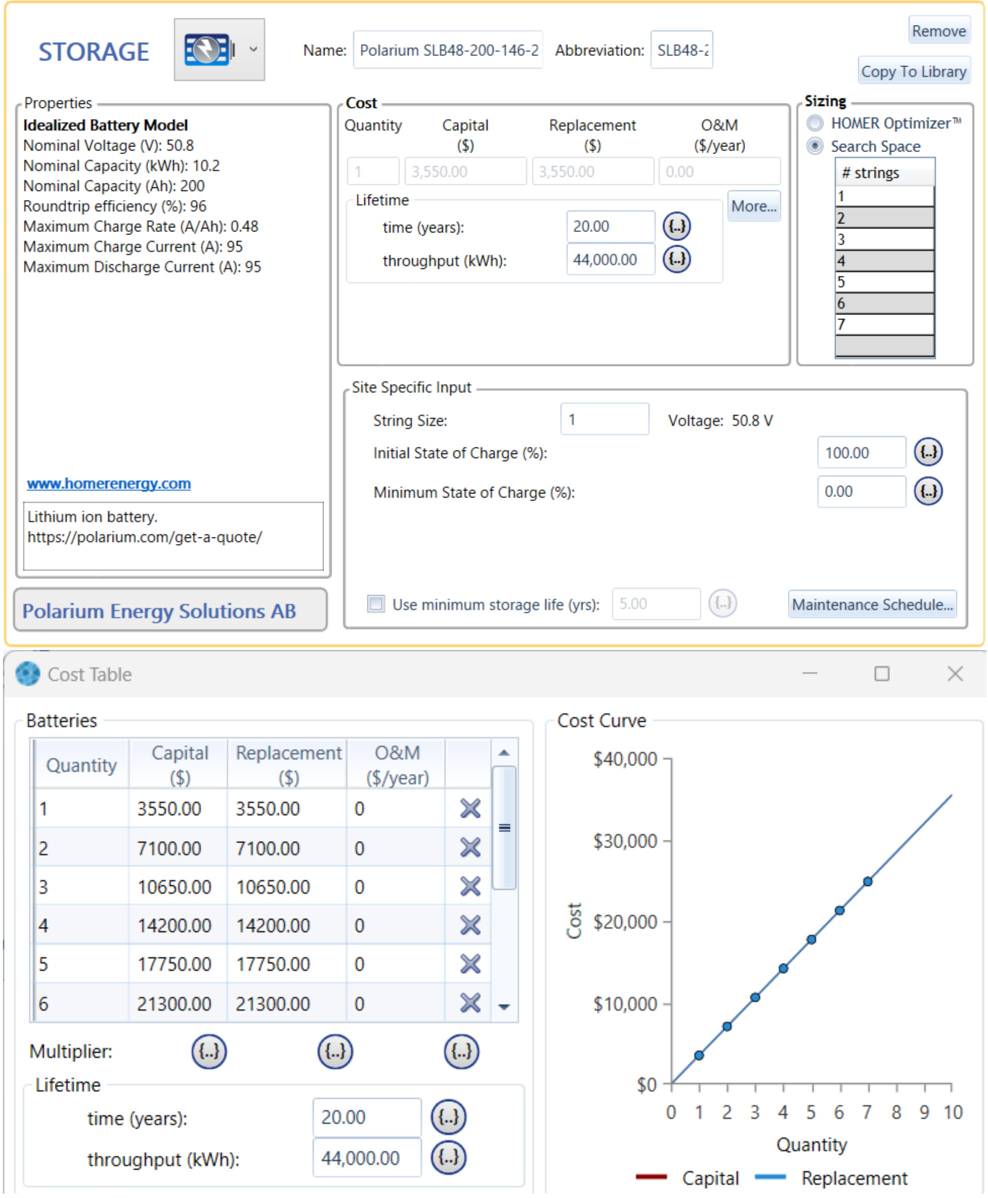


Figure 5-26: PV generation modelling in HOMER Pro.

The PV is modelled using HOMER Pro, as shown above in Figure 5-26.

5.6.1.2. Battery System Modelling using Homer Pro

Because solar irradiation is not available continuously in a day and through all seasons, electrical energy production also becomes irregular, defeating the main aim of a PV system of providing reliable power to the customer. To accommodate such irregular solar irradiation, storage is considered in the design and will supply the loads at night and on cloudy days. Figure 5-27. Illustrates the battery modelling.



Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	3550.00	3550.00	0
2	7100.00	7100.00	0
3	10650.00	10650.00	0
4	14200.00	14200.00	0
5	17750.00	17750.00	0
6	21300.00	21300.00	0

Figure 5-27: Battery System Modelling using HOMER Pro

In the solar system, cell batteries are commonly used as a form of electrical energy storage. Lead acid batteries, being the cheapest and most used currently, are considered in this paper. This figure shows how HOMER Pro has modelled the battery system. In HOMER Pro, battery modelling entails modelling a microgrid's battery performance, cost, and lifespan. This is useful in assessing the feasibility and efficiency of combining battery storage and solar generation in this case.

5.6.1.3. System Converter Modelling using Homer Pro

A generic system converter will be used in the design, as demonstrated in Figure 5-28 below.

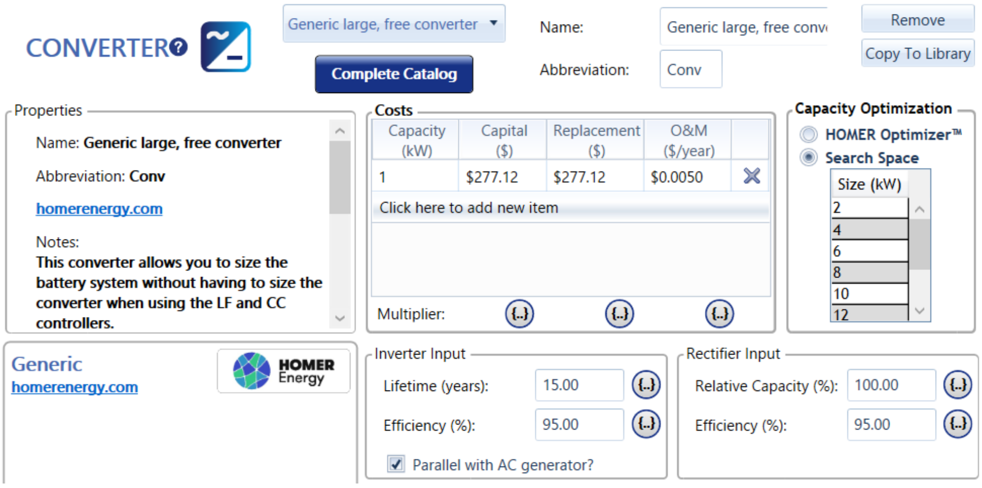


Figure 5-28: System Converter Modelling using HOMER Pro.

The above figure shows the simulated performance and efficiency of the converter in the microgrid. To integrate diverse energy sources, such as solar PV and batteries, which may run on different electrical standards (AC vs. DC), converters are essential.

5.6.2. Village B

The Marsabit county has wind potential to generate electricity as it is home to the Lake Turkana Wind Power project, featuring 365 wind turbines. Each turbine has a capacity of 850kW, collectively providing a substantial contribution to the country's energy landscape. The project's output is significant, capable of supplying 17% of the total installed capacity in Kenya (Lake Turkana Wind Power, 2022). Consequently, a wind microgrid is proposed for this location. In Table 5-7, below is a summary of the proposed structure.

Table 5-7: Summary of system architecture

Component	Description
Wind Turbine	20 kW Eocycle EO20
Storage	14.4 kWh Polarium SLB48-300-147-5
System converter	Generic large, free converter

The architecture includes a 20 kW Eocycle EO20 wind turbine, 14.4 kWh Polarium SLB48-300-147-5 Battery and a Generic large free converter.

5.6.2.1. Wind system modelling using Homer Pro

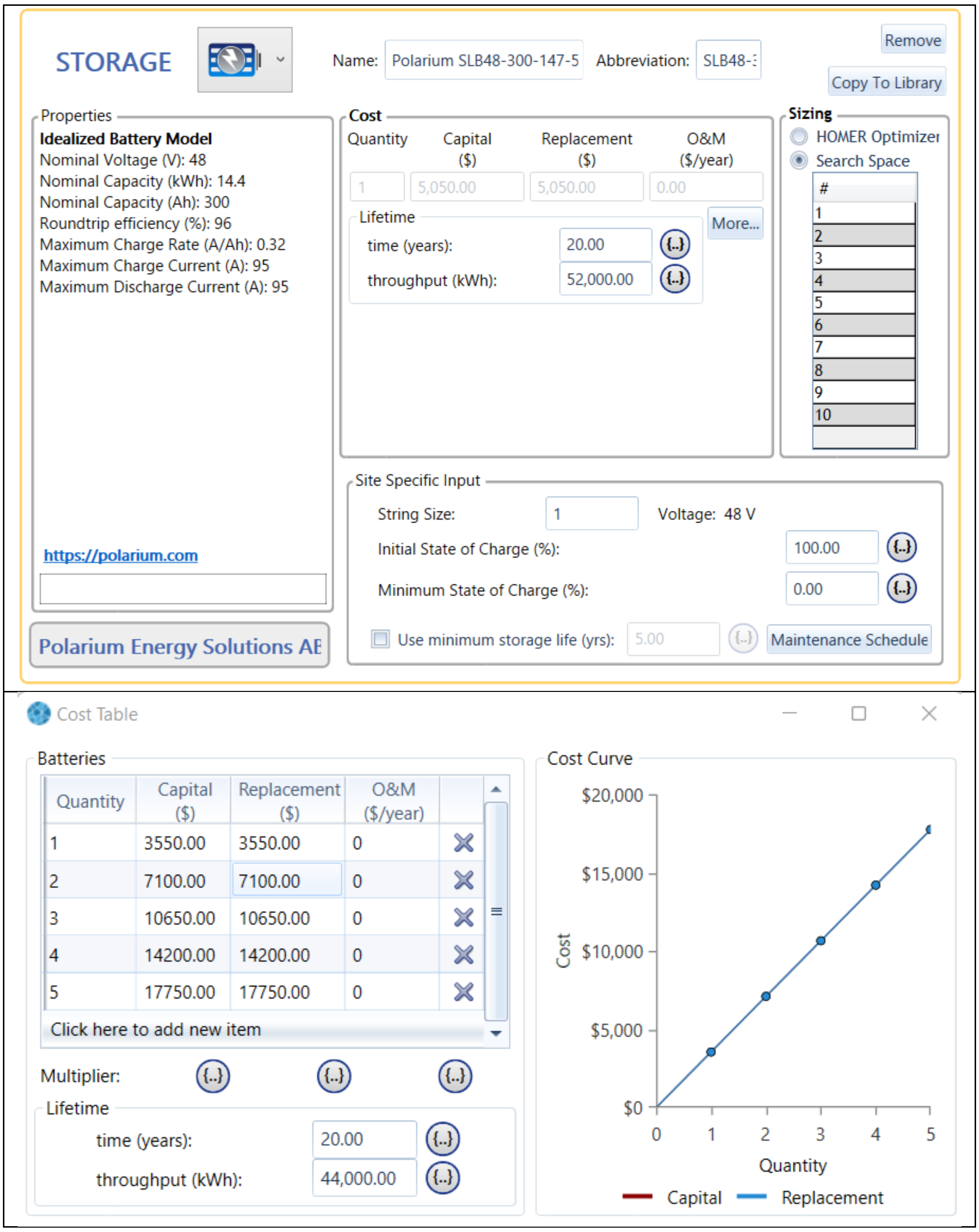
A 20 kW Eocycle EO20 Wind Turbine has been selected for the design. This site is hoped to generate enough capacity to meet the electrical demands of this location. The modelling is shown in Figure 5-29.

Figure 5-29: Wind generation modelling in HOMER Pro.

Figure 5-29 above represents the modelling of the wind generation. It demonstrates how HOMER Pro imitates the process of integrating wind energy into a microgrid, enabling the evaluation of costs, benefits, and effects on the energy system. Wind energy is transformed into electrical power by wind turbines, which can then be stored for later use or used to meet load demands.

5.6.2.2. Battery system modelling using Homer Pro

A storage system will be considered in the design to store excess electricity generated, which will be used when the wind is not strong enough to generate the needed capacity. The battery modelling is shown in Figure 5-30 below.



Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	3550.00	3550.00	0
2	7100.00	7100.00	0
3	10650.00	10650.00	0
4	14200.00	14200.00	0
5	17750.00	17750.00	0

Figure 5-30: Battery modelling in HOMER Pro.

A Polarium SLB48-300-147-5 battery has been modelled using Homer Pro Software. The software works with a variety of battery types, including flow, lithium-ion, and lead-acid batteries. Characteristics and performance indicators vary throughout types, in this case, the battery type is a lithium-ion battery.

5.6.2.3. Converter system modelling using Homer Pro

A generic large free converter will be used in the design for the necessary conversions of the microgrid. Figure 5-31 depicts the converter modelling.

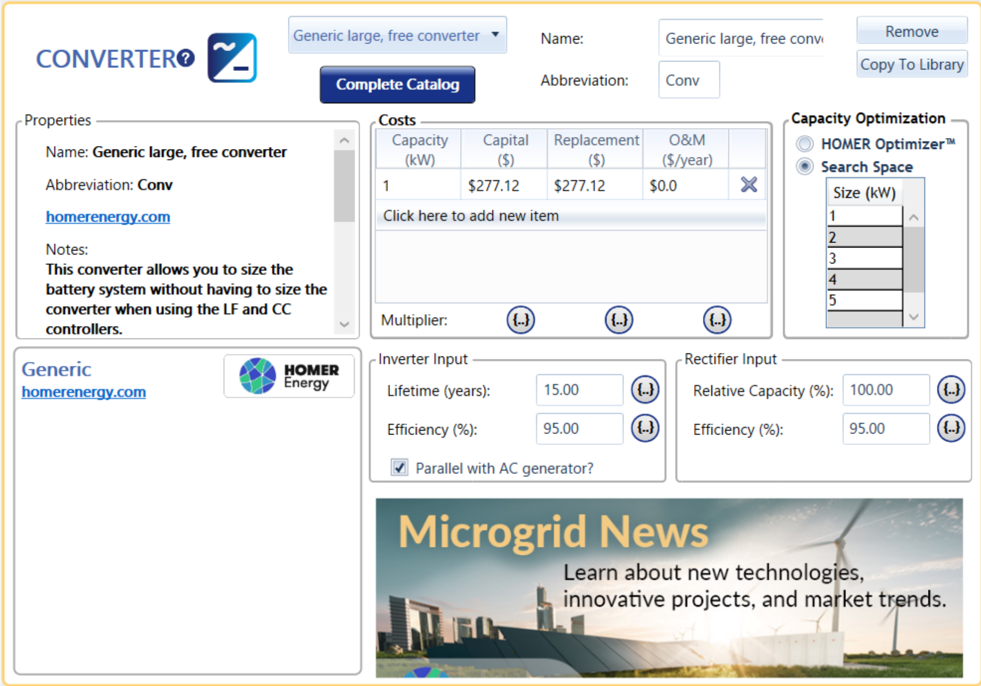


Figure 5-31: Converter modelling in HOMER Pro.

