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Presented by

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Techno-Economic feasibility study of a standalone Hybrid Renewable Energy System for Rural Electrification: A case of an isolated village in Malawi

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DECLARATION OF THE CANDIDATE

I Lackson Chisanu declare that this research entitled Techno-Economic feasibility study of a standalone Hybrid Renewable Energy Systems for Rural Electrification: Case of a typical rural village in Malawi is entirely the outcome of my own work and that to the best of my knowledge; it has never been presented for the award of a degree at this or any other University. It is submitted in partial fulfilment for the requirements of a Master of Science in Energy Engineering at the Pan African University of Water and Energy Sciences (PAUWES), Pan African University (PAU). Acknowledgement has been made where other sources of information have been used.

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12 September 2018

Certificate of Approval

I declare that this is from the student's own effort and that it has been submitted this day with my approval.

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DEDICATION

To my mum and my daughter with love!

ABSTRACT

In recent times, hybrid renewable energy systems are progressively being utilized to provide electricity in rural areas where the grid extension is considered too expensive. The current trend in rural electrification is to utilise renewable energy resources. The majority of Malawians in rural do not have access to electricity, the changing life styles and adaptations of new technologies in the rural household and agriculture are stimulating the energy needs in the rural populace. An easy solution is the provision of renewable energy at local scale with the available renewable energy resources. The fact that renewable energy sources are also distributed sources offers an opportunity to save on the capital investment for the transmission and distribution of electricity.

The aim of this study was to develop the small hybrid power system solution with best techno economic analysis and optimum configuration of RET for supply electricity in order to power local communities. First, through field research, an analysis was made of the actual electrical demand in the Mtambanyama rural community. Secondly the research used empirical and modelled data of solar irradiance and stream flow rate to ascertain the renewable energy potential. . Thirdly the costs for the photovoltaic and hydro turbine systems costs, diesel-generator operation costs were collected from different manufactures. The analysis was carried out by means of the software HOMER and was based on Mtambanyama village in Malawi. The feasibility of the use of hybrid PV-Micro hydro systems was analysed by comparing the Levelised Cost of Electricity (LCOE) and Net Present Cost (NPC) of solar PV-micro hydro with other system configurations.

Thus, this research focused on the optimum design of a hybrid energy system for an isolated community of Mtambanyama as case study. For the design of off-grid electrification of the study community, various combinations have been obtained for the hybrid systems with PV, micro-hydro turbines, batteries, convertors and generators from the HOMER optimization simulation. Findings were that From the optimal simulation result table the most cost effective system, i.e. the system with the lowest net present cost, is the PV micro hydro battery converter configuration and the cost of energy (COE) is 0.0833$/kWh and renewable resources fraction is approximately 100%. From this we can easily observe that almost the total portion of energy production is from renewable energy sources. The study proved that the use hybrid system in Mtambanyama village is financially acceptable and viable.

RÉSUMÉ

Ces derniers temps, les systèmes hybrides d'énergie renouvelable sont progressivement utilisés pour fournir de l'électricité dans les zones rurales où l'extension du réseau est jugée trop coûteuse. La tendance actuelle de l'électrification rurale est d'utiliser des ressources énergétiques renouvelables. La majorité des Malawites dans les zones rurales n'ont pas accès à l'électricité, l'évolution des modes de vie et l'adaptation des nouvelles technologies dans les ménages ruraux et l'agriculture stimulent les besoins énergétiques des populations rurales. Une solution facile est la fourniture d'énergie renouvelable à l'échelle locale avec les ressources d'énergie renouvelables disponibles. Le fait que les sources d'énergie renouvelables soient également des sources distribuées offre une opportunité d'économiser sur l'investissement en capital pour le transport et la distribution d'électricité.

Le but de cette étude était de développer la solution de petit système de puissance hybride avec la meilleure analyse techno-économique et la configuration optimale de RET pour fournir de l'électricité afin d'alimenter les communautés locales. Tout d'abord, grâce à des recherches sur le terrain, une analyse a été faite de la demande réelle en électricité dans la communauté rurale de Mtambanyama. Deuxièmement, la recherche a utilisé des données empiriques et modélisées de l'irradiance solaire et du débit du cours d'eau pour déterminer le potentiel d'énergie renouvelable. . Troisièmement, les coûts pour les systèmes de turbines photovoltaïques et hydroélectriques, les coûts d'exploitation diesel-générateur ont été recueillies auprès de différents fabricants. L'analyse a été réalisée à l'aide du logiciel HOMER et était basée sur le village de Mtambanyama au Malawi. La faisabilité de l'utilisation des systèmes hybrides PV-Micro hydro a été analysée en comparant le coût actualisé de l'électricité (LCOE) et le coût actuel net (NPC) de la PV-micro-énergie solaire avec d'autres configurations de systèmes.

Ainsi, cette recherche s'est concentrée sur la conception optimale d'un système énergétique hybride pour une communauté isolée de Mtambanyama comme étude de cas. Pour la conception de l'électrification hors réseau de la communauté étudiée, diverses combinaisons ont été obtenues pour les systèmes hybrides avec PV, micro-turbines hydroélectriques, batteries, convertisseurs et générateurs de la simulation d'optimisation HOMER. Selon le tableau de résultats de simulation optimal, le système le plus rentable, c'est-à-dire le système présentant le coût actuel net le plus bas, est la configuration du convertisseur microhydraulique PV et le coût de l'énergie est 0,0833 $ / kWh. est d'environ 100%. De cela, nous pouvons facilement constater que presque toute la production d'énergie provient de sources d'énergie renouvelables. L'étude a prouvé que l'utilisation du système hybride dans le village de Mtambanyama est financièrement acceptable et viable.

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SDG	Sustainable Development Goals
(MAREP)	Malawi Rural Electrification Project
(DoEA)	Department of Energy Affairs
(GoM	Government of Malawi
MGDS	Malawi Growth and Development Strategy
VAT	Value Added Tax
SPV	Solar Photovoltaic
LED	Light Emitting Diode
MPP	Maximum power point
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
HOMER	Hybrid Optimization Model for Multiple Energy Resources
MREAP	Malawi Renewable Energy acceleration Programme
WTG	wind turbine generator
IHOGA	Improved Hybrid Optimisation Genetic Algorithm
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
LCOE	Levelized Cost of Energy
HPS	Hybrid Power System
RET	Renewable Energy Technologies
CRF	Capital Recovery Factor
NSO	National Statistics Office
COE	Cost of Electricity
Disp. Strgy	Dispatch strategy
RET	Renewable Energy Technologies
ESCOM	Electricity Supply Corporation of Malawi
LF	Load following
NASA	National Aeronautics and Space Administration of the United States of America
SSE	Surface Meteorology and Solar Energy

Chapter 1: Introduction and Objectives

1 Introduction

Energy is the lifeblood of each and every economy. Lack of reliable energy supply system is one of the common problems facing many African countries. It is widely accepted that energy and development are closely related to each other. Access to Modern energy has proved to be the utmost factor in improving people's livelihood. Actually energy is a crucial input into any industrial processing. Sustainable development Goal 7 (SDG 7) which aims at ensuring access to affordable, reliable, sustainable, and modern energy for all. It has been established that the objectives of SDG 7 which aims at are directly or indirectly linked to all the different SDGs as the aims of SDG 7 are means for the achievement of other goals rather than ends in themselves (Loewe & Rippin, 2015).

Malawi is a sub-Saharan land locked country located in south central Africa. Malawi is an increasingly energy-stressed country. Malawi's energy supply is dominated by biomass (firewood, charcoal, agricultural and industrial wastes) accounting for 84% of the total primary energy supply (2008 statistics - 88% biomass, 2% coal, 7% petroleum, 3% hydro). Wood and charcoal use for cooking is highly unsustainable and is estimated to destroy around 75,000 hectares of natural forests across Malawi annually (Hivos, 2013). The provision of electricity remains a challenge in Malawi evidenced by persistence blackouts. Over 98 % of the rural communities do not have access to electricity of which they mostly depend on biomass for their energy needs. Rural electrification has proved worldwide that it plays a pivotal role in bringing about direct and indirect economic and social benefits by enhanced livelihood opportunities, better health care and education (Renewable & Agency, 2017). Malawi Rural Electrification Project (MAREP) has also been established with the primary aims of reducing the large unsustainable wood consumption and improving the dependability of imported oil and coal. The Rural Electrification Bill (2004) deals with all aspects of renewable energy systems.

Malawi is endowed with a number of renewable energy resources yet utilization of these resources is still in infancy stages. The resources range from solar, wind, biomass and hydro. Technologies that use solar energy have shown a high potential of being implemented successfully since solar energy is a resource that is available in abundance throughout the country (Gamula, Hui, & Peng, 2013b). However a single renewable energy technology may not suffice at all times the demand of the region in question due to the intermittent nature of the solar resource. In such cases an integrated energy system with a combination of different technologies operating simultaneously, can solve the reliability issues arising out of using just one technology. Such systems in the absence of reliable grid electricity emerge as an advanced and sustainable solution for a disadvantaged region. A hybrid energy system, usually consists of two or more renewable energy sources used together to provide increased system efficiency as well as greater balance in energy supply (Marcus Wiemann, Rolland, & Glania, 2014).

1.1 Overview of the Malawi energy sector and its REP

According to the government of Malawi 89% of Malawi's energy supply is sourced from biomass, mainly in the form of firewood and products derived from wood such as charcoal. Electricity only accounts for around 3% of the total energy consumed in the country. Fossil fuels contribute about 8% of the total energy mix. As of 2014 the electricity grid in Malawi reached around 10% of Malawi's 17 million residents, with access levels lower than 2% in rural areas and higher than 30% in urban areas. Electricity is provided by other means to a small but growing percentage of Malawi's population through off-grid solar panels and products (around 2%) and from mini-grids (currently a negligible amount) (GoM, 2018).

According to the department of energy affairs (DoEA) Over 95% of the power which fuels the grid is sourced from hydroelectric schemes situated on the Shire River, the remaining power is from smaller diesel-powered generation schemes. As things stand total generation capacity connected to the National Grid is at just over 360MW from a number of schemes. It is a known fact that electrical energy is one of the most preferred forms of energy because of a number of advantages among which are ease of transformation into other forms, it is easy to change to the required voltage and it is relatively cheap to produce (Gamula, Hui, & Peng, 2013a). Looking at the current trend, it can be observed that the cumulative generation capacity is growing quite slowly and not conducive to national development's requirements.

1.2 Malawi Growth and Development Strategy (MGDS)

The Malawi Growth and Development Strategy (MGDS) is the overarching framework that guides development interventions within Malawi. Energy generation and supply is one of six key priority areas within the MGDS. The government of Malawi set the Integrated Energy Policy and then introduce the legislation to meet those goals outlined in the energy policy. The all-embracing objective of the policy is to match energy supply with energy needs. The Malawi government has a number of laws that govern the use, regulation, and conservation of energy typically designed to both ensure good governance of the energy sectors and the safety of energy consumers notably, Energy Regulation Act, Electricity Act, and Rural Electrification Act.