It is expected that the converter will convert DC electricity from the battery system and AC electricity from the wind turbine for the use of the community load demand. The energy converted is expected to be from the energy generated by the wind turbine (20 kWh) and that stored in the battery (14.4 kWh).

5.6.3. Village C

A study conducted in the Machakos area (Muchiri, K. et al., 2023, p. 1) used simulation and onsite experiments to see if the Wind and Solar resources would be viable if put in a hybrid system. In the examination, a reciprocal relationship was observed between wind and solar resources across hourly, diurnal (day and night), and monthly (seasonal) timeframes. This observed pattern suggests a notable level of complementarity in both the availability and energy production of wind and solar resources (Muchiri, K. et al., 2023, p. 11).

It is proposed to design a hybrid system of solar and wind to find the optimum design for the un-electrified village. Table 5-8 below illustrates the proposed system architecture.

Table 5-8: Summary of system architecture

Component	Description
PV	80 kW Fronius Symo 24.0-3-M with generic flat plate
Wind Turbine	25kW SWP25-16TV20
Storage	55.8 SAFT Intensium Max PLUS 2
System converter	Generic large, free converter

To design a microgrid that will improve the community's access to cost-effective, sustainable, and reliable energy, Table 5-8 contains the proposed components to be used in the microgrid.

5.6.3.1. Solar system modelling using Homer Pro

A Fronius Symo 24.0-3-M with Generic PV will be used in the design. This PV has a capacity of 80 kW, and together with the wind turbine generation, the electrical demand of the location will be met. PV modelling using Homer Pro is demonstrated in Figure 5-32.

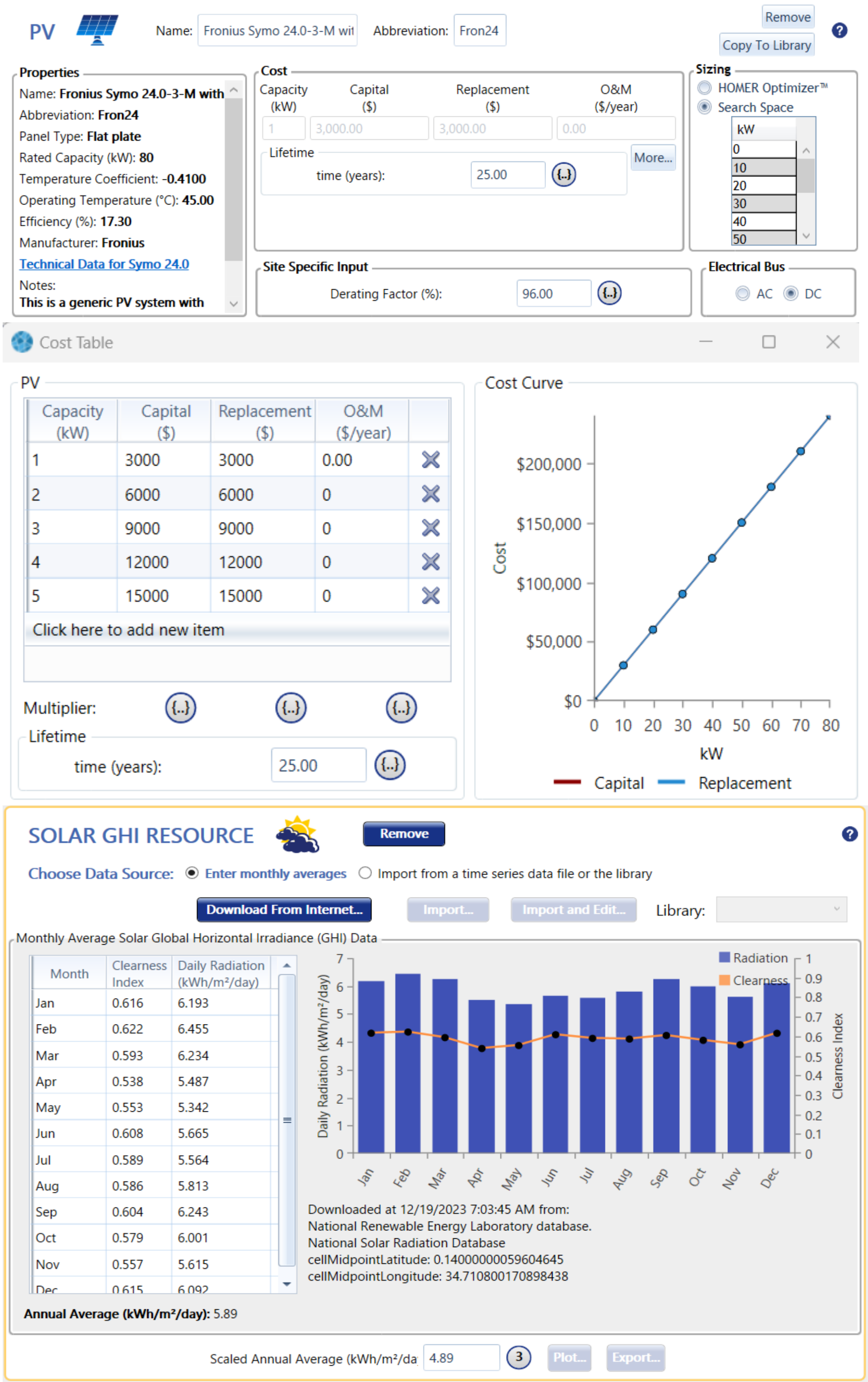


Figure 5-32: PV modelling in HOMER Pro.

Figure 5-32 shows the properties of the PV, the cost information of the PV and the available solar resources of the selected location. The figure shows that the annual average GHI for this location is 4.89 kWh/m²/day, indicating a good solar resource. The clearness index values for this location are relatively high, ranging between 0.538 (minimum in April) and 0.622 (maximum in December) throughout the year; this indicates mostly clear skies throughout the year. It is noted that the highest daily radiation occurs in February (6.455 kWh/m²/day), while the lowest occurs in May (5.342 kWh/m²/day).

5.6.3.2. Wind system modelling using Homer Pro

The wind system modelling is demonstrated in Figure 5-33.

Figure 5-33: Wind generation modelling in HOMER Pro.

A 25 kW wind turbine has been selected to be used in the hybrid system. Figure 5-33 above provides the monthly average wind speed data at the site, which has been extracted from historical data. The annual average of 3.34 m/s indicates a good wind resource that can provide sufficient energy for the community.

5.6.3.3. Battery system modelling using Homer Pro

The battery storage system will be used to store excess electricity generated by both the PV and wind turbine, and the modelling is shown in Figure 5-34.

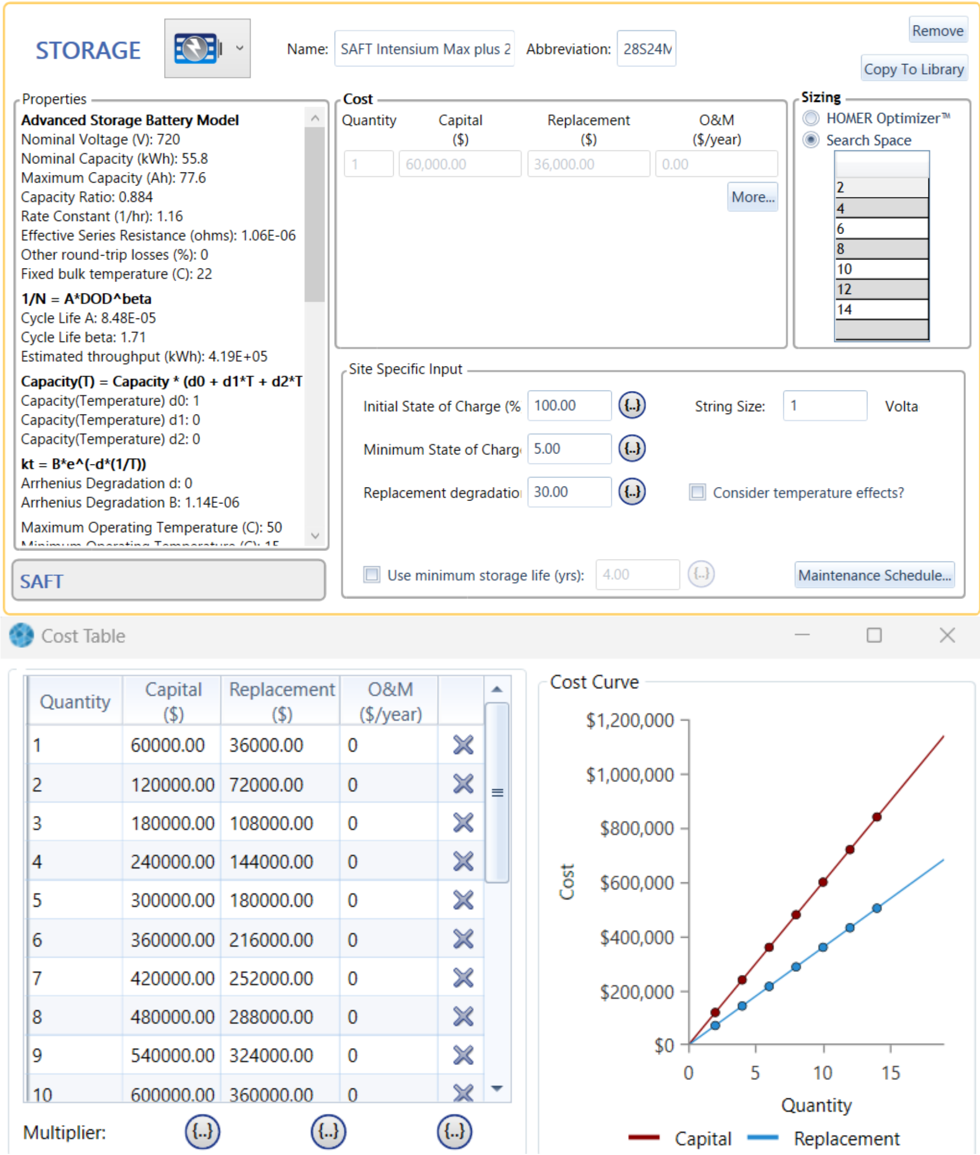


Figure 5-34: Battery modelling in HOMER Pro.

A 55.8 kWh SAFT Intensium Max plus 2 battery has been selected in the design, and the modelling is shown in Figure 5-34. This is a Lithium-ion based energy storage system. This battery's lifespan is 30 years, meaning that for this microgrid, the battery is not expected to be changed for the entire project lifetime.

5.6.3.4. Converter system modelling using Homer Pro

The large free generic converter is modelled in Figure 5-35 below.

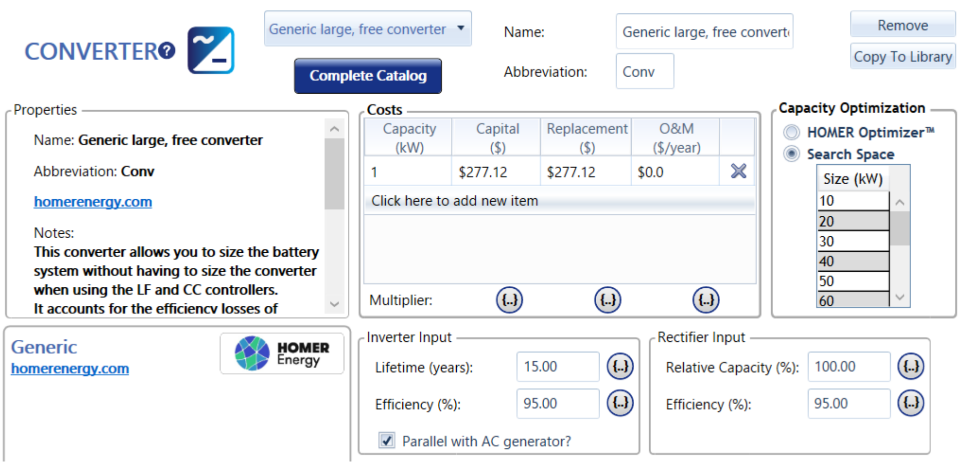


Figure 5-35: Converter modelling in HOMER Pro.

This figure shows how Homer Pro simulates the performance and efficiency of the microgrid's converter. The efficiency is 95%, indicating that only 5% of the energy is lost during the conversion process, meaning that 95% of the input energy is successfully converted to the required output form (AC to DC or DC to AC).

5.6.4. Village D

According to (Olaofe, Z. O. 2018, p. 1107) the Coastal Regions of Africa, they have a potential for wind energy. Moving from the East coastal regions to the South Coastal regions, the mean inter-annual wind speed ranges from 6.0 m/s to 10 m/s. The proposed system structure is depicted in Table 5-9.

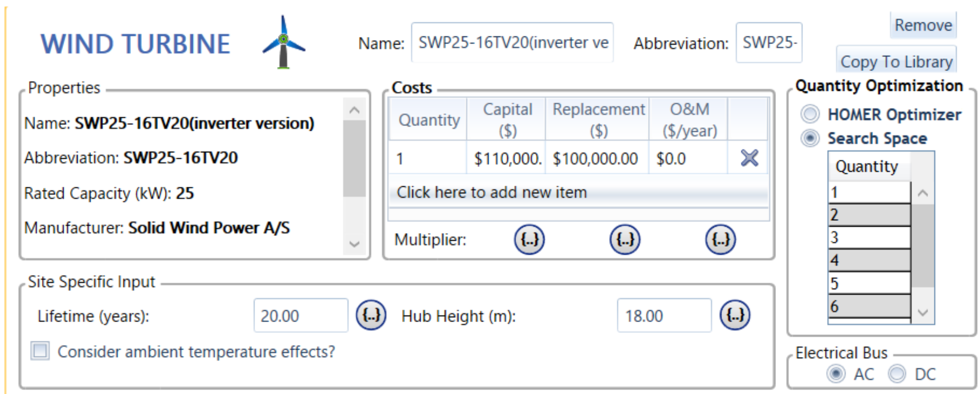
Table 5-9: Summary of system architecture

Component	Description
Wind Turbine	25 kW SWP25-16TV20(inverter version)
Storage	14.4 Polarium SLB48-300-147-5
System converter	Generic large, free converter

The renewable energy source in this proposed system architecture is a wind turbine with a 25 kW capacity.

5.6.4.1. Wind system modelling using Homer Pro

For Village D, a SWP25-16TV20 Wind Turbine will be used with a capacity of 25 kW, as shown in Figure 5-36.