1.2.1 Rural electrification in Malawi

Most of the rural areas are not connected to the grid and many of these rural areas remain without electricity. Grid extension to these remote villages has proved to be costly and not economically feasible. Most of these rural areas are sparsely populated which makes it difficult and uneconomical to extend the grid. In addition to that these remote areas have low demand of electricity. The Government started implementing the rural electrification in 1980 under the Malawi the Malawi rural electrification programme (MAREP). The objective of MAREP is to increase access to electricity for people in peri-urban and rural areas as part of Government's effort to reduce poverty, transform rural economies, improve productivity and improve the quality of social services (Girdis & Hoskote, 2005). However little progress has been made in electrifying rural areas, and new connections are virtually at a standstill this mainly due to low generation capacity of ESCOM.

Currently the department of energy affairs is implementing a rural electrification in various rural trading centres using solar-wind hybrid energy system. The coverage for the project is a radius 2-3 km with an estimated capacity of 25 kW. The main thrust of this project is to experiment on the suitability of stand-alone renewable energy technologies for rural electrification in order to increase access to modern energy services by the rural communities. This is expected to transform the rural communities who are far from the national grid.

According to Girdis & Hoskote, (2005) the provision of electricity supply to rural areas in Malawi requires either the extension of the distribution network or the establishment of standalone, decentralized networks not connected to the national grid. Progress in both areas has been extremely slow. As it stands now ESCOM has today virtually given up on rural electrification, finding it impossible to reconcile the heavily loss-making extension of electricity supply to rural areas with the need to meet profitability and loan repayment requirements.

1.2.2 Rural Electrification act in Brief

The Act states that no person shall carry on or be engaged in any Activities to be manner in any rural electrification activity without a licence licenced issued by the Malawi Energy Regulatory Authority. For off grid electrification a generation licensee may apply and be granted a distribution licence or renewable energy licence and vice-versa. The tariffs for grid extension or off grid rural electrification shall be approved by the Authority and shall be set, administered and revised in Accordance with the Electricity act (GoM, 2004).

1.3 Problem statement

The electric power supply sector in Malawi which is mostly dominated by hydroelectric power is facing energy shortage due to high demand and climatic conditions. Due to these reasons load shedding has been the order of the day especially during periods with lower water levels. At present more than 90% in Malawi do not have access to electricity with only 7% of the country having access to electricity. Only 1% of the rural households are electrified while around 25% of the urban households have access to electricity. A plan to extend the Grid to the rural areas is constrained due to low generation capacity and high cost of transmission and distribution infrastructure. The majority of Malawians live in the rural areas where the main sources of light for the non-electrified households are battery torches, elephant grass, candles and paraffin. For cooking, about of households are depending on firewood and charcoal (Hivos, 2013). Without such access to electricity, it is virtually impossible to carry out productive economic activity or to achieve environmental sustainability (Tenthani, Kaonga, & Kosamu, 2013). The absence of power in different rural areas has affected the rural livelihood in general

Electricity providers have for many years depended on producing electricity at a centrally located position and distribute it through extensive transmission and distribution networks. However, as the demand increases the capacity to generate, transmit and distribute the energy is always constrained. The most obvious direction to take is to build new plants to meet the increasing demand. The fact that renewable energy sources are also distributed sources offers an opportunity to save on the capital investment for the transmission and distribution of electricity. The current international trend in rural electrification is to utilize renewable energy resources such as solar, wind, biomass, and micro hydro power systems.

1.4 Objectives

The main objective of this research is to study the techno-economic feasibility of a stand-alone hybrid power system for local electricity production in order to power rural communities.

1.4.1 Specific objectives

Here are the specific objectives to help to answer the main objective.

a) To investigate renewable energy potential and electric load demand for a selected area in Malawi.

b) To design a hybrid energy system for an isolated community in Malawi

c) To model, simulate, optimize and control various RE technologies using HOMER

d) To evaluate the technical (power production) and economic (cost of energy and capital cost of the system) performance of various combinations of RE technologies.

1.5 Justification

The current installed generating capacity of about 298.6 MW is far less than the estimated demand of 408 MW and that the demand for electricity is expected to jump to 603 MW in 2015 before edging up further to 829 MW by 2020. It is further projected that the demand will be 1193 MW in 2025 and 1597 MW in 2030 (Ojukwu, C., Cheikhrouhou, H., & Kanonda, 2013). As a result, only a small percent of the Malawi population is part of the national electricity grid which means that large percent of the nation's populace is hindered from actively participating in the industrialization of the nation, situation that further retards the development of this nation. The improvement of the electrification ratio in rural areas is the most important problem to be solved in order to cope with poverty.

Malawi has a huge renewable energy potential ranging from solar, low temperature geothermal, hydro power and wind resources. If the country is to break out of the vicious circle of poverty, it has to use its available energy resources more effectively and efficiently.

1.6 Research question

- What are the renewable energy resources potential in selected areas in Malawi?
- What is the electricity load or power consumption of the selected area
- What is the best combination of renewable energy system to meet the energy demand for the isolated community?
- What are the economic (cost of energy $/MWh), social (improving the life of people), environmental (greenhouse gas emissions reductions) and technical feasibility of installation of a hybrid energy system in a rural community of Malawi?

Chapter two: Literature review

2 Introduction

In this chapter we provide background review as related to the hybrid energy systems for rural electrification. Mainly the chapter will be divided into two: theoretical background and empirical evidence. The theoretical background will encompass all the theory regarding hybrid renewable energy systems and the renewable energy technologies present. Under empirical evidence, a review of relevant studies that have looked at the techno-economic feasibility of a hybrid energy system for rural electrification will be reviewed.

2.1 Solar photovoltaic technology and solar potential in Malawi

In the last decade, capturing solar energy through photovoltaic panels, in order to produce electricity is considered one of the most promising markets in the field of renewable energy technology. This type of renewable energy technology is pollutant free during operation, reduces global warming issues, lowers operational cost, and offers minimal maintenance and highest power density compared to the other renewable energy technologies (Siecker, Kusakana, & Numbi, 2017). Renewable Energy (REN21) Global status reports (REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)(REN 21, 2017)that solar PV technology is the widest growing technology in the world. Solar PV electricity has also proved to be one of the potential sustainable sources of electricity that may empower rural communities to generate their own electricity.

2.1.1 Solar photovoltaic technology (photo-electric generation)

Markvart & Bogus, (1994) outlines well the conversion process of solar radiation to electricity. They start by pointing out that the sun provides energy in the universe which is responsible for supporting all life in the universe. The sun radiates energy radially, from an effective surface temperature of about 5760 K, as electromagnetic radiation known as `solar energy' or sunshine. The amount of solar radiation received by the Earth is much higher than annual global energy use. The most common ways in which human beings have exploited the solar energy is through photo-electric generation and thermal conversion (Charlier, 2009).

Solar cell is the basic unit of Solar Photovoltaic (SPV) arrays and is a type of diode generating electricity when illuminated. The output of the solar cells, in terms of current and voltage and thus power, varies depending upon operating conditions such as solar radiation, temperature, wind speed, etc. therefore solar cells behave differently with locations and season. Solar cells are usually manufactured from different semiconductor materials such as such as Silicon (Si), Germanium (Ge), Indium Phosphide (InP), Gallium Arsenide (GaAs), Cadmium telluride (CdTe). Silicon is the primary and mostly widely used material.

There are three different components of the solar radiation that reach the surface of a photovoltaic panel namely; direct or beam radiation, which arrives to the surface unchanged, and diffuse radiation, which has changed its direction and/or intensity through contact with other atmospheric elements, and in the case of inclined solar panels, radiation reflected on the Earth surface. The total radiation reaching the collector is the addition of these components. Solar irradiance is the measurement unit for solar radiation on a surface and it's generally measured in W/m^2. The Global Horizontal Irradiance (GHI) is the magnitude that quantifies the total radiation per unit of space that reaches the Earth surface throughout a period of time, generally a day. GHI data throughout the period of one or more years are used to assess the photovoltaic energy generation potential on a particular location.

2.1.2 Components of Solar photovoltaic systems

All photovoltaic systems are similar in nature but differ in details from each other. It is therefore important to have a general view of the system design. Once the true nature of the system is understood any other individual product becomes a mere corollary. Solar power plants can be broadly categorized as stand-alone SPV systems, grid connected SPV systems and SPV hybrid systems. Here are the main components of all the subcategories of an SPV system as illustrated below.

2.1.2.1 The PV array

The PV array is made up of several PV modules; each module is assembled from a large number of solar cells which can be made from single, polycrystalline or amorphous silicon or other materials. A module is assembled from a large number of cells, to increase its voltage primarily, connecting them in series. Each solar cell produces only a few watts of power, typically 2 W, at approximately o.5 V DC. The number of solar cells per module is thirty six, or more depending on the power level required but the voltage is adjusted to give an MPP approximately at the multiple of six volts for the battery charging. Basically modules are connected in parallel to increase the voltage and in parallel to increase the current further, to suit any particular requirement.

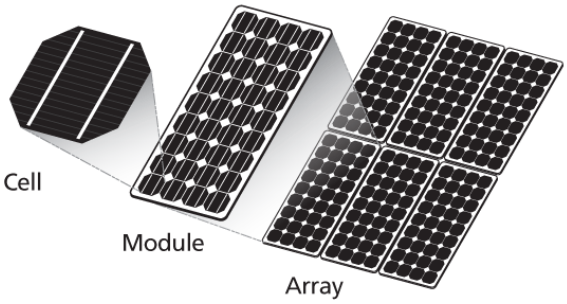


Figure 1: PV cell, Module and Array.

Sourced: (Rajyaguru, Somupra, & Vachhani, 2016)

2.1.2.2 Battery charge/Discharge controller

The charge controller ensures that the battery is not overcharged or discharged below a certain limit, and thus prevents the battery from being damaged. The charging of batteries in most PV systems is done in the constant current-constant voltage mode. As the battery charges its voltage rises slightly until at full charge the voltage reaches a certain specified value beyond which permanent damage can occur. At this point the voltage input to the battery is floated by using by using electronic circuits. Most batteries when left idle over long periods lose charge because of internal losses. This slow leakage of charge lowers the voltage leading to the discharge of the battery which, if left unattended, may cause irreversible damage. For this reason a small charge should always be allowed to enter the battery to replenish the losses (Al-shamani et al., 2013).

2.1.2.3 Inverter for AC Loads

Batteries give DC voltages at different voltages, in multiples of 6 V, to drive DC loads. However, to operate conventional electrical appliances the operating voltage has to be increased to a nominal value of 220 V AC. To accomplish this conversion an inverter is necessary. When sizing the inverter, the actual power drawn from the appliances that will run at the same time must be determined as a first step. Selecting the correct size and type of wire will enhance the performance and reliability of a photovoltaic system (Al-shamani et al., 2013). Most of the times the inverter is attached an MPPT tracker. The MPPT is a device that extracts the maximum power available from the PV array at any given instant. The power available from the PV module passes through a peak at a particular operating point and this peak also changes with atmospheric conditions (Al-shamani et al., 2013).

2.1.2.4 Loads

Loads are all the pieces of electrical equipment people want to use in their homes and offices. In PV systems the loads are divided into two main categories namely the AC loads and the DC loads (Al-shamani et al., 2013).

2.1.3 Characteristics of a solar cell

A PV cell is an electronic component called “LED” (Light Emitting Diode), the device has the property of passing current only in one direction (with a voltage drop of about 0.6 volt) and that blocks its passage in the other direction. In the case of a PV cell, we try to keep the surface of the junction as wide as possible to collect the maximum of solar energy. The simplified electric diagram of such a PV cell is shown in the figure below:

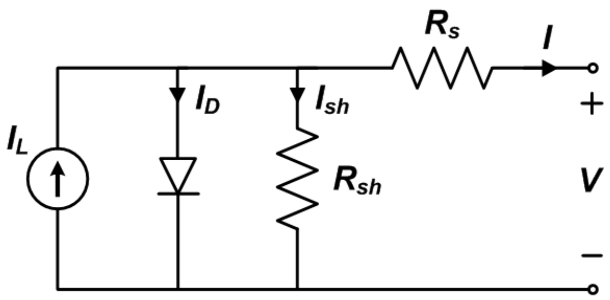


Figure 2: schematic circuit of a solar cell.

Sourced: (Fezai & Belhadj, 2014)

The governing equation for this equivalent circuit is formulated using Kirchoff’s current law for current I and it is given by the equation below:

$$I = I_L - I_o \left\{ (e^{\frac{V_p + IP.Rs}{KT/q}} - 1) \right\} - \frac{Vp + Ip.Rs}{Rsh}$$

2-1

Where:

I_0 = reverse saturation current (ampere)

n = diode ideality factor (1 for an ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

R_{SH} = shunt resistance (Ω)

The power output by a source is the product of the current supplied and the voltage at which the current was supplied. Solar Cell I-V characteristic Curves show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. From the I-V plot of a solar cell or a module several parameters can be obtained which enable scientists to improve the efficiency of these devices. They are the parameters are illustrated and stated below.

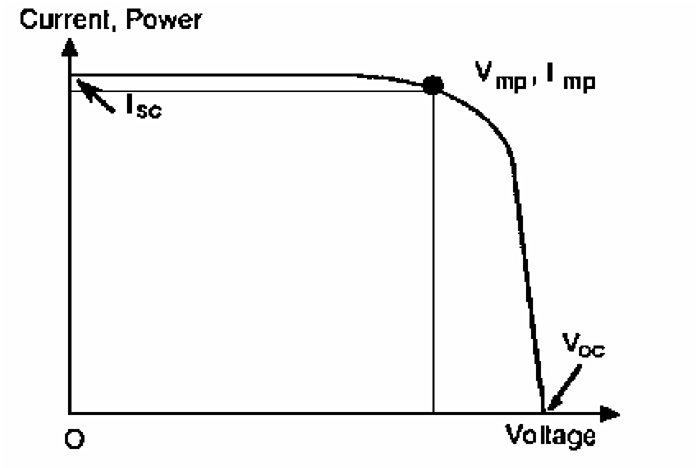


Figure 3: IV characteristics of PV panel.

Sourced: (Fezai & Belhadj, 2014)

2.1.4 Solar panel parameters

a) **Open circuit voltage (V_{OC}):** This is the maximum voltage that the panel provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than V_{mp} which relates to the operation of the PV array which is fixed by the load. This value depends upon the number of PV panels connected together in series.

b) **Short circuit current (I_{SC}):** The maximum current provided by the PV panel when the output connectors are shorted together. This value is much higher than Imp which relates to the normal operating circuit current.

c) **Maximum power point (MPP):** This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Imp x Vmp. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).

d) **Fill factor (FF):** The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage times the short-circuit current, (Voc x Isc) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.

e) **Percent efficiency:** Percent efficiency of a photovoltaic panel is defined as the ratio between the maximum electrical power outputs from the array to the amount of solar irradiance hitting the array. The efficiency of a typical solar panel is normally low at around 10-12%, depending on the type of cells (mono-crystalline, polycrystalline, amorphous or thin film) being used.

2.1.5 Solar energy resource in Malawi

In the field of solar, quite high levels of solar energy in the range of 1200 W/m^2 in the warm months and 1900 W/m^2 in the cool months are received in most parts of the country which would enable photovoltaic systems and solar thermal systems to reform well. Solar irradiation potential is estimated at 21.1MJ/m^2/day which is adequate for photovoltaic and solar-thermal applications, (Kaunda, 2013b).

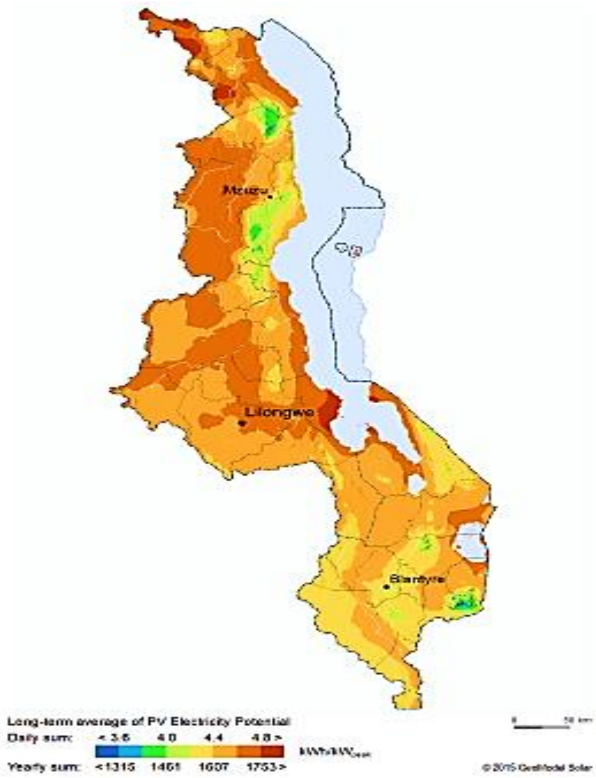


Figure 4: PV electricity output from a free-standing fixed-mounted PV system.

Sourced: (Fluri, 2009)

The solar resource in Malawi has been employed for various applications. Solar water heaters have been developed and are manufactured locally for domestic purposes. Solar irrigation systems have also been used in the agricultural sector (Taulo, 2015). At present, there are more than 10 000 photovoltaic systems installed in various parts of the country, with a total capacity of 165 kWp (CSR, 2005). More recently, an 870 kWp solar photovoltaic plant has been commissioned at Lilongwe International Airport.

2.2 Micro hydro power generation and Hydro resources in Malawi

Hydropower energy is the oldest renewable energy technique and has the greatest potential of all the renewable energy sources. Hydroelectric power comes from water at work, water in motion. It can be seen as a form of solar energy, as the sun powers the hydrologic cycle which gives the earth its water. The water flowing down from places of higher elevations to those with lower elevations lose their potential energy and gain kinetic energy. This kinetic energy of the flowing water turns blades or vanes in hydro turbines, and then energy is changed to mechanical energy. The turbine turns the generator rotor which converts this mechanical energy into electrical energy (Dametew, 2016).

Both small and large hydropower remains by far the most important of the 'renewables' for electrical power production worldwide. According to the World Hydropower Atlas 2000, reported that the world's technically feasible hydro potential is estimated at 14,370 TWh/year, which equates to 100% of today's global electricity demand (Dametew, 2016). Micro Hydro Power has the advantage that it can be made on small streams, canals and river tributaries in the hilly areas. This technology does not require the storage of water or building a reservoir or dam. Water is only diverted from a river through a power channel towards a power house. The water that is used to run a turbine can again meet the same river without any loss (Umar, 2010).

Hydropower plants are energy systems that generate electricity and/or mechanical energy from hydraulic energy in the flowing water. Hydro-turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator, or other machinery. The power available is proportional to the product of *pressure head* and *volume flow rate*. The general formula for any hydro system's power output is

$$P\ (W) = \rho g \eta Q H \qquad 2\text{-}2$$

Where: P = the power output (W),

ρ = the density of water (1000 kg/m^3),

g = the gravity (9.81 m/s^2),

η = the turbine efficiency (%),

Q = the discharge rate (m^3/s),

H = the head (m).

Substituting: g = 9.81m/s^{2}`

$$\boldsymbol{P\ (kW) = 9.81\ \eta Q H} \qquad 2\text{-}3$$

2.2.1 Classification of micro hydro power

Depending on generation capacity hydroelectric power plants are classified in different categories. The first classification is based on its energy generation capacity. Large hydro has a generation capacity of over 100MW. While medium- hydro has a generation capacity of 20 MW- 100 MW. Small hydro has a capacity of 1MW to 20 MW. Mini-hydro ranges from 100KW to 1MW. This may be a stand-alone or grid connected. Micro-hydro has a capacity of 5KW to 100KW that usually supply electricity to a small community in rural areas (Umar, 2010).

Depending on hydroelectric characteristics that is, with respect to the water flowing through the turbines that run the generators hydroelectric plants are classified as; run-of-river, dam based and pumped storage hydroelectric schemes. In small-scale hydro schemes there is little to no water stored, with no need for a dam or a barrage except maybe a small weir. Johansson & O'Doherty, (2017) further reports that the potential of a river is often described in terms of the head of the river, and this is the vertical distance that the water descends along a slope. Run-of–the-River Hydro electricity generation utilizes the natural flow of the river, extracting water from a high point, where it flows to a micro turbine generator, and the kinetic energy is captured. In general, the Run-of-the-River systems have an installed capacity of between <100kW to 5MW, with an efficiency of over 80%, and it remains one of the cheapest forms of renewable energy (Johansson & O'Doherty, 2017).

2.2.2 System components of a micro hydro power generation

Micro hydro systems are composed of several components. They generally include the forebay, penstock, turbine, and the electrical system. A Forebay is basically small civil works typically performed to divert a portion of the flow to the forebay tank, which is a reservoir upstream of the turbine. Figure 5 illustrate a typical small hydro scheme the forebay moderates head and flow to the turbine while also lowering the risk of damage due to flooding.

The penstock is a pipe that delivers water from the reservoir or upstream source to the turbine. Care must be taken when determining length, material, inner diameter, and layout as all of these greatly impact cost and performance due to pipe flow losses. In addition, debris, such as leaves and branches, constantly threaten to create blockages in the system. Filters can be employed at the penstock inlet to keep out large foreign objects that could damage the turbine. However, the presence of filters causes a restriction of flow and therefore a loss in pressure head.