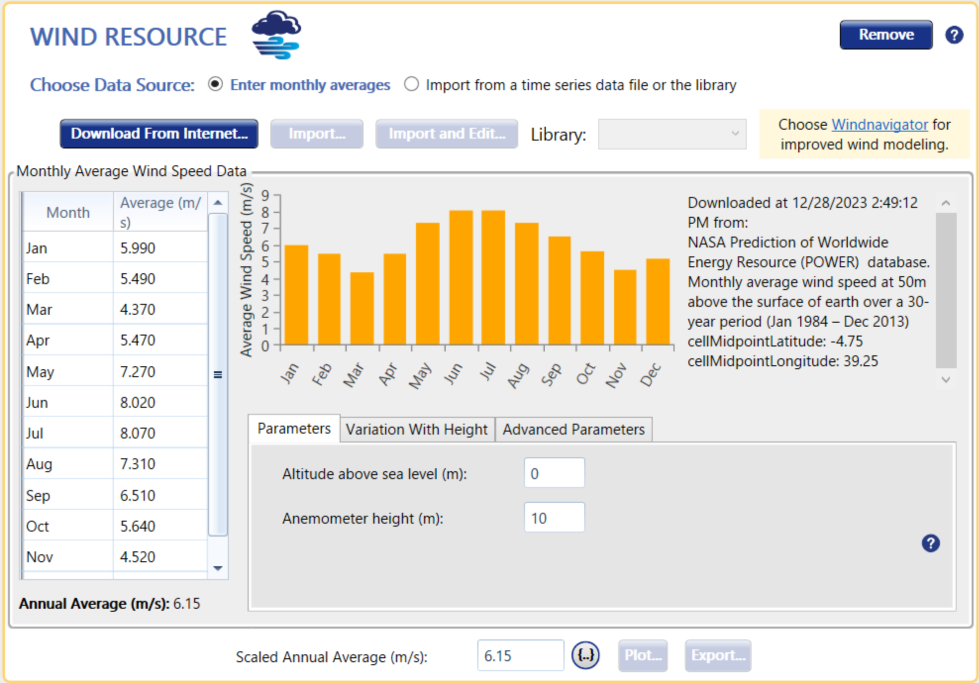
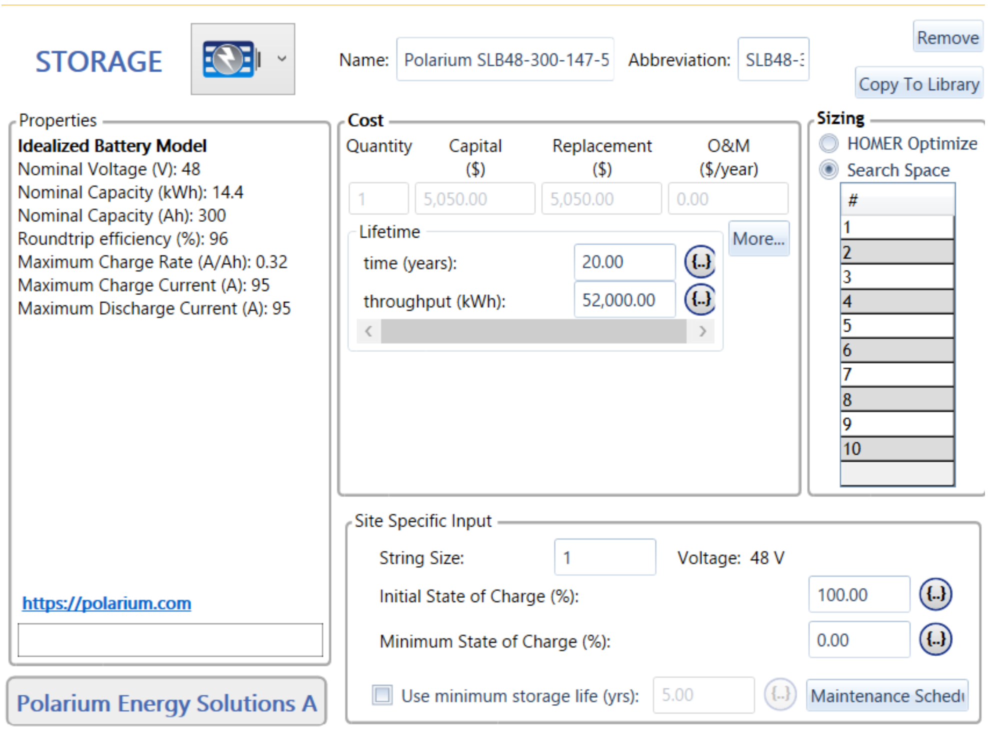


Figure 5-36: Wind modelling in HOMER Pro.

The modelling of the selected Wind Turbine is shown in Figure 5-36. The wind speeds are strongest between June and July at 8.02 m/s and 8.07 m/s, respectively. The lowest winds are in March at 4.37 m/s; however, the wind speed is still enough to produce sufficient energy for the demand.

5.6.4.2. Storage system modelling using Homer Pro

The storage system's modelling is demonstrated in Figure 5-37.



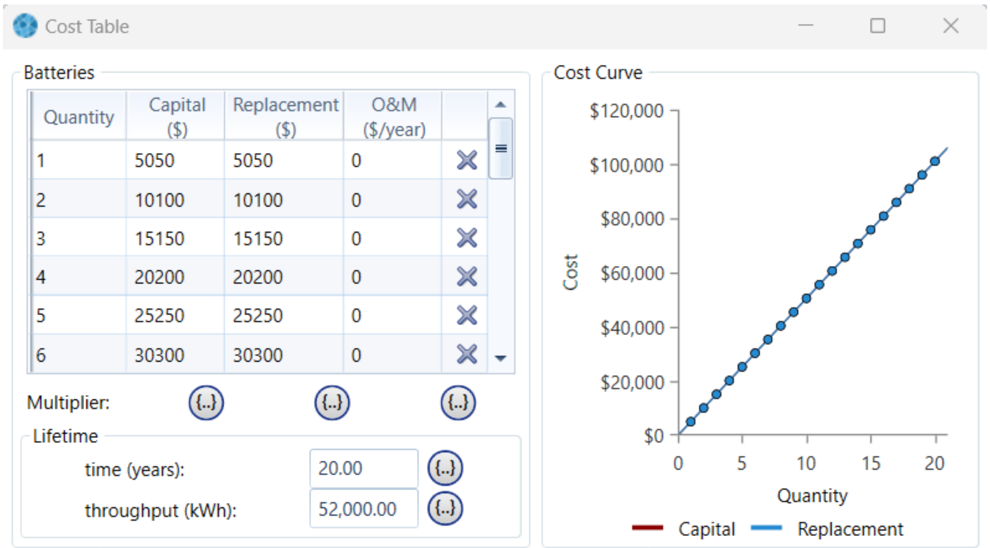


Figure 5-37: Storage modelling in HOMER Pro.

The costs and properties of the battery are demonstrated in Figure 5-37. The battery has a lifespan of 20 years because of its high throughput of 52 000 kWh, and it will be used for a long duration of the project until needing to be changed.

5.6.4.3. Converter system modelling using Homer Pro

The converter is modelled in Figure 5-38.

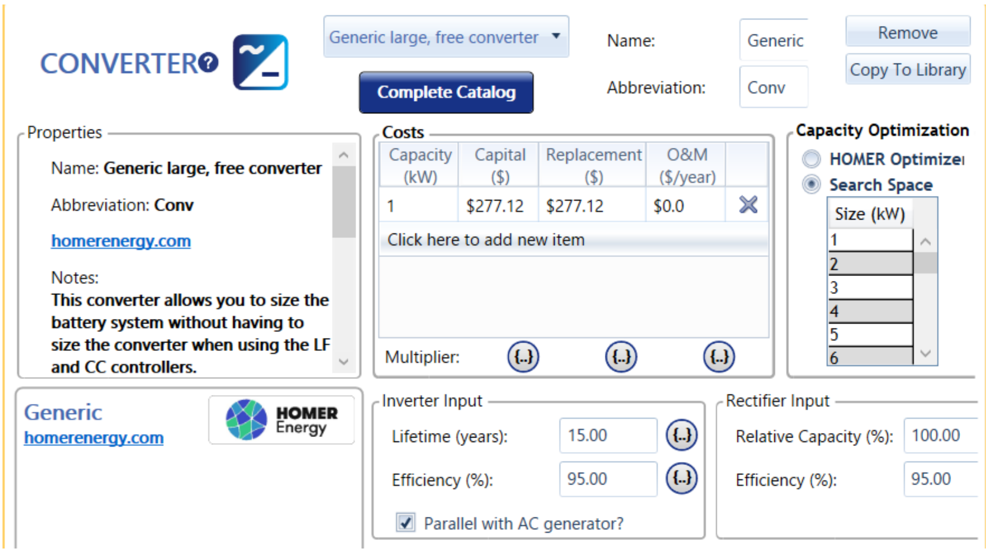


Figure 5-38: Converter modelling in HOMER Pro.

It is anticipated that the converter will employ both the wind turbine's AC power and the battery system's DC electricity to meet the community load demand. It is anticipated that the energy converted will come from the battery's saved energy (14.4 kWh), as well as the wind turbine's electricity produced (25 kWh).

5.6.5. Village E

Table 5-10 below shows the system architecture proposed for this village. Because the village is located on the edge of a big forest with a vast opportunity for biomass. The proposed structure only includes two components, a biomass generator and a converter, and this is because of the vast biomass potential in the location as studied by (Kinyanjui, M. J. et al., 2014, pp. 621-624) who recorded an average of 236 Megagram per Hectare of natural forest in the Mau Forest Ecosystem (MFE).

Table 5-10: Summary of system architecture

Component	Description
Generator	Autosize Genset

The biofueled generator will generate electricity to suit the community's demand.

5.6.5.1. Generator system modelling using Homer Pro

The modelling of the generator system is shown in Figure 5-39 below.

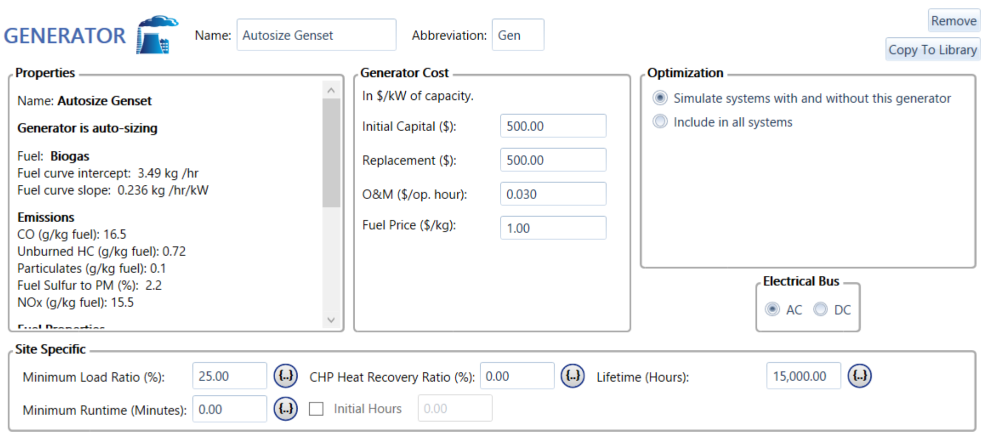


Figure 5-39: Generator modelling in HOMER Pro.

An auto-size generator was selected, and the fuel chosen was biogas. The above figure illustrates how HOMER Pro models the incorporation of generators, which are fuelled by biogas, into a microgrid. It assesses the system's economy, emissions, fuel consumption, and generator performance. The CO emissions, however, are high at 16.5 g/kg fuel (equivalent to 9.26 g/kWh), compared to the typical range of 0.1 to 1.0 g/kWh. This then defeats the purpose of a renewable power system in the aspect of reducing emissions if it still produces high emissions to the atmosphere.

5.7. Economics Modelling

What the project wants to achieve is to find a suitable optimal system configuration that, when installed in the villages, will be able to meet the power demand of that village. The system needs to consist of renewable energy sources with the least cost. The simulations heavily rely on economic modelling. Microgrids that use hybrid renewables as their energy source must undergo a levelized cost of energy (LCOE) analysis to assess the system's economic viability throughout its entire life because they have lower O&M costs and higher initial capital costs than mini-grids that generate electricity using conventional fossil fuels.

The computation program HOMER Pro, which is utilised in this research, determines the best system configuration by calculating the net present cost (NPC) and the average cost of 1 kWh of energy generated, both of which include all expenditures spent over the system's lifespan.

The present value of all the costs a system will incur over its lifespan minus the present value of all the revenue (including salvage value and grid sales revenue) it will generate is the system's total net present cost (NPC). Costs include start-up costs, set-up costs, replacement costs, operation and maintenance costs, and fuel costs. The total NPC value is the base from which HOMER determines the total annualised and levelized cost of energy (LCOE) and categorises all system configurations in the optimisation findings.

The system fixed capital cost.

The system fixed capital cost is the initial capital expense that is incurred at the beginning of the project regardless of the size or architecture of the power system. The system’s fixed capital cost increases the system's overall initial capital cost and, as a result, increases the overall net present cost. It does not affect the system rankings.

For this thesis project, the fixed capital cost is estimated at $ 5,000.00 allocated for:

- Building for storage of electrical equipment such as batteries, charge controllers, generators, inverters, and other essential equipment.
- Construction of distribution lines for the whole village.
- Project Management costs, engineering design costs, labour costs, logistics, legal compliance, and others.

System fixed operation and maintenance cost

This is the ongoing annual expense that always exists in the project regardless of the size or architecture of the power system. The total net present cost of each system configuration is equally impacted by the system fixed O&M cost; hence, the system rankings are unaffected. The System fixed O&M includes monthly salaries of the technician and insurance costs. The estimated System fixed O&M are presented in Figures 5-40 to 5-44 below.