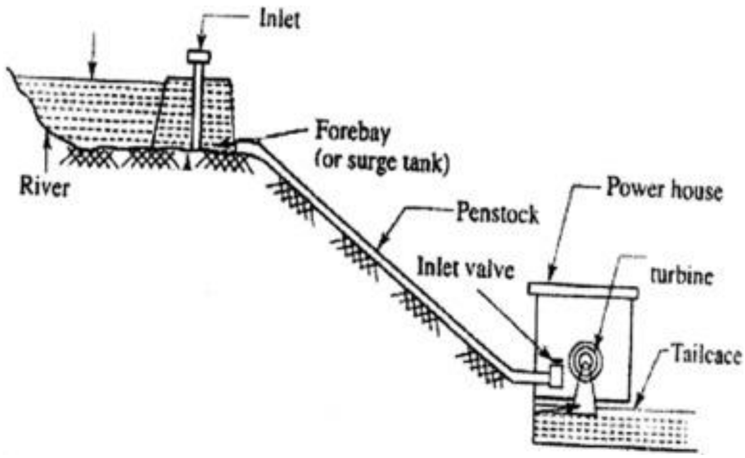


Figure 5: Schematic of a micro hydro power plant.

Sourced: (Renewable Energy Agency, 2012)

2.2.3 Hydropower system turbine

The turbine is an assembly consisting of a nozzle or stator, runner, and shaft that collectively convert momentum and pressure in a water flow into rotational mechanical work. Hydraulic turbines can be categorized mainly in two types namely Impulse turbine and Reaction turbine. Jawahar & Michael, (2017) reports that the heart of any micro hydro project is the turbine that is capable of generating electricity through the rotation of the shaft. Hence much attention should be taken in genuine choice and performance of such turbine as the clue rest in the coherence transfiguration of the energy in the water to useful electrical energy. According to head, turbines are classified as Low Head, medium and high Head (Jawahar & Michael, 2017). The figure below shows typical applications of various turbines.

Table 1: Impulse and reaction turbine types.

Sourced: (Paish, 2002)

Turbine type	High (>50m)	Medium (10-50m)	Low(<10m)
impulse	Pelton Turgo Multi-jet Pelton	Cross-flow Turgo Multi-jet Pelton	Cross-flow
Reaction		Francis (spiral case) Propeller Kaplan	Francis (open-flume)

2.2.3.1 The head and flow rate of a hydro power

Basically hydroelectric power emanates from the potential energy of dammed water driving a water turbine and generator. In this case the energy extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. In designing a hydro power plant turbine choice is guided by several factors such as the head and the flow rate.

The main reason that different types of turbine are used at different heads is that electricity generation requires a shaft speed as close as possible to 1500 rpm to minimize the speed change between the turbine and the generator. The speed of any given type of turbine tends to decline in proportion to the square-root of the head, so low-head sites need turbines that are inherently faster under a given operating condition. The approximate ranges of head, flow and power applicable to the different turbine types are summarised in the chart of figure 6 (up to 500 kW power).

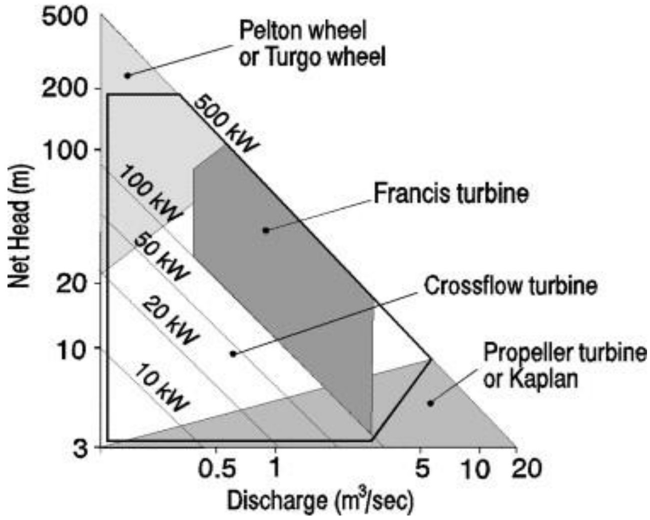


Figure 6: Turbine selection chart based on head and flow rate

Sourced:(Kaunda, Kimambo, & Nielsen, 2012)

2.2.4 Micro-hydro generation in Malawi

Every country in the world is now in the quest for new available energy sources on the earth to alleviate the potential of current and future energy shortages. Malawi as country is not left alone on this quest of energy, according to (Kaunda, 2013a) the country has considerable potential for decentralised hydropower generation, which if fully exploited, can contribute to the country's electricity and power supply especially for rural electrification. A proven potential of 7.6 MW can be harnessed. An inventory of small-scale hydropower systems shows there is an installed capacity of 5.8 MW with most of the plants not functioning due to various reasons (Kaunda, 2013a).

The study by the Millennium Challenge Corporation in Malawi, estimates that the country has a hydropower generation potential of over 1,000 MW of which only about 350MW has been installed, as stated earlier. Current hydropower generation is about 17% of the nation's hydropower potential and represents 98% of total installed grid-connected electricity generation capacity. Hydropower potential of Malawi is concentrated on the Shire River. The capacity ranges from 18 to 140 MW. The estimated hydro potential of the Shire River is about 600 MW, equivalent to an annual production of 3500 GWh. In addition, several smaller rivers such as the Songwe, South Rukuru, Dwangwa and Bua, have limited potential at a number of sites estimated to total about 300-400 MW (WEC, 2002) (Taulo, 2015).

2.3 Wind power technology and potential in Malawi

The application of wind energy for power generation has become one of the most attractive renewable energy sources in the world due to the advantage of being a clean, sustainable and ecological friendly energy source (Aririguzo & Ekwe, 2018). Human efforts to harness wind for energy date back to the ancient times, when they used sails to propel ships and boats. Later, wind energy served the mankind by energising his grain grinding mills and water pumps (Sathyajith, 2006). Currently wind energy through wind turbines is used to generate electricity energy which is being to power different uses.

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. Wind turbines convert the kinetic energy from wind into electric energy. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms, depending on our end use. Hybrid mini-grids use small wind turbines ranging from 1kW to 20 kW. Larger turbines also can be installed although this will increase the complexity of the system and require higher construction costs for foundations and control stations. Currently, this energy has been most popularized worldwide. A stand-alone wind energy conversion system is composed of the wind turbine, the turbine tower, the battery bank and an inverter. Usually small turbines are used for this application; a small wind turbine can operate even if the amount of wind speed is not high.

The factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. Effect of the wind velocity is more prominent owing to its cubic relationship with the power. The power that can be extracted from the wind is given by the formula below:

$$P = \frac{1}{2}\rho_a A_T V^3 \qquad 2\text{-}4$$

Where: ρ is density

A_T is the cross section area

v is the wind speed.

The relatively smaller density of air compared to water leads to utilization of larger size of wind turbine rotor than water turbine. The wind turbine cannot take all of energy from the moving air, since the air would then have to stop dead. It was shown in 1919 by Albert Bets that, for any wind turbine, the optimum energy extraction occurs when the wind speed behind the turbine is 1/3 the incident wind speed, The theoretical maximum amount of energy in the wind that can be collected by a wind turbines rotor is approximately 59%. This value is known as the Betz limit. In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will (depending on the model) deliver between 10% and 30% of the original energy available in the wind (Ahmed, 2016).

2.3.1 Wind resource assessment

In order to estimate the future energy production from a wind farm, a wind resource assessment is one of the crucial steps to be done before the project is implemented. Among the parameters assessed in a wind resource assessment, wind speed is a critical feature of wind resources, because the energy in wind is proportional to the cube of the wind speed. Typically available wind speed measurement has been done at a certain elevation and thus we need to estimate the wind speed at the elevation of interest. In wind energy calculations, we are concerned with the velocity available at the rotor height. The data collected at any heights can be extrapolated to other heights on the basis of the roughness height of the terrain. Due to the boundary layer effect, wind speed increases with the height in a logarithmic pattern. The power law that is commonly used in wind energy is defined by the following equation:

$$u(z) = u_{ref} (\frac{z}{z_{ref}})^p \quad (2\text{-}5)$$

Where $u(z)$ the wind speed at height z is, u_{ref} is the wind speed at height z_{ref} , and p is the power law exponent. Traditionally, neutral atmospheric conditions have been associated with p = 1=7, with values higher (lower) than 1/7 indicating stable (unstable) conditions (Newman & Klein, 2011). By gathering wind speed data and processing them, we are able to specify a distribution of wind speeds that shows us the period of time for having a specific wind speed as a percentage of total time. This is reflected in wind speed probability distribution functions and would be helpful for predicting the frequency of wind speeds if we do not have wind data for a full year.

The distribution of wind speeds can often be approximated by a Weibull/Rayleigh distribution$f(v) \sim v\ exp(-v2)$. We choose normalisation constants for this distribution so that $\int f(v)dv = 1$

$$f(v, v0) = \frac{\pi}{2}\frac{v}{v0^2}\exp\left(-\frac{\pi}{4}\frac{v^2}{v0^2}\right) \qquad 2\text{-}6$$

V_0 is the average velocity, i.e. $(v) = \int f(v, vo)dv = vo$. It is interesting to note that the Rayleigh distribution is the distribution of the rms value of Gaussian noise. Two most commonly used functions are Weibull and Rayleigh functions from which Weibull is used in HOMER. The probability density function of the Weibull distribution is given as:

$$f(U) = \frac{k}{C}\frac{U}{C}^{k-1}\exp\left[-\left(\frac{U}{C}\right)^k\right] \qquad 2\text{-}7$$

Where $f(U)$ is the probability of observed wind speed of U, k is the dimensionless shape factor and C is the scale parameter.

Wind classes are set are at varying levels of wind power and corresponding speeds shown in table 2. These are calculated from the Rayleigh distribution, that is, the "wind power density" is calculated as Power density=p(v)f(v,v0)dv. In general, wind power is economical for areas with wind class 4 or greater with a possibility of extending the useful range to class 3.

Table 2: wind classes at 50 m height showing power density per unit area

Wind power Class	Wind Power Density (W/m^2)	Rayleigh average wind speed (m/s)
1	0-200	0-5.6
2	200-300	5.6-6-4
3	300-400	6.4-7.0
4	400-500	7.0-7.5
5	500-600	7.5-8.0
6	600-800	8.0-8.8
7	800-2000	8.8-11.9

2.3.2 Classification of wind turbines

Morden wind turbines fall into two broad categories; the horizontal axis wind turbine and the vertical axis wind turbine. Most of the current wind turbines are horizontal axis turbines.

Wind turbines exist in different sizes, and therefore power ratings (Sathyajith, 2006). Wind turbine systems are available ranging from 50W to 3-4 MW. The energy production by wind turbines depends on the wind velocity acting on the turbine. Wind power is able to feed both energy production and demand in the rural areas.

Horizontal axis wind turbines (HAWT) have their axis of rotation horizontal to the ground and almost parallel to the wind stream (Fig. 7). Most of the commercial wind turbines fall under this category. The Vertical axis wind turbines axis of rotation of vertical axis wind turbine (VAWT) is vertical to the ground and almost perpendicular to the wind direction as seen from Fig 7. The VAWT can receive wind from any direction. Hence complicated yaw devices can be eliminated. The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover the maintenance of these turbines can be done at the ground level. (Mathew, 2007).

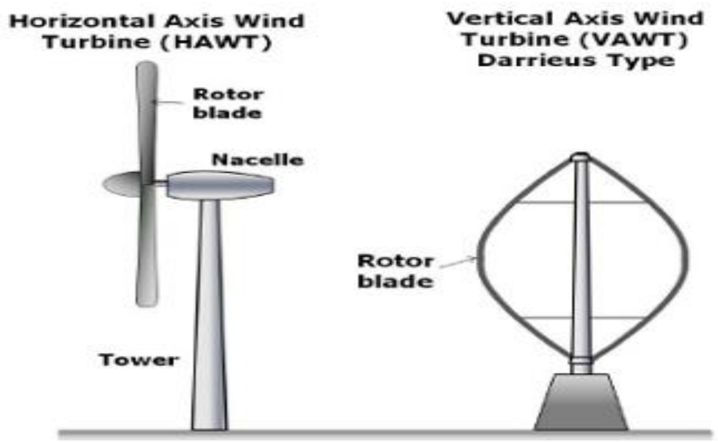


Figure 7: horizontal and vertical axis Wind turbines**.**

Sourced: (Mathew, 2007).

2.3.3 Wind power system performance (The power curve)

The power curve or performance curve is the most important characteristics of a wind turbine generator. It describes the amount of electricity generated at different wind speeds. Experience has shown that measured power curves are more reliable than calculated power curves which tend be too optimistic. As a result measurements have the character of references, serving as the sales arguments for the wind turbine generator (WTG) manufactures. Potential Investors are therefore advised to pay attention on the reliability of the power curve.

A typical power curve is given below. The important issues of a power curve are cut in wind speed and cut out wind speed hysteris, power in the operating range and regulations. The power curve gives a very realistic indication of the performance and the safety. A typical scheme for power curve measurements is shown in the figure below. The measured power curve is often used by developers and manufactures for a realistic terrain and environment conditions.

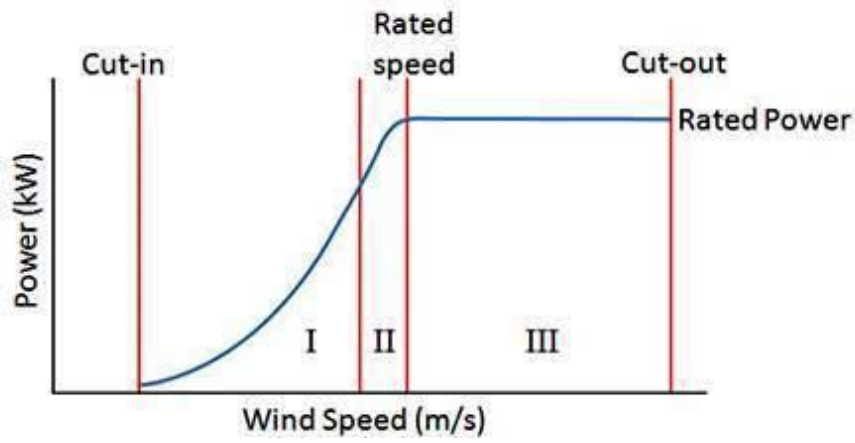


Figure 8: Ideal turbine curve.

Sourced: (Mathew, 2007).

Basically the cut-in wind speed is the wind speed at which a turbine starts to operate and produce electricity. Usually, low wind powered turbines are designed to start running at wind speeds of 3 to 5 meters per second but some can operate under very low wind speeds. The cut out wind speed is the speed at which the turbine shuts down. At a high enough wind speed the turbine shuts down to protect the rotor blades, the generator and other components, No power is generated above the cut-out speed **(**Ahmed, 2016).

2.3.4 On-grid and off-grid wind turbines

The production of electric power from wind speeds can be achieved by using appropriate turbines. Turbine choice is the critical stage in any wind energy project. Proper designing must be done in order to harness the power from the wind. The turbine must also be deigned to produce a maximum of power at wide spectrum of wind speeds. According Mohammed all wind turbines are designed for a maximum wind speed, called the survival speed, above which they do not survive. The survival speed of low wind powered electricity generators ranges from 3m/s to 25m/s. the following table shows the classification of wind turbines against the rotor diameter.

Table 3: rotor design diameters for wind turbines of varying power ratings (Ahmad et al., 2018a)(Ahmad et al., 2018a)

Power rating (kW)	Rotor diameter (m)
300	27-33
500	33-40
600	40-44
750	44-48
1000	48-54
1500	54-64
2000	64-72
2500	72-80

Wind turbines can be used for either on-grid or off-grid applications. Most medium-size and almost all large-size wind turbines are used in grid tied applications. One of the obvious advantages for on-grid wind turbine systems is that there is no energy storage problem. While most of small wind turbines are off-grid for residential homes, farms, telecommunications, and other applications. However, as an intermittent power source, wind power produced from off-grid wind turbines may change dramatically over a short period of time with little warning. Consequently, off-grid wind turbines are usually used in connection with batteries, diesel generators, and photovoltaic systems to form a hybrid for improving the stability of wind power supply. In many places, a wind power is the least-cost option for providing power to homes and businesses that are remote from an established grid. It is estimated that wind produces more power at less cost than diesel generator at any remote site with a wind power density above 200 W/m^2 at 50m elevation.

2.3.5 Wind resources in Malawi

Wind speeds averaging 2–7 m/s for electricity generation and provision of mechanical work (Kaunda, 2013b). For the wind energy systems, there are quite a good number of areas in the country with mean wind speeds above 5 metres per second almost throughout the year. With large lakeshore area with Mwera winds, Malawi has exceptional wind resources. Researchers have found that Malawi could meet all their electricity demands from wind power through 2030 (Taulo, 2015). At present, the DoEA is collaborating with Malawi Renewable Energy acceleration Programme (MREAP) at the University of Malawi, an initiative funded by the Scottish Government, to undertake detailed wind measurements at five strategic sites as part of developing Malawi's wind atlas.

2.4 Hybrid renewable energy systems

Under the DG paradigm, HPSs (Hybrid Power Systems) (or micro-grids) are getting greater attention as they allow for the deployment of local generation. In power engineering hybrid energy system describes a combined power and energy storage system. Hybrid power systems combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either. Hybrid systems can be designed to maximize the use of renewables, resulting in a system with lower emissions than traditional fossil-fuelled technologies. In addition to that Hybrid systems can be designed to achieve desired attributes at the lowest acceptable cost, which is the key to market acceptance (HOMER Energy LLC, 2016).

As it has been already reported earlier using one renewable energy source may not be sufficient as it may not suffice all the time due to the intermittent nature of most renewable energy sources. A hybrid intergrated system comprising the combination of two or more sources of energy can be a solution. When designing such systems it better to design systems that are reliable and require little assistance and maintenance as these areas repairs and maintenance might not be easy. A hybrid mini-grid is composed of three subsystems namely:

The production which includes the generation (RETs and genset), storage (batteries), converters (convertors, rectifiers, and inverters to convert DC power to AC), and management (energy management systems) components, the distribution, and demand subsystems. Each subsystem can vary greatly in its components and architecture according to the availability of resources, desired services to provide, and user characteristics. This subsystem includes. The production subsystem determines the capacity of the hybrid system to provide electricity, and connects all the components through the bus bar (i.e. the electrical wiring connecting the different components together) at the required voltage (AC/DC) for the distribution subsystem (HOMER Energy LLC, 2016).

The Distribution subsystem includes the distribution equipment. This subsystem is in charge of distributing the produced electricity to the users by means of the mini-grid. The primary issues are whether to use a distribution mini-grid based on DC or AC, and whether to build a single phase or three-phase grid. This decision will have an impact on the cost of the project and will mainly determinate the devices which can be used.

User or application subsystem or demand subsystem. This subsystem includes all the equipment on the end-user side of the system, such as meters, internal wiring, grounding, and the devices which will use the electricity generated by the hybrid power plant.

2.4.1 Hybrid power system configurations

The selection of the bus bar depends on the technologies used in the system and on the energy management strategy. While PV and batteries run on DC, electro-mechanic technologies such as genset, small wind, and small hydro normally produce AC power. In hybrid mini-grids the use of AC bus bars is more common when the battery is the central component of the system; a bidirectional master inverter can be installed to control the energy supply between AC loads and battery charge. Village mini-grids often rely on an AC bus bar since the efficiency is higher, the losses lower and the system is more flexible and expandable, although the wiring is more complex. Regarding costs, the difference between both types of installation is negligible.

2.4.2 Review of design, modelling and optimisation of hybrid renewable energy systems

Various studies reported on the analysis and assessment of renewable energy integration for rural electrification. Ahmad et al., 2018 presented an optimised model of PV-wind hybrid renewable energy system with battery and converter. The system was optimally simulated by using IHOGA (Improved Hybrid Optimisation Genetic algorithm) tool developed by the Electric engineering department of the university of Zazagoza Spain. Sensitivity analysis of hybrid system was done by considering the effect of sensitivity variables such as global solar radiation, wind speed, and PV panel cost. The result showed that for each variable system consisting of solar, wind with battery and converter bring out the most economical and viable solution for the proposed site.

Chedid & Ieee, (1997) also conducted a research entitled unit sizing and control of hybrid wind-solar power systems, with an aim to provide a tool that can help designers determine the optimal design of a hybrid wind-solar power system for either autonomous or grid-linked applications. The proposed analysis employed linear programming techniques to minimize the average production cost of electricity while meeting the load requirements in a reliable manner, and takes environmental factors into consideration both in the design and operation phases. The proposed analysis allows the user to study the interaction among economic, operational and environmental factors and hence it offers a useful tool for the design and analysis of hybrid solar- wind power systems.

Ahmad et al., (2018b) focuses on the techno-economic feasibility of a grid-tied hybrid micro-grid system for local inhabitants of Kallar Kahar near Chakwal city of Punjab province in Pakistan and investigates the potential for electricity generation through hybrid wind, photovoltaic and biomass system. HOMER Pro software is used to model a hybrid micro-grid system. The results of techno-economic feasibility study show that hybrid power system can generate more than 50 MW. The study found that the cost of energy for a grid-connected hybrid system is lower compared to an off-grid hybrid system with similar load profiles. The techno-economic study shows that other places with similar climatic and economic conditions are prospective candidates for deployment of the proposed hybrid system for electricity generation.

A study conducted in Egypt entitled" Optimization and energy management of hybrid standalone energy system. The study aims at evaluating economical optimization of a renewable energy system supplying desalination unit load in an Egyptian site. Optimal hybrid standalone energy system is reached by selecting the components that are most suitable to supply intended load. Load pattern is managed adapting it to reach the best fitted profile that decreases Net Present Cost (NPC), and Cost of Electricity (COE). Best fitted load profile is reached by increasing the direct utilization of the generated energy rather than storing in batteries or wasted as excess energy. Decreasing the battery charging energy leads to the reduction of the number; hence cost of batteries.