Figure 5-40: Economic modelling window for Village A

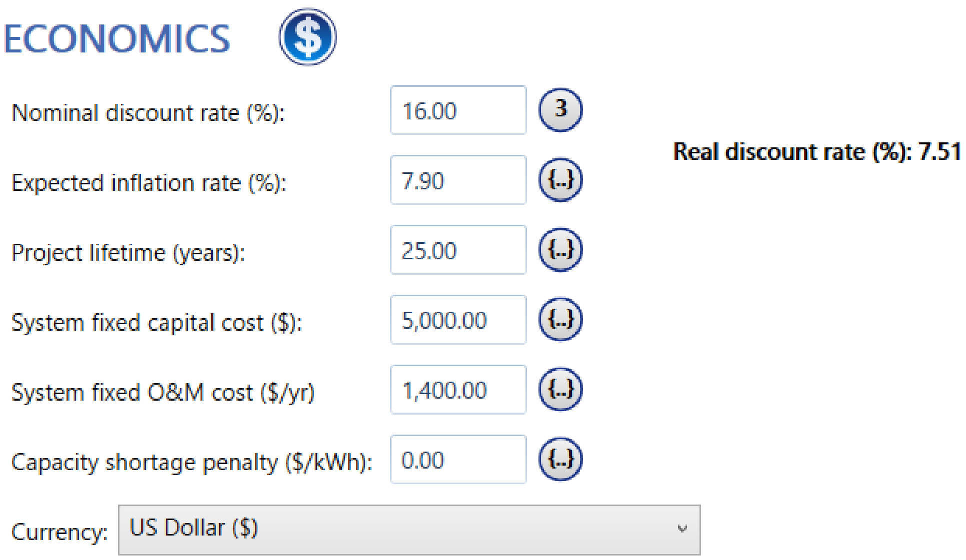


Figure 5-41: Economic modelling window for Village B

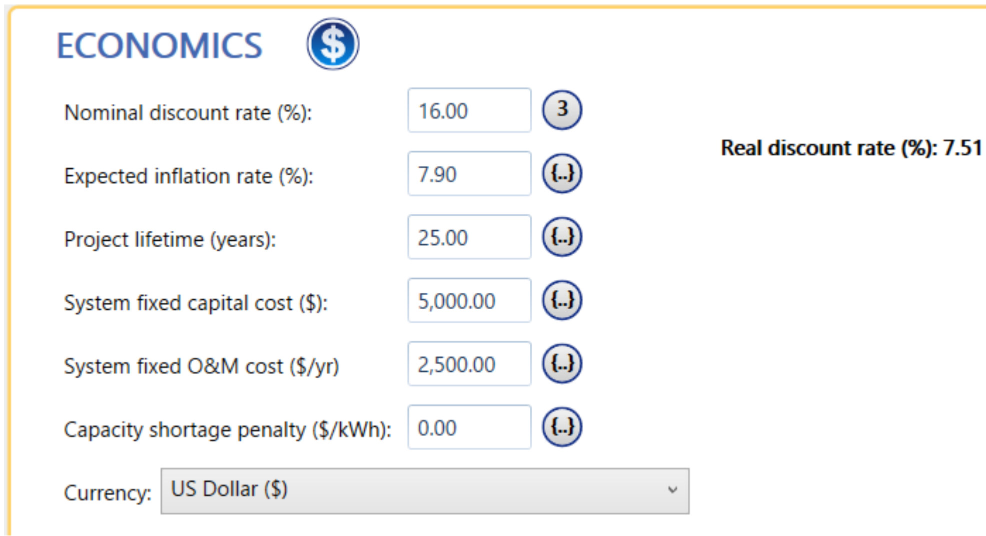


Figure 5-42: Economic modelling window for Village C

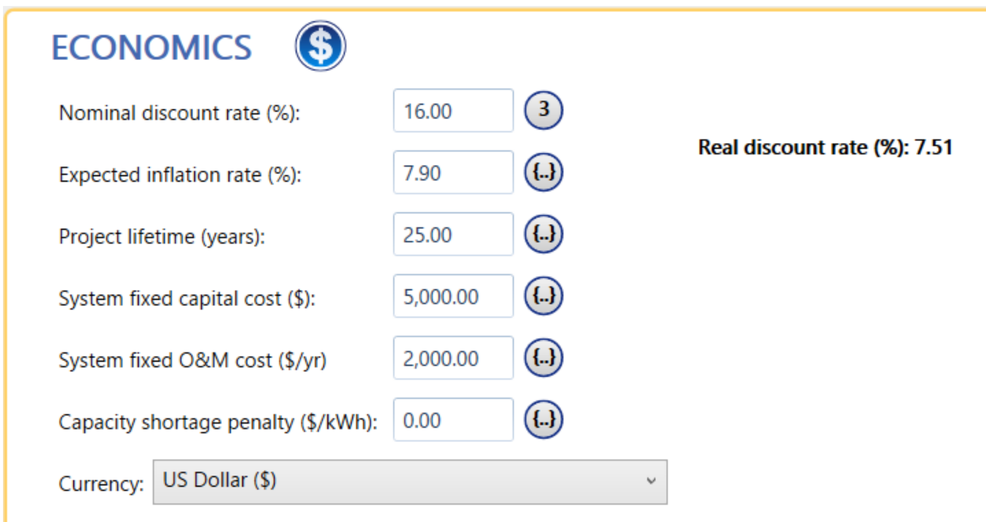


Figure 5-43: Economic modelling window for Village D

Figure 5-44: Economic modelling window for Village E

The figures show how HOMER Pro performs sensitivity analysis and considers a variety of economic variables to assist designers in identifying the most economical microgrid option. The estimated system fixed O&M costs are $25,684.93, $15,589.44.00, $21,403.75, $21,403.75, and $279,875.42, for Village A, B, C, D and E, respectively.

5.8. Sensitivity Inputs

Variables used typically in a microgrid, like solar, wind, hydro and biogas, are often unpredictable, even the economy of a country is uncertain. It is then important that the designed system overcomes this challenge. Homer Pro, by scaling variables, can perform a sensitivity analysis on hourly data sets. The sensitivity analysis enables the system modeller to produce a workable design despite uncertainties resulting from the factors mentioned above. In this way, uncertainties in the primary electric load, the country's economy, prices of the components and the renewable energy are considered.

The uncertain variables for which a sensitivity analysis had to be conducted were, firstly, the discount rate of 16%, 16.5% and 17% for all villages. Secondly, the variables were on the price of PV, with 1 kW PV costing $3,000.00 and 2 kW costing $6,000.00, and so on. Lastly, the uncertain variables were on the price of the battery, with one battery costing $3,550.00, $5,050.00, $60,000.00, and $5,050 for Village A, B, C, and D, respectively, up to the price of several batteries as per the search space.

Chapter 6 : Results and Discussion

This chapter presents analyses and discusses the summary of results obtained from the Homer Pro simulations. The term optimal system will be used here for the configuration that has the lowest net present costs (NPC) or the lowest cost of energy (COE) with the capacity to use the existing energy resources to supply electricity without any shortages.

6.1. Homer Pro Optimisation Results

A cost-optimal system component is suggested by the Homer Pro techno-economic optimisation tool based on the design boundary and lowest Net Present Value (NPV). After analysing the suggested combinations for the five villages, considering the previous inputs and design boundaries, the following result tables are obtained. Firstly, the main results from the optimiser will be shown in a table form, and then afterwards, each of the main component's results will be analysed to provide a clearer outcome of the obtained results.

6.1.1. Village A Optimisation Results:

Figure 6-1 below shows the installation's schematic.

AC Side (Alternating Current)

- Mumbiri Village Load: This represents the electrical demand of the village, with an average daily consumption of 50.52 kWh and a peak demand of 6.94 kW.

DC Side (Direct Current):

- Solar Panels convert sunlight into DC electricity to supply the village's electricity needs.
- Polarium SLB48-200-146-2 (Battery Bank) is a battery bank used to store excess energy generated by solar panels.
- Bidirectional Converter/ inverter between the AC and DC bus

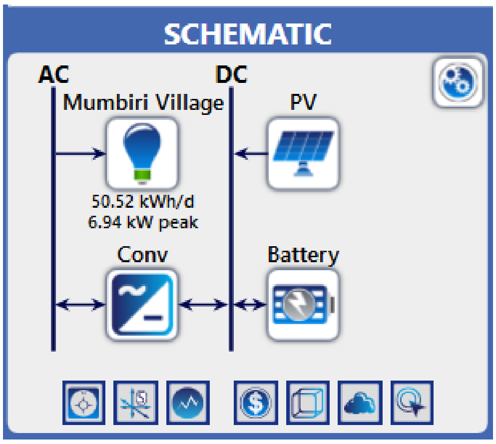
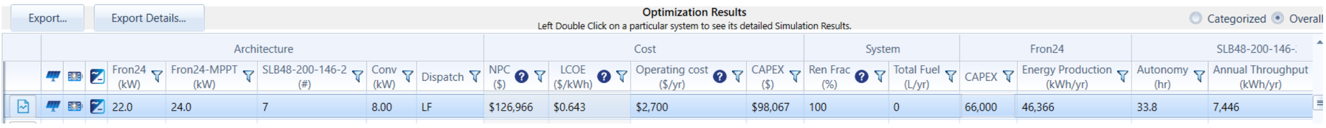


Figure 6-1: Schematic Diagram

Figure 6-2 provides the main optimal results from the Homer Pro software and shows the NPC, LCOE, operating costs, etc.



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

Categorized | Overall

Architecture					Cost				System		Fron24		SLB48-200-146-.	
Fron24 (kW)	Fron24-MPPT (kW)	SLB48-200-146-2 (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	CAPEX	Energy Production (kWh/yr)	Autonomy (hr)	Annual Throughput (kWh/yr)
22.0	24.0	7	8.00	LF	$126,966	$0.643	$2,700	$98,067	100	0	66,000	46,366	33.8	7,446

Figure 6-2: Optimal system results for Mumbiri Village

The results suggest that the software has optimised the system configuration based on certain criteria, likely including minimising costs or maximising renewable energy use. However, the LCOE of $0.643/kWh is way higher compared to the current cost of electricity grid power in the region, which is $0.0832/kWh.

The high autonomy of 33.8 hours suggests that the system can provide backup power for extended periods in case of insufficient generation from the solar panel.

Figure 6-3 provides the block diagram with the system architecture.

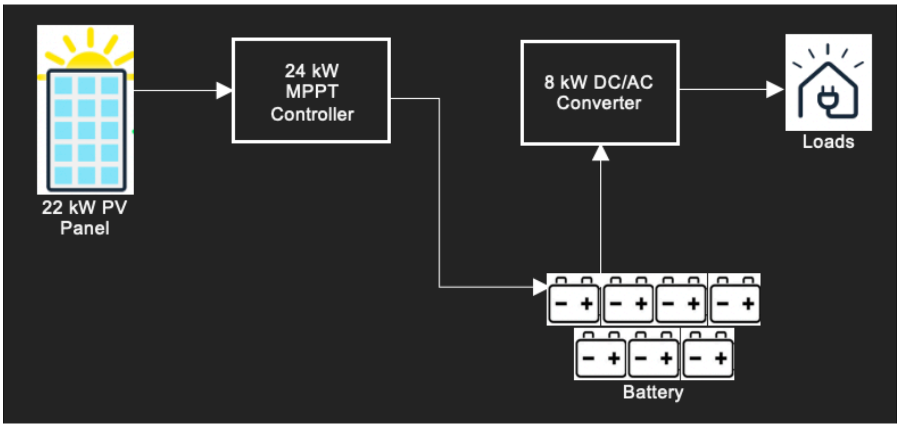


Figure 6-3: Architecture results Block Diagram Village for Village A

Solar Panels

Solar Panels will be the primary source of energy production in the design. They must deliver enough energy to meet the load demand for most of the time and to recharge the batteries during periods of high solar irradiation. As a result, the total amount of allowed solar arrays will be higher than the peak power demand.

A 22 kW Fronius Symo 24.0-3-M PV array is needed to satisfy the demanded energy supply to ensure the site operates in renewable and non-diesel dependent mode and with minimum costs. The price per kW is $3,000.00; this makes the total solar panel initial cost $66,000.00. Table 6-1 below shows the main operating values for the solar panels, taken from the annual average.

Table 6-1: Average Solar Panel Values for Mumbiri Village.

PV Array	Daily Production	Capital Cost
22 kW	111 kWh	$66,000.00

To optimise the match between the solar array and the battery bank, 24 kW MPPTs will be installed. MPPTs convert a higher voltage DC output from solar panels down to the lower voltage needed to charge batteries.

The total power production of the PV installation is displayed in the following Figure 6-4 The numbers displayed in the figures are the annual averages.

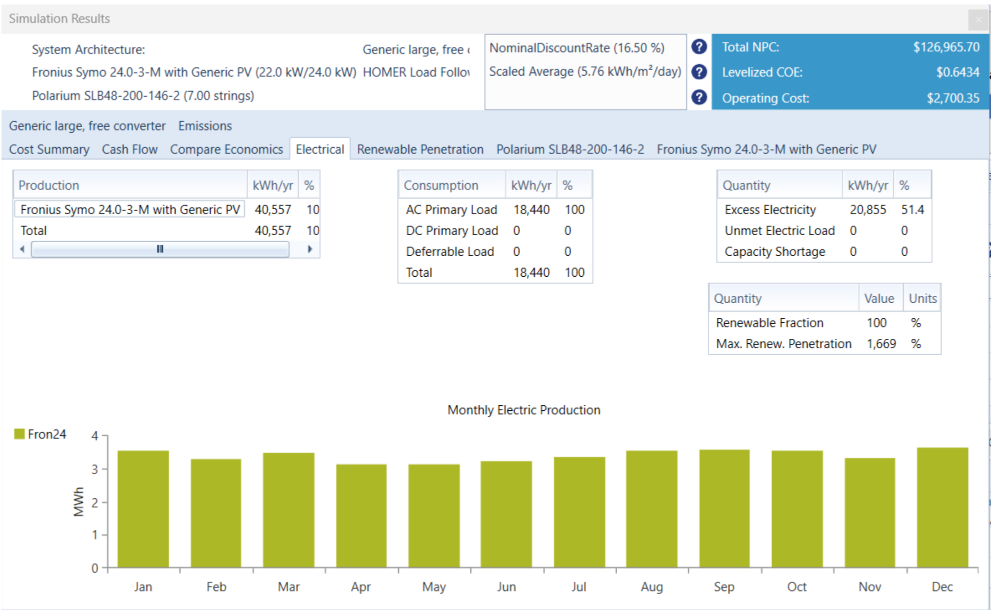


Figure 6-4: Monthly electricity generation for Mumbiri Village.

PV being the only source of energy production in this system then, the monthly electric production is what the PV renewable resource produces.

The system's annual energy production is 40,557 kWh with excess electricity of 51.4%, and the system has 0% unmet electric load. The system configurations have high excess electricity. However, excess electricity is always necessary for future load expansions.

Battery Bank

Table 6-2: Battery operating Values for Mumbiri Village.

Battery Storage	Number of batteries	Initial Capital	Autonomy	Daily Storage
10.2 kWh	7	$24,850.00	33.8 hr	20.7 kWh

Two batteries will be required in the battery bank to guarantee an acceptable site performance based on the previous input parameters. The batteries will be wired in parallel, operating in a load following dispatch strategy, and the bus voltage is 50.8 V.

Converter

Table 6-3: Converter Operating Values for Mumbiri Village.

Converter Capacity	Daily Operation	Initial Capital	Hours of Operation
8 kW	6.94 kW	$2,216.96	24

With previous inputs of a generic large, free converter, the optimisation results showed that the inverter needed for the system is an 8 kW converter.

6.1.2. Village B Optimisation Results:

Results for the Village are shown in Figure 6-5 and Figure 6-6.

AC Side (Alternating Current):

- South Korr Village Load: This represents the village's electrical usage, with a peak demand of 32.14 kW and an average daily use of 234.08 kWh.
- 20 kW Eocycle EO20 Wind Turbine is connected to the AC side because most commercial wind turbines are designed to produce direct AC power.

DC Side (Direct Current):

- SLB48-300-147-5 (Battery Bank) is a battery bank used to store excess energy generated by the wind turbine.
- Bidirectional Converter/ inverter between the AC and DC bus.