In addition that there is a study which was conducted in Malawi entitled "A Study into the Techno-economic Feasibility of Photovoltaic and Wind Generated Electricity for Enhancement of Sustainable Livelihoods on Likoma Island in Malawi". HOMER was used to determine the technical and economic feasibility of substituting the diesel genset with solar and wind hybrid system. It was found that there is a huge potential for both PV and wind resource in the island and from the socio economic survey showed that Likoma is a low income community. 14.1% of the population spend about 9-10% of their income on purchasing energy, and 28.9 per cent spent up to 20 per cent of their income on energy. Households with access to grid electricity expressed concerns about the intermittence of the electricity supply due to the intermittent dispatching of the diesel generators.

It has been found from literature reviewed that most researchers used HOMER/RETSCREEN/ MATLAB for their modelling and analysis. As already outlined several hybrid system simulation tools are available nowadays. For this research, HOMER was selected as the most suitable software. The following section explains the operation principle of this software as well as the analytic features that make it appropriate for this analysis.

2.5 HOMER

HOMER (Hybrid Optimization Model for Multiple Energy Resources) is a hybrid system modelling software developed by the National Renewable Energy Laboratory. This software is a powerful tool for the optimal designing, sizing and planning of hybrid renewable energy systems by carrying out techno-economic analysis for off-grid and grid connected power systems. The technical and economic assessments carried out by HOMER for this purpose are explained in the following sections.

2.5.1 Technical analysis

HOMER analyses the technical viability of the system and the ability of each configuration to meet the given energy load. This is accomplished by calculating the energy balance of the system for each time-step throughout a year: for every time-step HOMER calculates the power produced by the system and the electricity load, as well as the possibility to store excess energy in the system storage or to use previously stored electricity. The inputs required for this energy balance are the different components to consider and their technical specifications, the local resource availability and the load profile throughout a year. After analysing the viability of all possible system configurations, HOMER discards all configurations that were not technically feasible and carries out an economic analysis for all feasible configurations. The optimal design (that is, the optimal capacity of each component of the system) for each system configuration is displayed on the results screen at the end of the simulation. The optimization results are ranked and listed according to their economic performance, which assessment is explained in the following section. The next subsections give an overview on the calculation procedure of HOMER for the power input and output of the main system components for each time step (HOMER Energy LLC, 2016).

2.5.1.1 PV array power output calculation

HOMER calculates the output of the solar PV subsystem by means of Equation.

$$P_{out,PV} = C_{PV,STC} \cdot f_{PV} \cdot \left(\frac{G_T}{G_{STC}} \right) \cdot \left[1 + \alpha_T \cdot (T_T - T_{STC}) \right] \quad 2\text{-}8$$

Where $P_{out,PV}$ = the power output of the PV subsystem for the current time step [kW]

$C_{PV,STC}$ = the rated capacity of the PV array (that is, its power output at standard test conditions (STC)) [kW]

f_{PV} = the de-rate factor of the solar subsystem [%]

G_T = the solar radiation incident on the PV array in the current time step [kW/m2]

G_{STC} = the incident solar radiation on the PV array at STC [kW/m2]

α_T = the temperature coefficient of power, given by the user as an input [% /℃]

T_T = is the temperature of the PV array in the current time step [℃]

T_{STC} = the temperature of the array at STC [℃].

2.5.1.2 Hydro power output calculations

The nominal hydro power is the nominal power of the hydro system, or the power produced by the hydro turbine given the available head and a stream flow equal to the design flow rate of the hydro turbine. The calculation of the nominal hydro power includes the efficiency of the hydro turbine, but not the pipe head loss. In each time step, HOMER calculates the electrical power output of the Hydro turbine using the following equation:

$$P_{hyd} = \frac{\eta_{hyd} \cdot \rho_{water} \cdot g \cdot h_{net} \cdot Q_{turbine}}{1000W / kW} \quad 2\text{-}9$$

where:

P_{hyd} = power output of the hydro turbine [kW]

η_{hyd} = hydro turbine efficiency [%]

ρ_{water} = density of water [1000 kg/m^3]

g = acceleration due to gravity [9.81 m/s^2]

h_{net} = effective head [m]

$\dot{Q}_{turbine}$ = hydro turbine flow rate [m^3/s]

2.5.1.3 Battery charge and discharge power calculation

HOMER calculates the maximum amount of power that can be inserted in the battery bank in each time step as the minimum value among three different limits related to the kinetic storage model, the maximum charge rate and the maximum charge current. For information on the calculation of each of these limits and the kinetic storage model refer to tool kit for HOMER pro. HOMER calculates as well the maximum discharge power of the battery set (this is, the maximum amount of power that can be discharged from the load) as determined by the kinetic storage model. In addition, HOMER accounts for the discharge losses that occur when discharging power from the battery set by means of Equation (3.5):

$$P_{D,\max} = P_{D,\max,ksm} \cdot \eta_D$$

2-10

Where $P_{D,\max}$ = the maximum discharge power of the battery set [kW]

$P_{D,\max,ksm}$ = the maximum discharge power calculated from the kinetic model [kW]

η_D = the discharge efficiency given as an input in the battery specifications [%]

2.5.2 Economic analysis

After finding out which configurations are able to meet the required demand, HOMER carries out an economic analysis where the main outcome is the life-cycle cost or Net Present Cost (NPC) of each configuration. The NPC of a system is the present value of all the costs involved in the system throughout its complete lifetime, minus the present value of all the revenues generated by the system over the same period. The system costs include the capital costs or initial investment costs, component replacement costs, operation and maintenance (O&M) costs, grid power purchases, fuel costs (if applicable) and penalties for greenhouse gas emissions (if applicable). The system revenues account for the revenues generated from selling power back to the grid and the salvage value of the system, which is the value of the remaining components of the system when the project lifetime is reached (HOMER Energy LLC, 2016). HOMER calculates the NPC of the system as a sum of the total discounted cash flows of each year in the project lifetime, which are previously calculated according to the given input data. By means of the calculated NPC, HOMER determines the annualized cost of the system, which is the annualized value of the systems life-cycle cost. The annualized cost of the system is calculated according to Equation below:

$$C_{ann,tot} = NPC \cdot CRF(i, T_p)$$

2-11

Where $C_{ann,tot}$ = the total annualized cost of the system.

i = the real interest rate,

T_p = the project lifetime.

CRF = the capital recovery factor, which can be calculated as below:

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1}$$

2-12

Where n = the number of years in which the invested capital must be recovered (in this case the project lifetime). Making use of these values, HOMER calculates the Levelised Cost of Energy (LCOE) of the system (HOMER Energy LLC, 2016). The LCOE is the average cost of the system per kWh of useful energy supplied to the system load. Equation (3.4) shows the formula applied by HOMER for the calculation of the LCOE:

$$LCOE = \frac{C_{ann,tot}}{E_{\sup plied}}$$

2-13

Where $E_{supplied}$ is the sum of the energy served to the load from the system generation and grid imports.

Chapter three: methodology

3 Introduction

The knowledge gained from literature review is that hybrid renewable energy systems offer a reliable source of power as it reduces the problem of inconsistences in the power supply as different energy sources complement each other. Furthermore to that Tenthani et al (2007) also reports that a single renewable energy technology may not suffice at all times the demand of the region in question due to the intermittent nature of most renewable energy resources. In such cases a hybrid energy system with a combination of different technologies operating simultaneously, can solve the reliability issues arising out of using just one technology. The objective of this chapter was to outline the methods which were used to determine the feasibility of a standalone hybrid renewable energy system and as well as the methods which were used to check the results of the aforementioned design and optimisation problem**.**

3.1 Methodology and Methods

The study was conducted in two phases; the first phase addressed specific objective 1and 2, while the second phase addressed specific objective 3 and 4.

In the first phase we started by identifying a rural village in Malawi. Relevant data was then collected in order to ascertain the potential of renewable energy resources in that village, such as solar, wind, hydro, or biomass by measuring of each resource based on their parameters required for analysis of potential. A questionnaire was used to collect information on load profile which was needed to determine the total load demand of the village; the data were electricity consumption of households, public utilities and commercials. Using data that had been collected to make curves of hourly load demand, the total electricity demand per year is being calculated.

The second phase involved designing and modelling of the hybrid renewable energy with all the components involved. After finishing the model then making computer simulation of the system. Analyse the output results by the simulation. Finally make a justification of the hybrid system Optimization of energy generation cost based on suitable RE technologies. HOMER simulation tool will be used to simulate the hybrid size and its technical and economic feasibility. Last step is to Analyse and simulate under under an on-gird/off grid scenarios

3.2 Specific Study Area Description

The chosen isolated rural village for the study was Mtambanyama village. It is a small village located in Thyolo district in the southern region of Malawi. It is located at latitude -16.1299 ° S and longitude 35.1269 ° E and has an average elevation of 785 meters above sea level. According to the survey done by the National Statistics Office (NSO), the population is about 2245 people with about 350 households. The village was chosen for this study because it is far from the grid and even though the grid can be extended the country's grid is generally weak and unreliable. Furthermore to that it has been documented by the department of energy affairs that the area has a hydro power potential.

Figure 9: Location of Mtambanyama area
Sourced: (Kaunda, 2013b)

3.3 Collection of primary data

The first stage in any renewable energy feasibility study is to develop a simple method to identify an energy load profile. For accurate optimisation and simulation into the HOMER software hourly load data is required to ensure that the outcome of the optimisation is accurate and the system sizing accounts for the fluctuations of both supply and load. For this study primary hourly load data was obtained through a min-survey which was conducted in the village (see the attached questionnaire). Primary data on energy demand requirement was obtained by structured interview from the stakeholders in the village like village executive officer, school leaders, religious leaders and household heads. These were collected by visiting homes, schools, churches, shops groceries and small local bars. System rating for the appliances will be cross checked with that on the internet.

For better understanding of the village load, the load was broken down into four categories depending on the different users and institution setup. Basically there are residential load, public load and commercial load. The residential load basically constituted Small scale households while public load constituted dispensary (health centre), police unit, primary school, secondary school, churches and mosque. On the other hand commercial load constituted small scale bar, female saloon and barbershop and small shop. Load analysis was performed by using HOMER software. The data was then fed into HOMER to make curves of hourly load demand; the total electricity demand per year was calculated.

3.3.1 Sampling and selection of respondents for the questionnaire

The following procedures were followed in determining the sample size. Sampling for the residential load, household respondents was identified by simple random sampling from the population of registered villagers. MATLAB computer software was used to generate random numbers to be included in the sample. Barletts table for determining sample size for education research was used in this research to determine the sample size. Based on the Bartlett‘s table, the household population was approximately 400; a sample size of 69 households was adequate to achieve a confidence interval of 90 per cent and at the error rates of 10 per cent. Questionnaire was formulated in order to capture the necessary data of the electrical appliances being used and total electric load (see appendix).

3.4 Methods of estimating the renewable energy potential

In order to achieve specific objective number two the following methodology was adopted. Firstly, meteorological data and the localised site data of the study location was collected, the climatic data served as an input to HOMER. Renewable energy resources data such as solar irradiation and average flow rate of stream on monthly basis was collected. Due to data limitation, data was obtained from the NASA. The data was hourly solar irradiance (W/m^2) incident on a horizontal surface; and flow rate. The table below shows different types of data sets and there sources. The following are the parameters to be quantified.

Table 4: required data and their sources

Resource	Range/Period	Source of data
Solar radiation	20 years	NASA (RET screen international)/Department of MET
Clearness index	20 years	NASA (RET screen international)/Department of MET
Average wind speed	20 years	NASA (RET screen international) Department of MET

Chapter four: Results and Discussion

4 Introduction

This chapter presents the results found after modeling and simulation as per methods explained in chapter three of the methodology. Section one presents the electric load demand for Mtambanyama village which represents a typical isolated village. The renewable energy potential for the area is discussed in section two. The third section will outline the results obtained from the design of the hybrid system, which is objective number two. Modeling, simulation and optimization results are presented in section three. The last section discusses the technical (power production) and (cost of energy and capital cost of the system) performance of various combinations of Renewable Energy (RE) technologies.

4.1 Electric load demand estimation

Deciding on the load is one of the most important steps in the design of a hybrid system. Malawi has three seasons yet it doesn't encounter extraordinary winter and summer periods as such the load demand over the year was assumed to be constant i.e. peak demands due to extreme weather conditions were not considered. Normally load data can be found by measuring the consumption at the transformer, however for this study, there is no grid connection and no electricity power supply, thus the collection of data was done through surveys of power to be installed and their periods of electricity use needs for each consumption unit, which summing together would estimate the load demand for the community throughout the year, hence production of the average yearly load.

According to the interviews conducted with local authorities it was found that the village comprises of public and private infrastructure constituted by one primary school, one church, one community day secondary school, police unit, one trading centre and a milling house which should be prioritised for the electrical supply. Load survey data was entered in Microsoft Excel and computations of the load demand was based on system components ratings for the locally available electrical components.

The schools are closed during the winter break which runs from July to September. The electric loads for school contains lighting, refrigeration entertainment which incorporates Television, radio receiver, 3 desktops and a printer. During the weekend four classes are used by members of the community as churches and for various meetings. During weekdays electric lighting for the school in the evenings from 18:00-22:00 is supplied for the evening classes and those who wish to do studies.

The Primary school is made out of twenty classrooms, and it has an enrolment of 2176 students with 45 members of staff. The table below shows the results of the type of equipment the school has. During the weekends it is assumed that only about six classrooms are in use. The total consumption from the primary school was estimated as 39.76kWh/day.

Table 5: Load estimation for Mtambanyama primary school

Service item	Quantity	Power rating (W)	Duration(H)	Total consumption
Lighting	60 indoor	20	12	6.56
	10 outdoor	100	12	10.8
Refrigeration	1	250	24	5.4
Entertainment	1 TV	100	8	1.5
	1 Radio	100	8	1.2
	3 desktop	200	8	2.88
	1 printer	185	1	0.74
Electric jug	1	1400	1	1.4
Miscellaneous	1	200	24	4.8

The secondary school has 6 classrooms, and it has a total enrolment of 367 students. And the total number of staff is 27. The table below shows the results of the type of equipment the school has. Just like in the primary school. The total sum of the daily energy consumption for the school is estimated as 44.53kWh.

Table 6: Summary of electrical load demand the day secondary school

Service item	Quantity	power rating (W)	Duration (H)	Total consumption (KWh)
Lighting	25 indoor	20	12	2.12
	14 outdoor	60	12	10.08
Refrigeration	1	225	24	6.0
Phone charging	20	10	8	6.4
Entertainment	1Radio	200	12	0.8
	1 TV	100	8	0.8
	1 decoder	100	8	0.8
Electric jug	1	1400	1	1.4
Miscellaneous	1	200	24	4.8

The health clinic loads includes lighting, medical equipment, and other miscellaneous use. Mainly the dispensary is equipped with a refrigerator, light bulbs, stand-by communication radio, and microscope. The miscellaneous equipment incorporated in these load calculations includes personal gadgets like phones and laptops. The health centre lighting for the rooms have been assumed that the corridors laboratory examination room lamps will be working throughout the day during all the working days. The health centre has five rooms, one reception room, and two outpatient department rooms. The total load demand for the health clinic is estimated as 11.82kWh/day.

Table 7: load demand for health centre (dispensary)

Service item	Quantity	Assumed power rating	Duration	Total consumption (KWh)
Lighting	25 indoor	20	6	2.34
	4 outdoor	60	12	
Refrigeration	1	225	24	4.8
Equipment	1 Microscope	25	12	0.4
	Blood analyser	88	N/A	1.408
	Examination lamp	60	N/A	0.96
	Radio receiver	5	24	0.16
Miscellaneous	1	100	24	1.056

Apart from the trading centre the community also has a flour milling house. Currently the community does not have a flour milling machine it depends on nearby communities. This machine will not actually serve only the local community but also the nearby communities that do not have electricity access will also get the service, and thus it will help for the owners to increase their income. The machine has power rating of 12.5kW that will operate for 5:00 hours a day from 9:00-12:00 hours and from 14:00-17:00 hours only during the working days. The total daily electricity demand by the flour milling machine is shown in table 9.

Table 8: Electric Load Consumption Characteristics of Flour milling Machine

Service item	Quantity	Assumed power rating (KW)	Duration	Total consumption(kWh)
flour milling	1	13.500	6	75

Results from the sampled respondents on the number of rooms it was estimated that on average a household had 5 indoor light bulbs and 3 outdoor light bulbs i.e. a house with 3 bedrooms, living room, storeroom, kitchen and veranda. The three outdoor light bulbs included the light bulb on the veranda. The proposed load per household is 20 W indoor bulb for each and every room, three 60W bulbs for outdoor security lighting to be used between (18:00 to 6:00). The other electrical load for the households includes a 50W TV 50 W radio, 50 W decoder which are normally used for 8 hours in a day (08:00-21:00) and 1400 W small hotplate which is normally used for 2 hours in a day in the afternoon (12:00-13:00) and (07:00-08:00) The miscellaneous items which were assumed for the household include personal home computers, phones and other small entertainment gadgets. The main load for the village community is lighting which was calculated as 840 KWh. The following table shows a summary of different energy uses in the village households. The average daily consumption was estimated as 1339.4 kWh.

Table 9: Total load for the household

Energy need	Service Item	Power Rating	Duration	Total Consumption
Lighting	Indoor	15	3	264.00
	Outdoor	60	12	576.00
refrigeration	Refrigerator	225	24	158.4
Entertainment	TV	50	12	310.00
	Radio	50	12	310.00
Cooking	Hot plate	1400	2	336.00
Miscellaneous	1	200	24	4.800

.

The village also has a trading centre where people mostly sell their produce. The trading centre has about 20 groceries, 2 small local bars, female saloon, barber shop, 1 church, mosque, and a police unit. The groceries shops normally start operating from 6:00-21:00 while the bars are mostly open from 10:00-22:00 while the saloon normally operates from 08:00-17:00. The barbershop operates normally from 08:00-21:00. The proposed load for the trading centre indicating the electrical appliances with their power rating together with total energy consumption per day are shown in the table 10. The proposed load for the trading centre lighting with total average demand of 66.56 kWh, which constitutes 20 W and 60 W indoor bulbs for the groceries, barber shop, female saloon, church, mosque and police unit.

Table 10: load demand for trading centre and other public utilities

Energy need	Quantity	Power Rating	Duration	Total Consumption
Lighting	58 indoor	20	4	2.01
	11 outdoor	100	12	17.76
Refrigeration	2	225	24	13.5
Entertainment	1 TV	200	12	
	Radio	50	12	
	Decoder	50	12	25.8
Miscellaneous	1	200	24	4.80

The final load data regarding the Mtambanyama energy needs for electricity usage, which is mainly for illumination the above mentioned infrastructure, including the use of fridges, freezers for the conservation of vaccines and also for the use of communication devices such as radio, cello-phones and televisions. The load profile was modelled based on data collected from households and institutions as it was discussed in the chapter three. The electricity demand was estimated and modelled as follows.

4.1.1 Aggregated load demand

The energy demand changes every now and then, season to season and day to day and working days to weekend depending on the activities of the community. The day to day variability in HOMER was used to represent a realistic load pattern for the day. The day to day variability was set to 10% which is the recommended value in HOMER. Random variability was set for the variation of the daily load from month to month. The time step for the simulation of the data was set as default of 60 minutes. The variation range for each time-step was set to 20% of the load according to the default settings of HOMER. From the baseline data supplied to HOMER, the annual average power demand was calculated as 1,572.51kWh per day.

Based on the electricity needs and demand of the village discussed above, an aggregated electricity demand was calculated as follows. The total electricity needs for village were estimated at 1,572.51KWh per day. Figure 4-30 shows the modelled profile for the aggregated electricity demand for the area. Calculations for aggregation of three electricity demand are shown in appendix. The 24 hour primary load is given in the figure 3.2 below. The overall daily load profile of the community is estimated as depicted in figure 3. From the figure, it can be observed that the peak period is in the morning (18:00-19:00) and is estimated as 268kW. The estimated average power demand is 65kW with load factor of 23.0%.

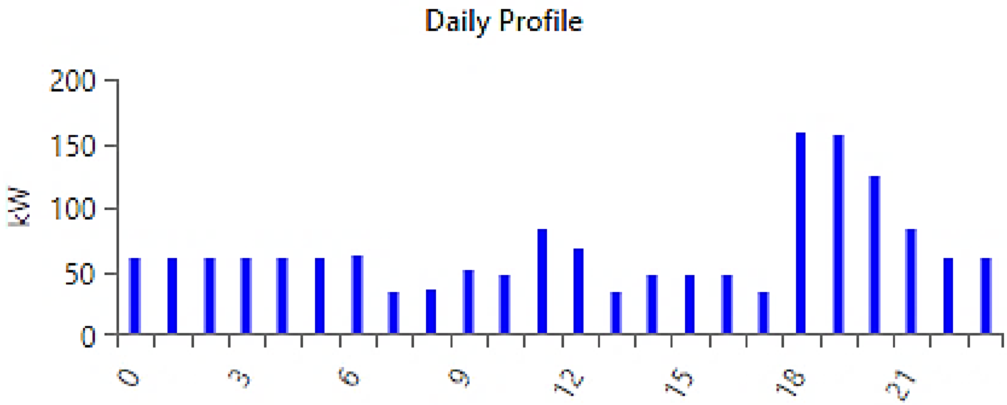


Figure 3.2: A Typical Daily Load Profile (HOMER)

The hourly load profile of the site for a typical day (1 January) is shown in Figure 3.2 from where scaled average energy consumption per day, scaled daily peak demand, and daily average demand are found to be approximately 1,572.5 kWh, 268 kW, and 65.52 kW, respectively. The mismatch in the peak value and value shown in Figure 3.2 is due to the scaling process and the random variability introduced in HOMER to make the load pattern more realistic. In addition, seasonal load profile showing monthly averages of AC primary load for site is shown in Figure 3.3.