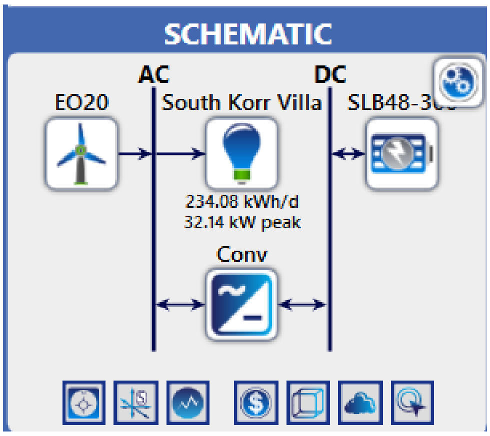


Figure 6-5: Optimal system results for Village B.

Export... | Export Details... | **Optimization Results** — Left Double Click on a particular system to see its detailed Simulation Results. | Categorized | Overall

Architecture				Cost				System		EO20			SLB48-300	
EO20	SLB48-300 (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	O&M Cost ($)	Autonomy (hr)	Annual Throughput (kWh/yr)
2	18	40.0	LF	$380,642	$0.400	$4,817	$326,985	100	0	220,000	221,331	0	26.6	14,010

Figure 6-6: Main results from the optimiser for South Korr Village.

Figure 6-5 has been extracted from the Homer Pro Software, showing the optimal results. The findings indicate that the system setup has been optimised by the software according to specific parameters, most likely cost minimisation or maximising the usage of renewable energy. Nonetheless, the region's current cost of $0.0832/kWh for energy from the National grid is lower in comparison to the LCOE of $0.4/kWh of this system. Figure 6-7 below provides the architecture of the system.

Given the system's high autonomy of 26.6 hours, it is possible that it can supply backup power for two extra hours when the day has ended if there is not enough wind power generation.

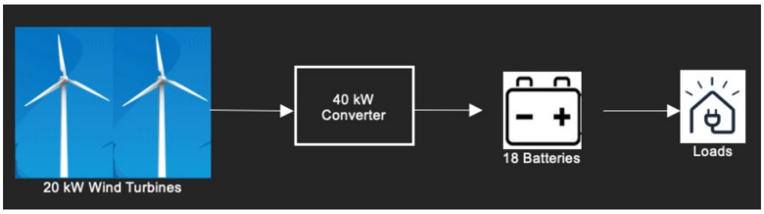


Figure 6-7: Architecture results Block Diagram Village for Village B

Wind Turbine

Table 6-4: Average Solar Panel Values for South Korr Village.

Wind Turbine Capacity	Daily Production	Capital Cost
20 kW	25.3 kWh	$220,000.00

This system for South Korr Village will require a 20 kW wind turbine, and the daily production is 25.3 kWh. Figure 6-8 below shows the simulation results of the wind turbine.

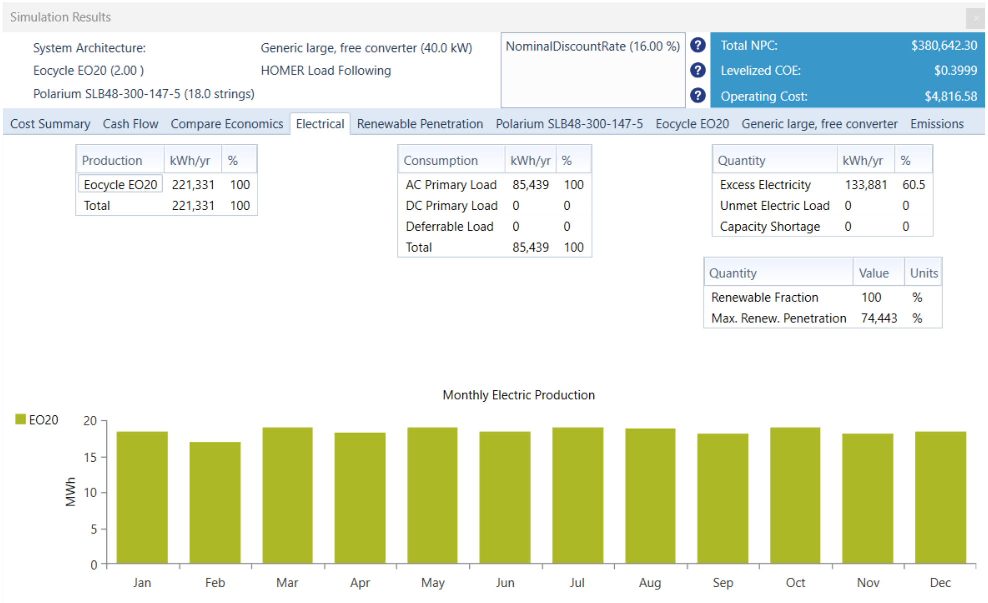


Figure 6-8: Monthly electricity generation for Village B.

Extracted from the Homer Pro software, Figure 6-8 is the electricity generation of the system where all electric loads are met, and there is no shortage of capacity.

Battery Bank

Table 6-5: Battery operating Values for Village B.

Battery Storage	Number of batteries	Initial Capital	Autonomy	Daily Storage
259 kWh	18	$90,900.00	26 hr	38.4 kWh

The battery operating values are shown above in Table 6-5.

Converter

Table 6-6: Converter Operating Values for Amakura Village.

Converter Capacity	Daily Operation	Initial Capital	Hours of Operation
40 kW	37.4 kW	$11,084.80	19

The operating values for the converter are given in Table 6-6.

6.1.3. Village C:

The proposed system for Village C was a PV/Wind hybrid system. The optimisation results presented simulation results that excluded the wind turbine, where all electrical demand has been met and is the least LCOE. The results are shown below in Figure 6-9 and Figure 6-10.

AC Side (Alternating Current):

- Kitulu Village Load: Reflects the village's electrical use, which is 21.85 kW at its peak and 159.14 kWh on average per day.
- 25 kW SWP25-16TV20 Wind Turbine is connected to the AC. Its designed original output is aligned with the AC bus therefore, no additional strain on the converter equipment is required to convert the wind turbine power.

DC Side (Direct Current):

- Solar panels use light from the sun to produce DC electricity to power the community.
- SAFT Intensium Max plus 2 (Battery Bank) is a battery bank used to store excess energy generated by both solar panels and wind turbines.
- Bidirectional Converter/ inverter between the AC and DC bus.

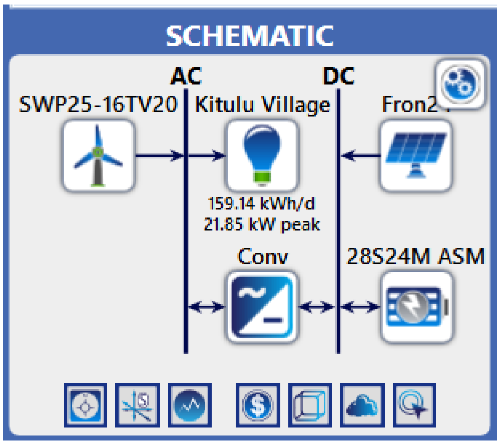
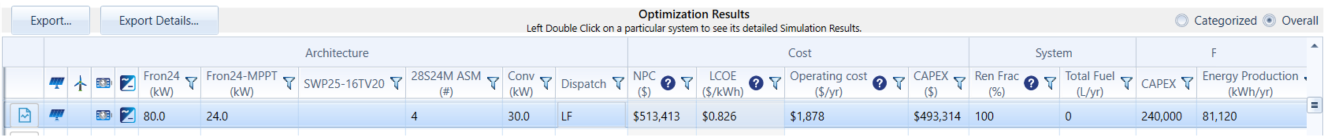


Figure 6-9: Optimal system results for Village C.


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

Fron24 (kW)	Fron24-MPPT (kW)	SWP25-16TV20	28S24M ASM (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	CAPEX	Energy Production (kWh/yr)
80.0	24.0		4	30.0	LF	$513,413	$0.826	$1,878	$493,314	100	0	240,000	81,120

Figure 6-10: Main results from the optimiser for Kitulu Village

The findings indicate that the system setup has been optimised by the software according to specific parameters, most likely cost minimisation or maximising the usage of renewable energy. As a result, the wind turbine has been excluded from the final system because the solar panels can produce sufficient energy of 81120 kWh/yr that will serve the community. A block diagram showing the system architecture is given in Figure 6-11.

The NPC of this system is among the highest at $513,413.00 compared to the rest of the system designs.

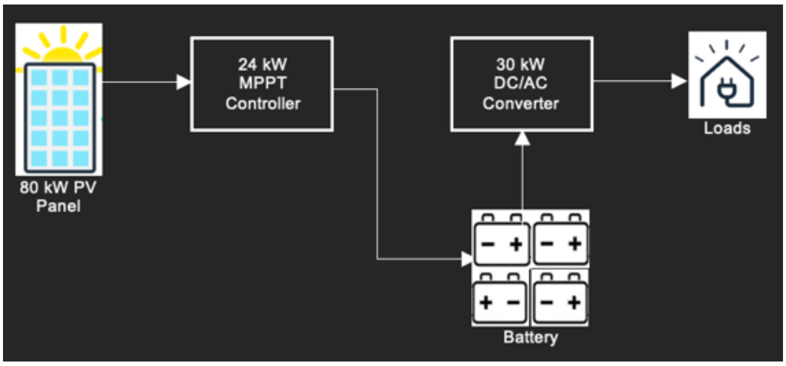


Figure 6-11: Architecture results Block Diagram Village for Village C

With a PV capacity of 80 kW, 24 kW MPPTs, four batteries and a 30 kW capacity converter, the load profile for Village C will be completely covered.

Solar Panels

Table 6-7: Average Solar Panel Values for Kitulu Village

PV Array	Daily Production	Capital Cost
80 kW	222.25 kWh	$240,000.00

The daily production, as presented in Table 6-7, is 18.99 kWh.

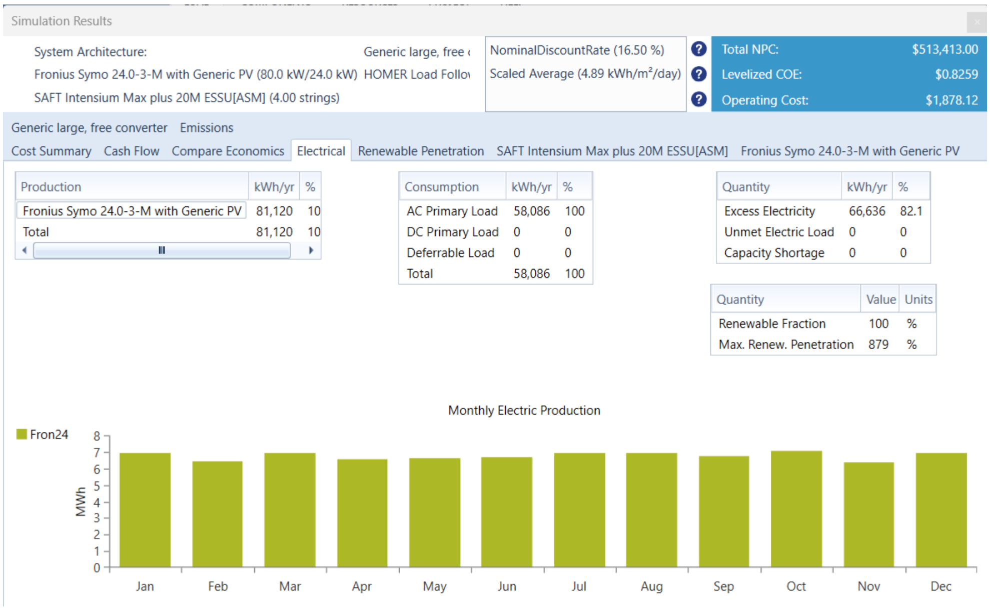


Figure 6-12: Monthly electricity generation for Kitulu Village.

The PV and battery-based renewable energy sources meet the demand for electricity 100% without any capacity shortage.

Battery Bank

The battery operating values are illustrated in Table 6-8.

Table 6-8: Battery operating Values for Kitulu Village.

Battery Storage	Number of batteries	Initial Capital	Autonomy	Daily Storage
55.8 kWh	4	$240,000.00	23.6 hr	64.14 kWh

The planned battery bank requires four batteries, and its initial capital cost will be $240,000.00. The daily storage capacity of these batteries will be 223 kWh/battery.

Converter

Provided in Table 6-9 below are the operating values for the converter.

Table 6-9: Converter Operating Values for Kitulu Village.

Converter Capacity	Daily Operation	Initial Capital	Hours of Operation
30 kW	21.9 kW	$8,313.60	24

This chosen model of the converter comes at an initial cost of $8,313.60 and has a maximum output power of 21.9 kW.

6.1.4. Village D:

The 25 kW Wind Turbine, 20 batteries, and a 15 kW converter were found to be the techno-economically best systems for this site. These results are shown in Figure 6-13 and Figure 6-14 below.

AC Side (Alternating Current):

- Mkwiro Village Load: Represents the electrical demand of the village, with an average daily consumption of 98.52 kWh and a peak demand of 13.53 kW.
- 25 kW SWP25-16TV20 Wind Turbine is connected to the AC for easy integration with community load.

DC Side (Direct Current):

- Polarium SLB48-300-147-5 (Battery Bank) is a battery bank used to store excess energy generated by both the solar panels and the wind turbine.
- Bidirectional Converter/ inverter between the AC and DC bus.

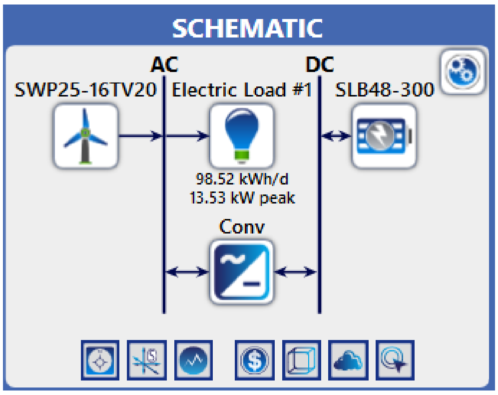


Figure 6-13: Optimal system results for Village D.

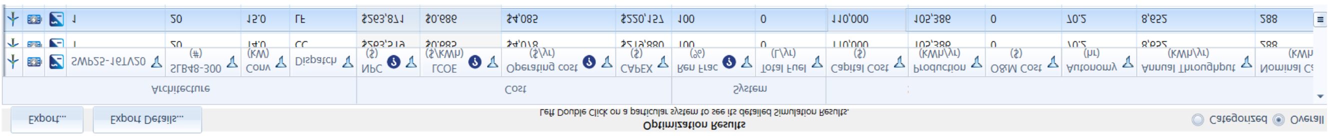


Figure 6-14: Main results from the optimiser for Mkwiro Village

The results indicate the optimised summary of the most feasible system configuration based on the criteria, and that includes meeting the community loads 100%. The NPC of this system is among the lowest at $263,871.00 compared to the rest of the system designs. The high Autonomy of 70.2hr is a good indication that the system can serve the community in case of unavailability of wind for longer periods than expected.

The architecture of village D includes a 25 kW wind turbine, 15 kW Converter, 20 batteries and the load, and is given in the below Figure 6-15.

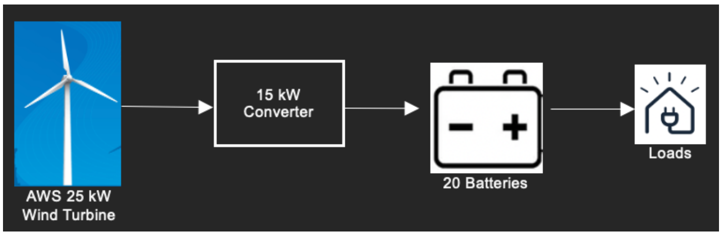


Figure 6-15: Architecture results Block Diagram Village for Village D

Wind Turbine

Table 6-10 provides the wind turbine size, daily production, and capital costs, while Figure 6-16 demonstrates the monthly electricity generation for Village D.

Table 6-10: Average Wind Turbine Values for Village D.

Wind Turbine	Daily Production	Capital Cost
25 kW	288.73 kWh	$110,000.00

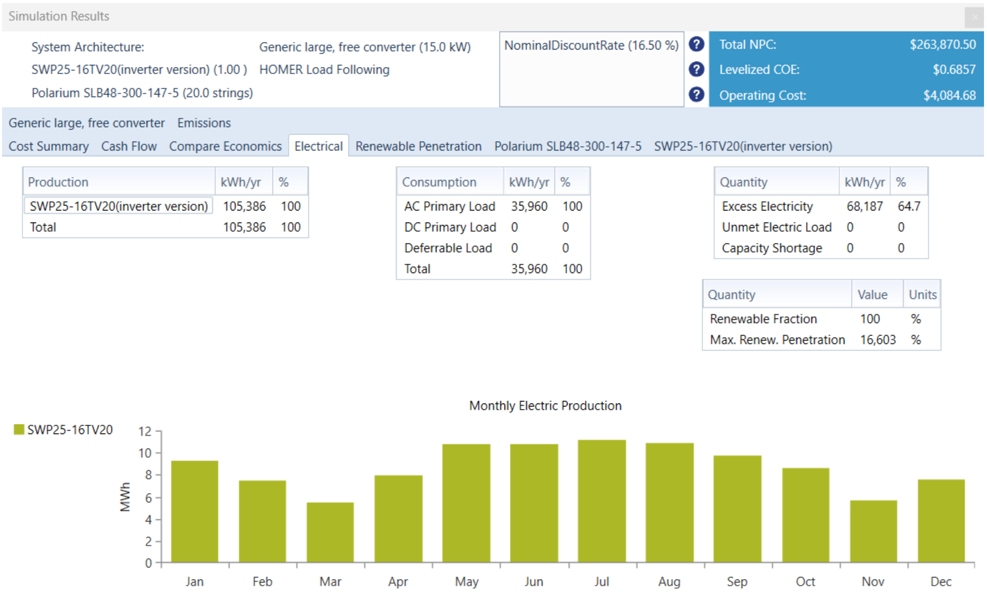


Figure 6-16: Monthly electricity generation for Village D.

The system's annual energy production is 105.386 kWh with excess electricity of 64.7%, and the system has 0% unmet electric load.

Battery Bank

Table 6-11 displays the battery operating values.

Table 6-11: Battery operating Values for Mkwiro Village.

Battery Storage	Number of batteries	Initial Capital	Autonomy	Daily Storage
14.4 kWh	20	$101,000.00	70.2 hr	23.7 kWh

The batteries of this system have a nominal capacity of 14.4 kWh and an autonomy of 70.2 hr.

Converter

The converter's operating values are listed in Table 6-12 below.

Table 6-12: Converter Operating Values for Mkwiro Village.

Converter Capacity	Daily Operation	Initial Capital	Hours of Operation
15 kW	288.7 kW	$4,156.80	20

Because the microgrid's power is completely supplied by the Wind Turbine, the 15 kW Converter will run continuously and its maximum output being 24.5 kW.

6.1.5. Village E:

Figure 6-18 shows the outcomes of the community microgrid component size optimisation for both technical and financial viability. Figure 6-17, on the other hand, shows the Schematic of the design. The size of the community microgrid consists of only a 1.80 kW Generator.

The Gen-set is connected directly to AC to simplify operation and ensure there is no use of a converter/inverter.

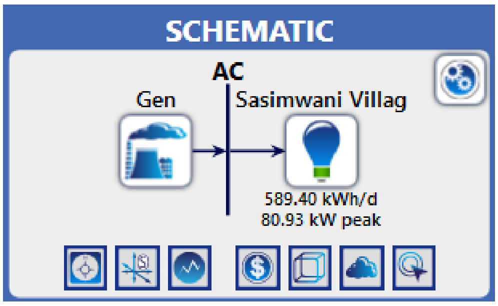
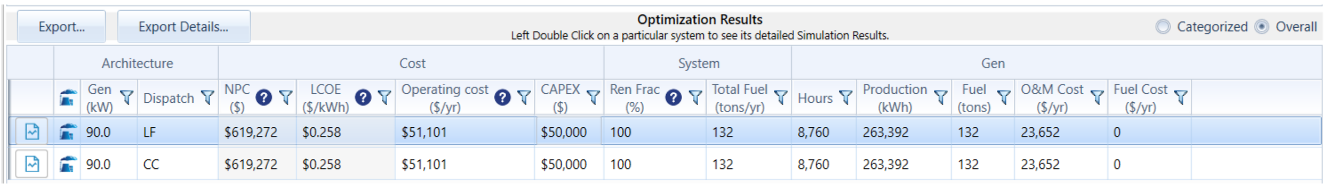


Figure 6-17: Optimal system results for Village E.



Export... Export Details...

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

Categorized Overall

Architecture		Cost				System		Gen				
Gen (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (tons/yr)	Hours	Production (kWh)	Fuel (tons)	O&M Cost ($/yr)	Fuel Cost ($/yr)
90.0	LF	$619,272	$0.258	$51,101	$50,000	100	132	8,760	263,392	132	23,652	0
90.0	CC	$619,272	$0.258	$51,101	$50,000	100	132	8,760	263,392	132	23,652	0

Figure 6-18: Main results from the optimiser for Sasimwani Village

This system has a Levelized Cost of Energy of $0.257 per kWh and a Net Present Cost of $619,272(see Figure 6-18 above). The findings indicate that the system setup has been optimised by the software according to specific parameters, most likely cost minimisation or maximising the usage of renewable energy. Nonetheless, the region's current cost of $0.0832/kWh for energy from the National grid is lower in comparison to the LCOE of $0.257/kWh of this system.

The renewable fraction on the system is 100%, dropping the fuel costs down to 0$/yr because the system is completely renewable, this makes the energy production cheaper than the other microgrid designs, however, as mentioned above, it is still higher than the grid power in the region.

The architecture results from the optimiser are given in Figure 6-19 below.

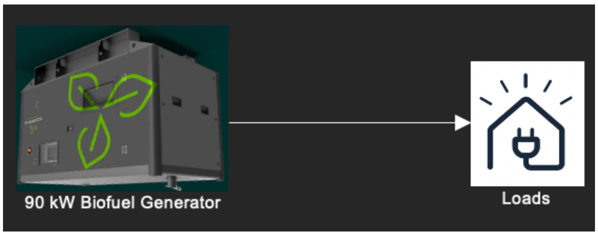


Figure 6-19: Architecture results from the optimiser for Sasimwani Village

Generator Set

Simulation results for the generator are depicted in Table 6-13 and Figure 6-20.

Table 6-13: Average Generator Set Values for Village E.

Genset	Daily Production	Capital Cost
90 kW	721.6 kWh	$50,000.00

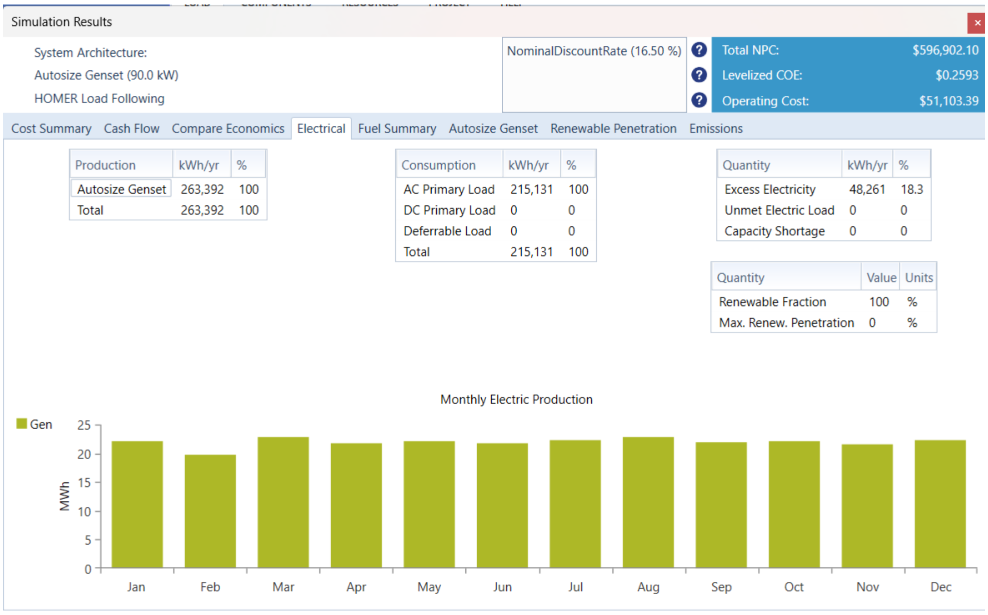


Figure 6-20: Monthly electricity production for Village E.

The biodiesel generator is the only source of energy production in this system, and the monthly electric production is what the biomass renewable resource produces. The total production, as shown above in Figure 6-20, is 263,392.0 kWh/yr and is meeting all electricity demands.

6.2. Cost Breakdown Overview

The several types of costs that should be considered while analysing the project from an economic standpoint are depicted in the following Figure 6-21 chart.

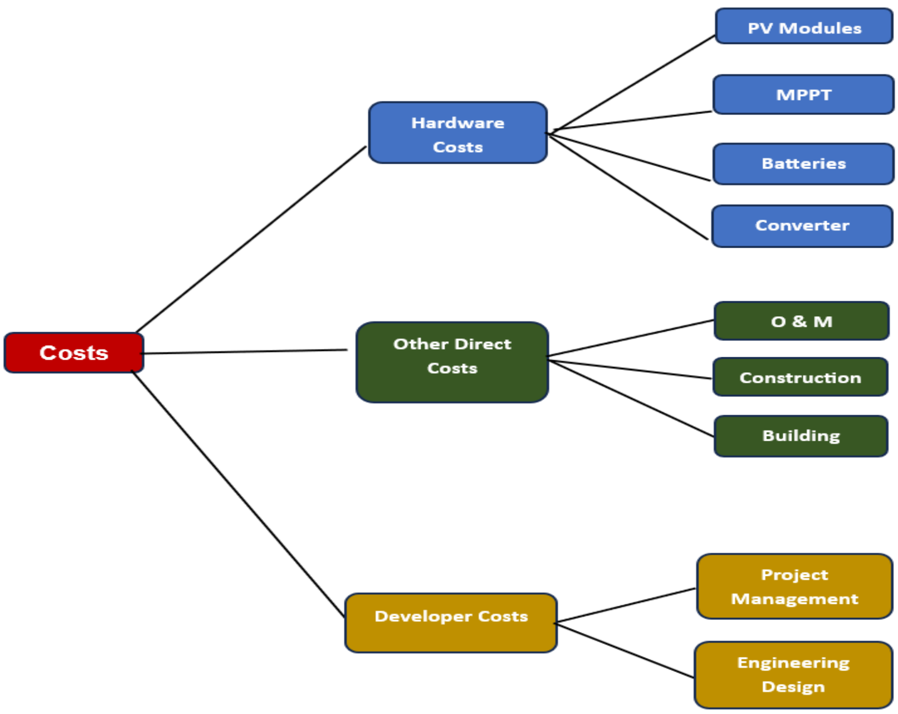
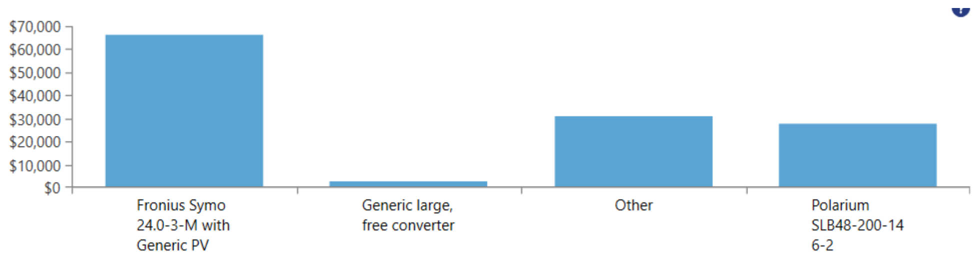


Figure 6-21: Cost breakdown of the All Village Microgrid.

Figures 6-22 to 6-26 below provide the financial information for the various system components, including their capital cost, O&M costs, and replacement costs. As demonstrated in these figures, the capital costs account for a larger portion of the overall costs. Once the PV, Wind Turbine and Genset have been installed, there is not much maintenance required. Hence, there are no allocated O&M costs. Instead, there has been allocation for other costs which will cater for any future requirements.

6.2.1. Village A:



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Fronius Symo 24.0-3-M with Generic PV	$66,000.00	$0.00	$0.00	$0.00	$0.00	$66,000.00
Generic large, free converter	$2,216.96	$701.76	$0.428	$0.00	($108.65)	$2,810.50
Other	$5,000.00	$0.00	$25,684.50	$0.00	$0.00	$30,684.50
Polarium SLB48-200-146-2	$24,850.00	$5,360.89	$0.00	$0.00	($2,740.16)	$27,470.73
System	$98,066.96	$6,062.65	$25,684.93	$0.00	($2,848.81)	$126,965.73

Figure 6-22: Cost Figures for Village A.

Figure 6-22 provides cost figures for the components. The Capital Cost is the initial expense for obtaining and setting up the microgrid's components, and for this village, it is $98,066.96. Replacement costs refer to expenses incurred during the project for component replacement. The recurring expenses related to microgrid operation and maintenance, which were found to be $25,684.92, are presented under the O&M column. The Fuel Cost is the cost of purchasing fuel that will be used for generators, because the source of energy for this system is solar, the fuel costs are $0.00. Lastly, the Salvage Cost is the projected value of the components after the project.

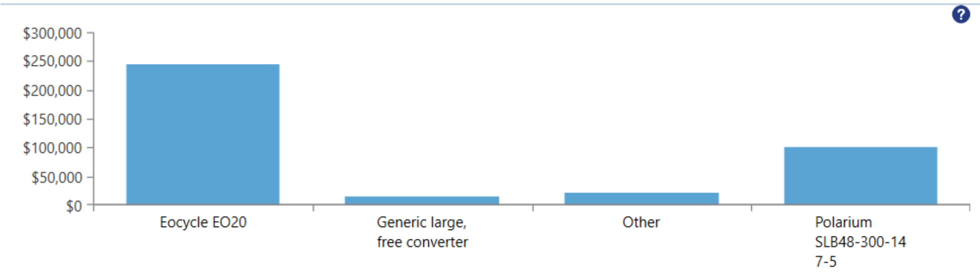
Table 6-14 below shows the Homer Pro optimisation result summary that now includes the LCOE, NPV, Renewable fraction and Capital, together with the rest of the system components.

Table 6-14: Homer Pro optimisation result summary for Village A.

Description	**Value**
PV (kW)	22
Battery (kWh)	10.2
Converter (kW)	8
NPC ($)	126,965.70
Capital ($)	98,066.96
LCOE ($/kWh)	0.643
Operating Cost ($)	2,700.35
Renewable fraction (%)	100

The optimal microgrid designs are shown in HOMER Pro's optimisation results summary table, which considers cost, reliability, and the percentage of renewable energy sources in the system. This table includes the optimised configuration to ensure the minimisation of costs and maximising renewable energy penetration.

6.2.2. Village B:



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Eocycle EO20	$220,000.00	$51,723.96	$0.00	$0.00	($27,012.85)	$244,711.12
Generic large, free converter	$11,084.80	$3,742.65	$2.23	$0.00	($604.91)	$14,224.77
Other	$5,000.00	$0.00	$15,596.21	$0.00	$0.00	$20,596.21
Polarium SLB48-300-147-5	$90,900.00	$21,371.40	$0.00	$0.00	($11,161.22)	$101,110.18
System	$326,984.80	$76,838.02	$15,598.44	$0.00	($38,778.97)	$380,642.28

Figure 6-23: Cost Figures for Village B.

The battery components cost more than the other components (Wind Turbine and Converter), and it costs $90,900.00. Polarium battery is an intelligent battery which gives full control remotely and needs no maintenance. No costs have been allocated for O&M, and the Other Costs will cater for any future requirements. According to the manufacturer's datasheet, it can last up to 20 years.

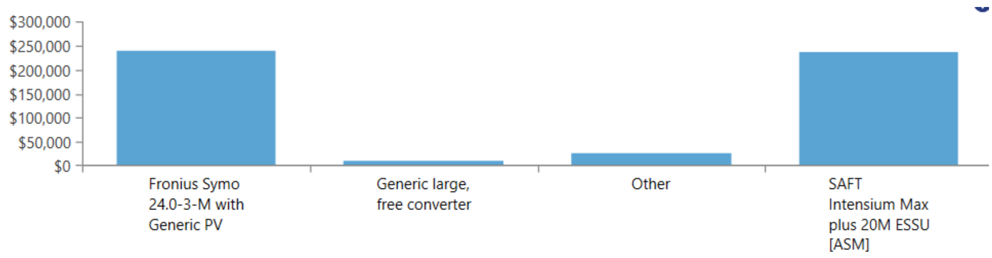
Table 6-15: Homer Pro optimisation result summary for Village B.

Description	Value
Wind Turbine (kW)	20
Battery (kWh)	14.4
Converter (kW)	40
NPC ($)	380,642.30
Capital ($)	326,984.80
LCOE ($/kWh)	0.4
Operating Cost ($)	4,816.58
Renewable fraction (%)	100

From the above table, the LCOE is at the price of $0.4/kWh. Looking at the consumption group this village falls under, this LCOE price is more than the current price of electricity in Kenya, which is $0.0832/kWh when connected to the grid. The Government would have to subsidise the electricity sale to the community so that they can afford it. Another option is for the Government to develop and build the microgrid and not include the costs as initial costs in the economy of the system, in that way, the LCOE will be lower, and the village communities will afford the electricity.

6.2.3. Village C:

The following figure represents the site's cost summary for its 25-year lifetime. It gives a total system cost of $513,412.95.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
▷ Fronius Symo 24.0-3-M with Generic PV	$240,000.00	$0.00	$0.00	$0.00	$0.00	$240,000.00
▷ Generic large, free converter	$8,313.60	$2,631.61	$0.00	$0.00	($407.43)	$10,537.78
▷ Other	$5,000.00	$0.00	$21,403.75	$0.00	$0.00	$26,403.75
▷ SAFT Intensium Max plus 20M ESSU[ASM]	$240,000.00	$0.00	$0.00	$0.00	($3,528.57)	$236,471.43
System	$493,313.60	$2,631.61	$21,403.75	$0.00	($3,936.01)	$513,412.95

Figure 6-24: Cost Figures for Village C.

The initial capital cost is the biggest element of the cost. This covers buying and setup of batteries, solar panels, converters, and other machinery. The capital cost for the system is $493,313.60, which is 49% of the total value of the system. Expensive technologies like sophisticated control systems and battery storage are the main causes of this expense.

Table 6-16 below presents the optimisation summary, which includes the components and the costs of the system.

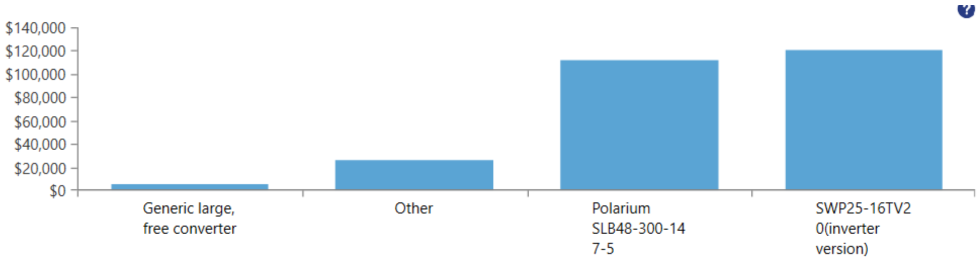
Table 6-16: Homer Pro optimisation result summary for Village C.

Description	Value
PV (kW)	80
Battery (kWh)	55.8
Converter (kW)	30
NPC ($)	513,413.00
Capital ($)	493,313.60
LCOE ($/kWh)	0.826
Operating Cost ($)	1,878.12
Renewable fraction (%)	100

The Capital costs for the system of Village C are $493,313.60, and the NPC is $513,413.00 with operating costs of $1,878.12 with all those costs considered, the LCOE comes to $0.826 kWh.

6.2.4. Village D:

The below Figure 6-25 shows the cost figures for Village D.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
▷ Generic large, free converter	$4,156.80	$1,315.81	$0.00	$0.00	($203.72)	$5,268.89
▷ Other	$5,000.00	$0.00	$21,403.75	$0.00	$0.00	$26,403.75
▷ Polarium SLB48-300-147-5	$101,000.00	$21,788.72	$0.00	$0.00	($11,137.06)	$111,651.66
▷ SWP25-16TV20(inverter version)	$110,000.00	$21,572.99	$0.00	$0.00	($11,026.79)	$120,546.20
System	$220,156.80	$44,677.52	$21,403.75	$0.00	($22,367.57)	$263,870.50

Figure 6-25: Cost Figures for Village D

In Figure 6-25, the Wind Turbine, battery, and Converter components contain only capital costs because the O&M costs are assumed to be included in the “other” costs, which will cater for the technician’s salary.

The summary of the optimisation results is given below in Figure 6-17.

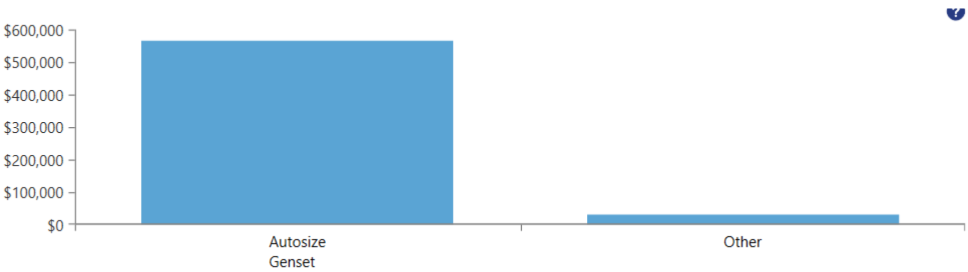
Table 6-17: Homer Pro optimisation result summary for Village D.

Description	Value
Wind Turbine (kW)	25
Battery (kWh)	14.4
Converter (kW)	15
NPC ($)	263,870.50
Capital ($)	220,156.80
LCOE ($/kWh)	0.686
Operating Cost ($)	4,084.68
Renewable fraction (%)	100

The NPC is $263,870.5, and this represents the microgrid's whole lifespan cost, adjusted for current value and considering both upfront and recurring expenses.

6.2.5. Village E:

Figure 6-26 and Table 5-18 demonstrate the total costs of all the required components for the desired system, showing the total NPC, Levelised COE and operating cost.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
▷ Autosize Genset	$45,000.00	$269,673.09	$253,120.73	$0.00	($2,646.43)	$565,147.40
▷ Other	$5,000.00	$0.00	$26,754.69	$0.00	$0.00	$31,754.69
System	$50,000.00	$269,673.09	$279,875.42	$0.00	($2,646.43)	$596,902.08

Figure 6-26: Cost Figures for Village E.

As shown in Figure 6-26, the replacement costs are almost the same value as the total capital cost of the genset system. This is because the system comprises just the generator, and when the generator's lifespan ends, the whole unit is replaced.

Table 6-18: Homer Pro optimisation result summary for Village E.

Description	Value
Genset (kW)	90
NPC ($)	596,902.10
Capital ($)	50,000.00
LCOE ($/kWh)	0.259
Operating Cost ($)	51,103.39
Renewable fraction (%)	100

The biomass-generated microgrid of Village E has the highest operating costs ($51,103.39) compared to other Villages, indicating that other renewable resources like solar and wind are cheaper to operate when used in a microgrid. However, this biomass microgrid yielded the cheapest LCOE compared to other villages.

6.3. Sensitivity Analysis

Sensitivity analysis is carried out to determine the impact of uncertainties like solar, wind, and biomass resources on the microgrid's cost sensitivity for NPV and LCOE. This is because the effectiveness of the components is affected by renewable energy resources. The sensitivity analysis helps in extrapolating the study's findings to various climatic situations. The first sensitivity analysis was conducted on renewable energy resources. Secondly, the sensitivity analysis was conducted on the Discount Rate ranges of 16%, 16.5% and 17% for all Villages, thirdly, the price of components with one PV costing $3,000.00 /kW and 2 kW costing $6,000.00 and so on. Lastly, the price of one battery costs $3,550.00, $5,050.00, $60,000.00, and $5,050 for Village A, B, C, and D, respectively, up to the price of several batteries as per the search space. Tables 6-19 to 6-23 below will summarise the sensitivity inputs, and Figures 5-22 to 5-26 will show the sensitivity results.

6.3.1. Village A:

The reference scaled annual average solar resource value generated by the National Renewable Energy Laboratory is 5.76 kWh/m²/day. Table 6-19 represents the sensitivity inputs summary for the village, and the results are shown in Figure 6-27.

Table 6-19: Sensitivity inputs summary for Village A.

Scaled Annual Average (kWh/m²/day)	5	5.763 (Reference value)	6.763
Nominal Discount Rate (%)	16	16.5	17

The sensitivity inputs shown in Table 6-19 were used to further assess the effect of increasing or decreasing the uncertain variable.

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Sensitivity		Architecture					Cost				System		Frc	
NominalDiscountRate (%)	Solar Scaled Average (kWh/m²/day)	Fron24 (kW)	Fron24-MPPT (kW)	SLB48-200-146-2 (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	CAPEX	Energy Production (kWh/yr)
16.5	5.76	20.0	24.0	6	8.00	LF	$117,041	$0.593	$2,665	$88,517	100	0	60,000	36,870
16.5	5.00	22.0	24.0	7	8.00	LF	$126,966	$0.643	$2,700	$98,067	100	0	66,000	35,547
16.5	6.76	16.0	24.0	7	8.00	LF	$108,966	$0.552	$2,700	$80,067	100	0	48,000	33,720
16.0	5.76	20.0	24.0	6	8.00	LF	$118,274	$0.576	$2,671	$88,517	100	0	60,000	36,870
16.0	5.00	22.0	24.0	7	8.00	LF	$128,223	$0.624	$2,707	$98,067	100	0	66,000	35,547
16.0	6.76	16.0	24.0	7	8.00	LF	$110,223	$0.537	$2,707	$80,067	100	0	48,000	33,720
17.0	5.76	20.0	24.0	6	8.00	LF	$115,884	$0.611	$2,659	$88,517	100	0	60,000	36,870
17.0	5.00	22.0	24.0	7	8.00	LF	$125,785	$0.663	$2,693	$98,067	100	0	66,000	35,547
17.0	6.76	16.0	24.0	7	8.00	LF	$107,785	$0.568	$2,693	$80,067	100	0	48,000	33,720

Figure 6-27: Sensitivity result for Village A.

Taking into consideration all the sensitivity inputs mentioned above, the simulation results show the optimal systems (highlighted in blue) where the solar scaled average generated from the National Renewable Energy Laboratory is 6.763, and the lowest discount rate is 16%. The sensitivity analysis gives the Lowest Cost of Energy of $0.537 with the lowest NPC of $110,223.

6.3.2. Village B:

Table 6-20 shows the wind resource sensitivity inputs, and Figure 6-28 shows the sensitivity simulation results.

Table 6-20: Sensitivity inputs summary for Solar Resource for Village B

Wind Scaled Average (m/s)	7.06	8.06 (Reference value)	9.06
Nominal Discount Rate (%)	16	16.5	17

RESULTS

Summary | Tables | Graphs | Calculation Report

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Sensitivity		Architecture					Cost				System		AWS1.5kW			SLB48-2
NominalDiscountRate (%)	Wind Scaled Average (m/s)	AWS1.5kW	SLB48-200-146-2 (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	O&M Cost ($)	Autonomy (hr)
16.0	7.06	2	2	2.00	CC	$51,019	$1.22	$1,410	$36,654	100	0	24,000	9,221	0	43.3
16.0	8.06	1	5	2.00	CC	$49,669	$1.19	$1,410	$35,304	100	0	12,000	4,753	0	108
16.0	9.06	2	3	2.00	CC	$54,569	$1.30	$1,410	$40,204	100	0	24,000	9,274	0	64.9
17.0	7.06	2	2	2.00	CC	$50,058	$1.28	$1,410	$36,654	100	0	24,000	9,221	0	43.3
17.0	8.06	1	5	2.00	CC	$48,708	$1.25	$1,410	$35,304	100	0	12,000	4,753	0	108

Figure 6-28: Sensitivity result for Village B.

Nine systems are produced by the simulation results for this sensitivity, and LCEO rises as the discount rate rises.

6.3.3. Village C:

From Figure 6-29 below, all sensitivity cases with all inputs put into consideration can be seen. It can also be seen that from the sensitivity results, the higher values of the sensitivity inputs produce a higher LCOE. The capacity of PV has varied between 20kW and 30kW in all sensitivity cases, and the rest of the components are the same. Table 6-21 illustrates the solar resource, wind resource, and nominal discount rate sensitivity inputs for the village.

Table 6-21: Sensitivity inputs summary for Village C.

Scaled Annual Average (kWh/m²/day)	4.89	5.89 (Reference value)	6.89
Nominal Discount Rate (%)	16	16.5	17

Export... | Export All... | **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. | Compare Economics | Column Choices...

Sensitivity		Architecture										Cost				System		Fron24	
NominalDiscountRate (%)	Solar Scaled Average (kWh/m²/day)					Fron24 (kW)	Fron24-MPPT (kW)	SWP25-16TV20	28S24M ASM (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)	CAPEX	Energy Produ (kWh/yr)
16.5	4.89					30.0	24.0		2	10.0	LF	$238,152	$0.492	$1,904	$217,771	100	0	90,000	47,872
16.5	5.89					30.0	24.0		2	10.0	LF	$238,993	$0.450	$1,983	$217,771	100	0	90,000	56,013
16.5	6.89					20.0	24.0		2	10.0	LF	$208,152	$0.472	$1,904	$187,771	100	0	60,000	43,266
16.0	4.89					30.0	24.0		2	10.0	LF	$238,871	$0.474	$1,894	$217,771	100	0	90,000	47,872
16.0	5.89					30.0	24.0		2	10.0	LF	$239,808	$0.434	$1,978	$217,771	100	0	90,000	56,013
16.0	6.89					20.0	24.0		2	10.0	LF	$208,871	$0.455	$1,894	$187,771	100	0	60,000	43,266
17.0	4.89					30.0	24.0		2	10.0	LF	$237,468	$0.510	$1,914	$217,771	100	0	90,000	47,872
17.0	5.89					30.0	24.0		2	10.0	LF	$238,224	$0.467	$1,987	$217,771	100	0	90,000	56,013

Figure 6-29: Sensitivity result for Village C

6.3.4. Village D:

The sensitivity input values and sensitivity results are shown in Table 6-22 and Figure 6-30, respectively.

Table 6-22: Sensitivity inputs summary for Wind Resource for Village D.

Wind Scaled Average (m/s)	4.15	6.15 (Reference value)	8.15
Nominal Discount Rate (%)	16	16.5	17

Export... | Export All... | **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. | Compare Economics | Column Choices...

Sensitivity	Architecture							Cost				System	
NominalDiscountRate (%)				SWP25-16TV20	SLB48-300 (#)	Conv (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (L/yr)
16.5				1	1	1.00	CC	$152,884	$0.478	$3,042	$120,327	100	0
16.0				1	1	1.00	CC	$154,485	$0.464	$3,066	$120,327	100	0
17.0				1	1	1.00	CC	$151,374	$0.492	$3,017	$120,327	100	0

Figure 6-30: Sensitivity result for Village (D).

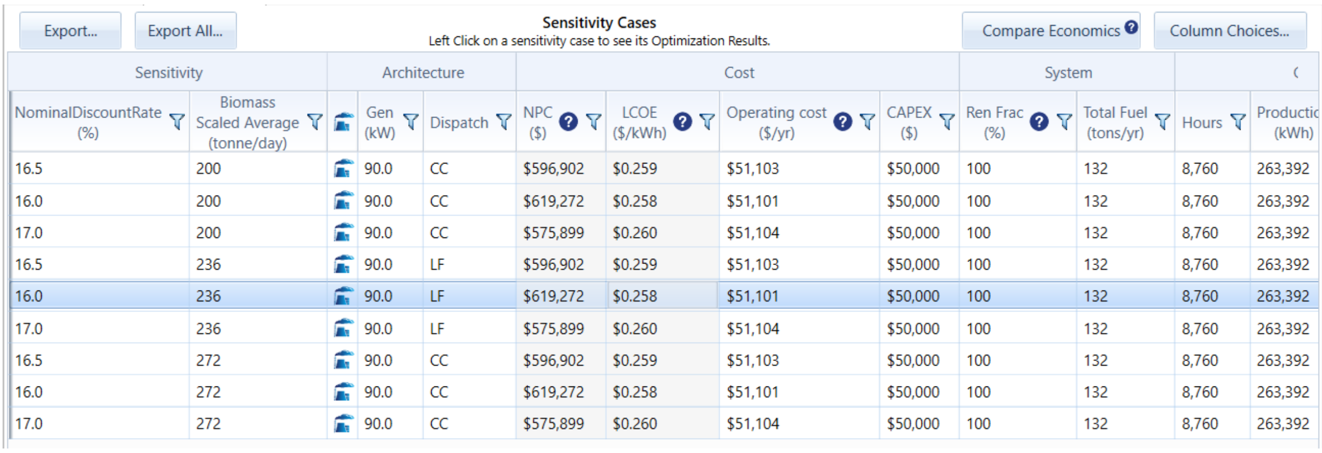
The configuration in this sensitivity study with the lowest cost of energy comprises one battery, a 1 kW bidirectional converter, and one 25 kW wind turbine (highlighted in blue). However, this did not prove to be the optimal system as it has a capacity shortage and unmet electric demand.

6.3.5. Village E:

Tables 6-23 and Figures 6-31 show sensitivity inputs and results, respectively.

Table 6-23: Sensitivity inputs summary for Biomass Resource for Village E.

Biomass Scaled Averages (tonne/day)	200	236 (Reference value)	272
Nominal Discount Rate (%)	16	16.5	17



Export... | Export All... | Sensitivity Cases — Left Click on a sensitivity case to see its Optimization Results. | Compare Economics | Column Choices...

Sensitivity		Architecture			Cost				System			
NominalDiscountRate (%)	Biomass Scaled Average (tonne/day)		Gen (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Ren Frac (%)	Total Fuel (tons/yr)	Hours	Productic (kWh)
16.5	200		90.0	CC	$596,902	$0.259	$51,103	$50,000	100	132	8,760	263,392
16.0	200		90.0	CC	$619,272	$0.258	$51,101	$50,000	100	132	8,760	263,392
17.0	200		90.0	CC	$575,899	$0.260	$51,104	$50,000	100	132	8,760	263,392
16.5	236		90.0	LF	$596,902	$0.259	$51,103	$50,000	100	132	8,760	263,392
16.0	236		90.0	LF	$619,272	$0.258	$51,101	$50,000	100	132	8,760	263,392
17.0	236		90.0	LF	$575,899	$0.260	$51,104	$50,000	100	132	8,760	263,392
16.5	272		90.0	CC	$596,902	$0.259	$51,103	$50,000	100	132	8,760	263,392
16.0	272		90.0	CC	$619,272	$0.258	$51,101	$50,000	100	132	8,760	263,392
17.0	272		90.0	CC	$575,899	$0.260	$51,104	$50,000	100	132	8,760	263,392

Figure 6-31: Sensitivity result for Village E.

In Figure 6-31, it is seen that the configuration in this sensitivity study with the highest cost of energy of $0.260/kWh is one of the highest Nominal Discount Rate (highlighted in blue).

6.4. Summary of Results

A summary of the simulation results for the five villages is shown below in Table 6-24. A comparison between the villages is conducted to see the similarities and differences in the economics of the system, and that is shown in Figure 6-32. The comparison is done between the components of the initial design and the optimal configurations from the results.

Table 6-24: Homer Pro optimisation result summary for all five villages.

Village		**A**	**B**	**C**	**D**	**E**
Components	**PV (kW)**	22		80		
	Battery (kWh)	10.2	14.4	55.8	14.4	
	Converter (kW)	8	40	30	15	
	Wind Turbine (kW)		20		25	
	Biogas Genset					90
	MPPT Controller (kW)	24		24		
NPC ($)		126,965.70	380,642.30	513,413.00	263,870.50	596,902.10
Capital ($)		98,066.96	326,984.80	493,313.60	220,156.80	50,000.00
LCOE ($/kWh)		0.643	0.4	0.826	0.686	0.259
Operating Cost ($)		2,700.35	4,816.58	1,878.12	4,084.68	51,103.39
Renewable fraction (%)		100	100	100	100	100

The initial design for Village C included the PV, Wind Turbine, Battery Storage and Converter. After the simulation, as shown in Figure 6-29, an optimum design with the least cost of energy excluded the Wind Turbine, making the microgrid design of village C a PV system. Village E results also show that the inclusion of Battery Storage did not yield optimum results as per the design parameters of the Village's microgrid. Therefore, the results came out without the battery. The results for the rest of the Villages included all the components which were in the design parameters.

When you compare the cost of energy for all these villages, Village E has the lowest LCOE at $0.259/kWh, followed by Village B at $0.4/kWh. The village that has the most expensive cost of energy is Village C at $0.826/kWh.

The simulation results for the selected villages indicate that LCOE ranges from $0.259/kWh to $0.826/kWh. These costs were unexpectedly found to be higher compared to the current energy tariff for the Domestic Lifeline customers, which is $0.0832/kWh for the period 2023/24. According to the literature above, all the villages studied in this research fall under the category of Domestic Lifeline because their electricity usage is 0-30 kWh/month.

The wind speeds were observed to align with the wind speed ranges documented in relevant literature identified in the onsite experiment conducted (Muchiri, K. et al., 2023, p. 9). These wind speeds hold practical utility for small-scale turbulence applications within the region. However, the limited availability of wind resources in this specific area may explain why the inclusion of a wind turbine did not yield optimum results.

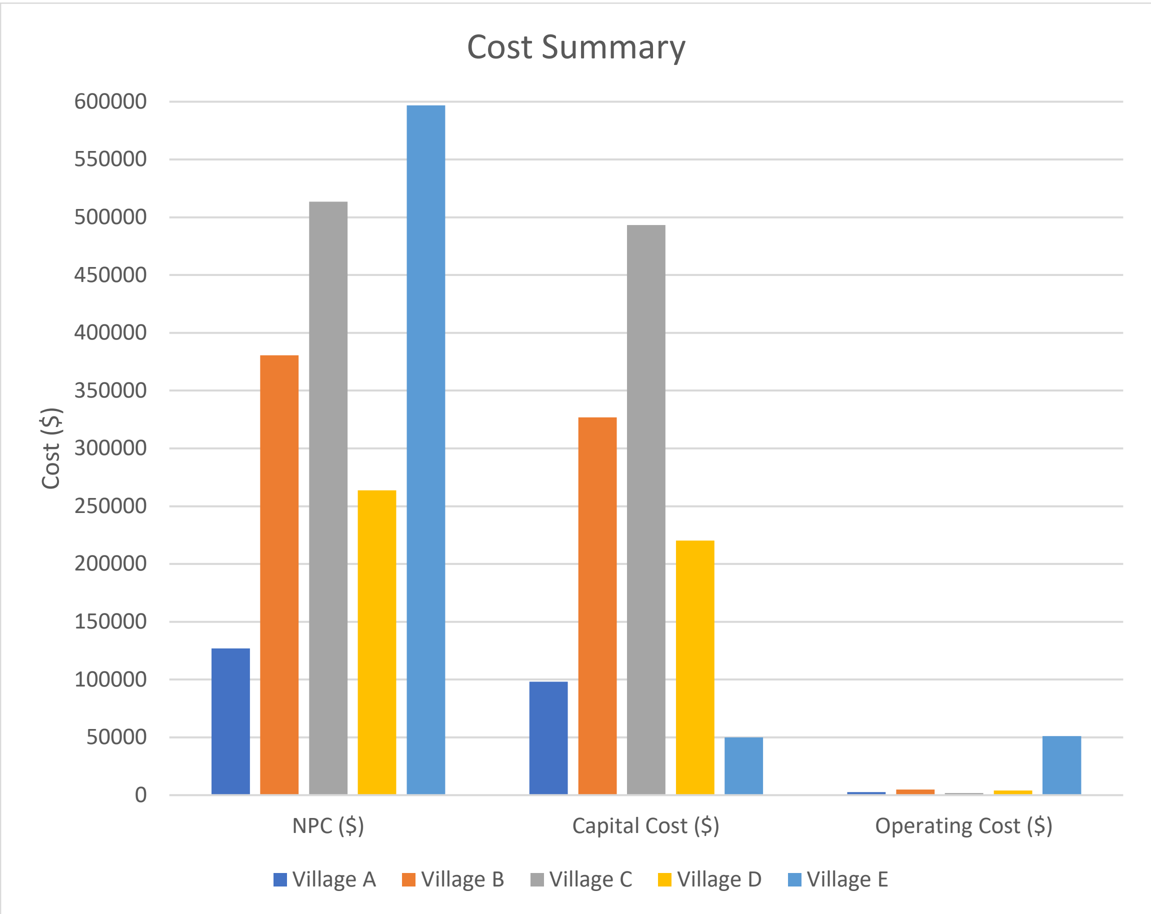


Figure 6-32: Cost Summary for all Villages.

Figure 6-32 indicates that Village C has the highest capital cost of $493,313.60, followed by Village B with a cost of $326,984.8, the village with the least Capital costs is Village E with a cost of $50,000.00.

Chapter 7 : Conclusion

The first objective of this research study was to conduct a review of mainstream literature to understand the availability of renewable energy resources in the selected locations. This goal was achieved by identifying that Machakos County has solar and wind potential. Mostly, the West of Kenya was found to have the potential for the solar resource. Narok County was found to be home to one of the largest forests in East Africa, with a total of 236 Megagram per Hectare of natural forest. This forest provided a substantial potential for biomass renewable resources. A wind resource was also found to be available for energy generation in Marsabit County and Machakos County. The recorded monthly average wind speeds for Machakos County ranged from 2.5 m/s to 4.9 m/s under standard temperature and pressure conditions. Marsabit County housed the Lake Turkana Wind Power Project, which contributed a total installed capacity of 17% to the country.

The second objective was to review the relevant mainstream literature to understand Independent renewable energy microgrid design. This was achieved by investigating the load profiles for rural areas, and they were found to have the lowest demand of 0.003 kW and a peak of 0.68 kW for each household. The microgrid typical system costs were found to be at an average of $ 584,90 per panel, $ 1 464,26 per turbine, $ 69 184,20 for a 30 kW diesel generator, $ 1 081,38 per battery and $ 1 385,60 per inverter.

The third objective of the study involved the modelling and design of the microgrid system using Homer Pro. This goal was successfully achieved by thoroughly exploring the most practical and viable models for the microgrids, considering the availability of renewable energy resources for each village through the utilisation of Homer Pro software. The outcomes of this investigation yielded optimal designs for different villages. Village A and C exhibited the most efficiency with a combination of PV solar panels, lithium-ion batteries, and a system converter. In the case of Village B and D, the optimal components included a wind turbine, lithium-ion battery, and a converter. Lastly, for Village E, the most cost-effective and efficient renewable energy-based microgrid system involved solely a biogas genset.

The last objective was to conduct a techno-economic analysis of the designs and select a suitable and cheapest microgrid design for the selected locations. The technical part of this goal was achieved as design systems that met the electric load of 100% were found for all villages. Surprisingly, the economic goal was not achieved because the LCOE of the systems were expensive, ranging from $0.259/kWh to $0.826/kWh compared to the current energy tariff of $0.0832/kWh for the Domestic Lifeline customers. All the villages studied in this research fall under the category of Domestic Lifeline because their electricity usage is 0-30 kWh/month.

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