4.2 Seasonal load demand profile

The load demand profile for the village is mostly AC load with scaled annual average of 1,572.51 kWh and a peak load of 268.73 kW which are presented in the figure below. From this figure, it can be observed that the maximum load ranges between 216.66 kW and 268.73 kW monthly with lowest in February and highest in November and the daily peak it seen to vary from 169.45 kW to 185.45 kW, whereas the average load is almost the same in all the months. All this variation is due to the above mentioned random variability factor introduced in HOMER to cater for the variation that may occur in the load each day of the year.

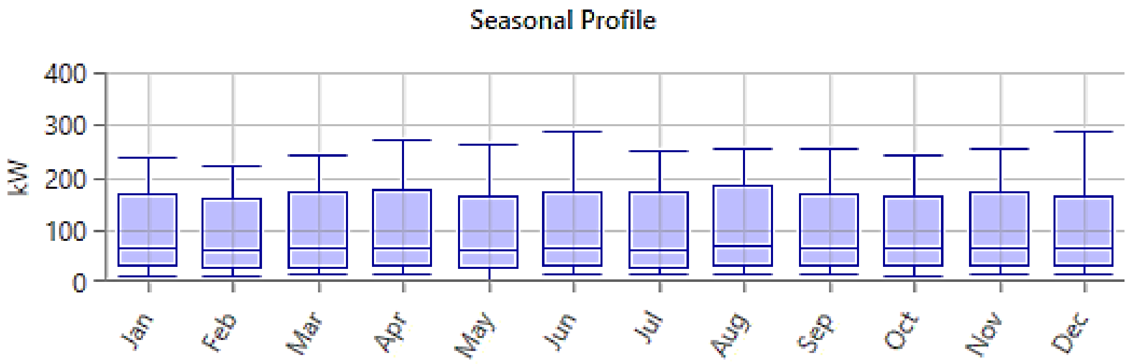


Figure 3.3: Monthly Load Profile of the Study Area (HOMER)

Figure 9 shows the predicted variation in AC load over the whole year. While figure 10 shows a diurnal variation of the load profile.

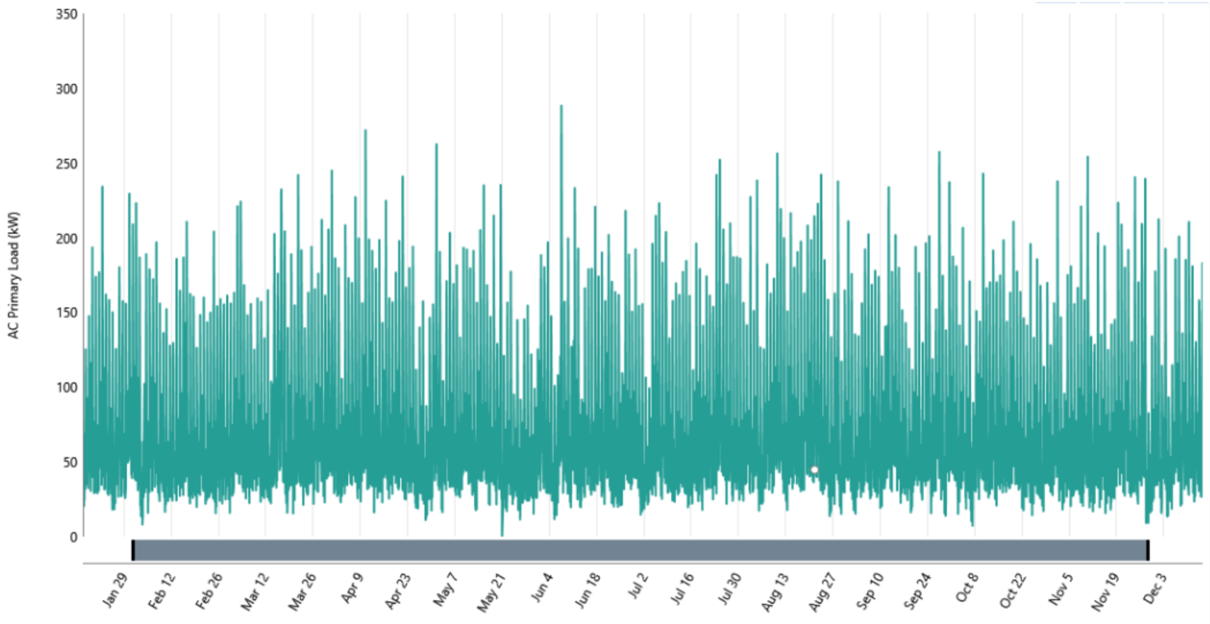


Figure 10: AC Load for the whole year.

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

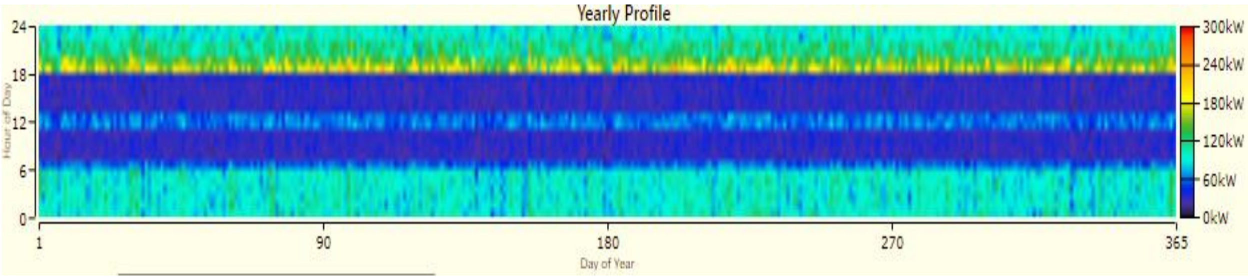


Figure 11: Diurnal Variation of Primary Load Profile

4.3 Renewable energy potential

The knowledge of energy resources of a given location is important to design hybrid system for such location. This section presents the energy resource (hydro and solar) for Mtambanyama community. The potential of solar resource and hydropower resource for the village was assessed.

4.3.1 Solar resource assessment Thyolo (Mtambanyama)

Global horizontal irradiation is mostly considered as a climate reference for area. Direct components of GTI (or GHI) indicate how different PV technologies may perform. The solar GHI data from this source are estimated from monthly averaged values over a 22 year period from July 1983 until June 2005. The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extra-terrestrial radiation. The clearness index has a high value under clear, sunny conditions, and a low value under cloudy conditions. The clearness index and daily radiation in kWh/m^2/day for the locality of Mtambanyama are illustrated in Figure below.

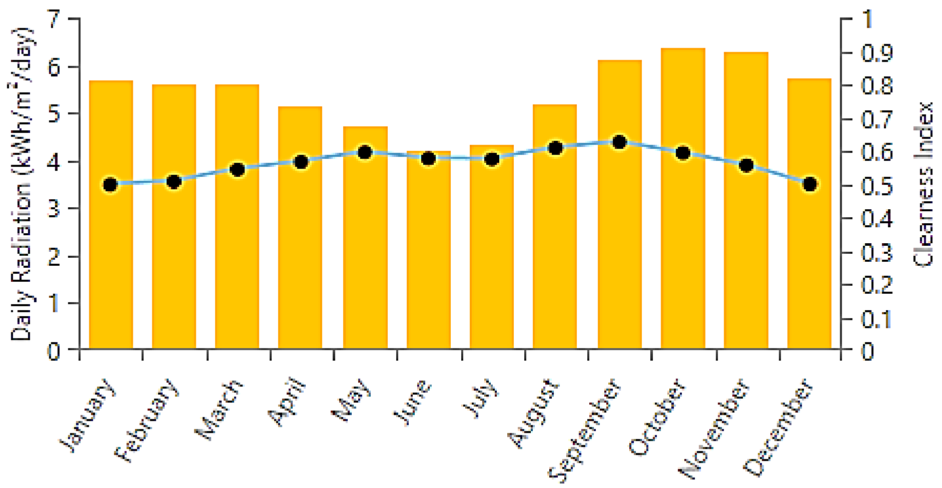


Figure 12: Solar Radiation and Clearness Index of the Study Area

Malawi's climate is generally tropical. October is sunniest month of the year at which the normal sun powered irradiance for the month is 6.5kWh/m^2/day; January is the month with the lowest irradiance which is approximately equal to 3.7 KWh/m^2/day. September to November has been identified as the months with high GHI, but also with higher variability. The clearness index increases from January to May, from June to July it stays relatively the same, where as in the month of September to December the clearness index deceases from month to month as (0.6), (0.56), (0.52) and 0.5 respectively.

4.3.2 Water resource assessment Nsuwazi River Thyolo

The Msuwazi River hydrological data from 1973 to 2003 (station 14B2) was collected and is presented in the table below. The site gloss head is 25m at Nsandama area. It was observed from the analysis of the mean monthly discharge data that the discharge peaks up from November and is the highest in the month of January with an average flow rate of 700L/s. The monthly average stream flow and its pictorial representation is given in Table 4.2 below

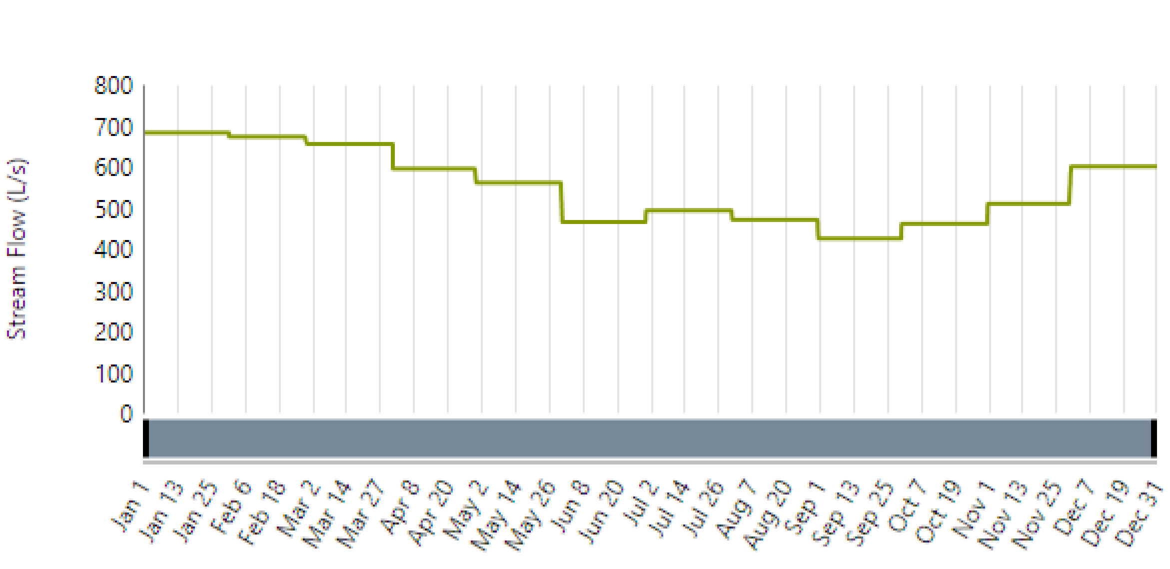


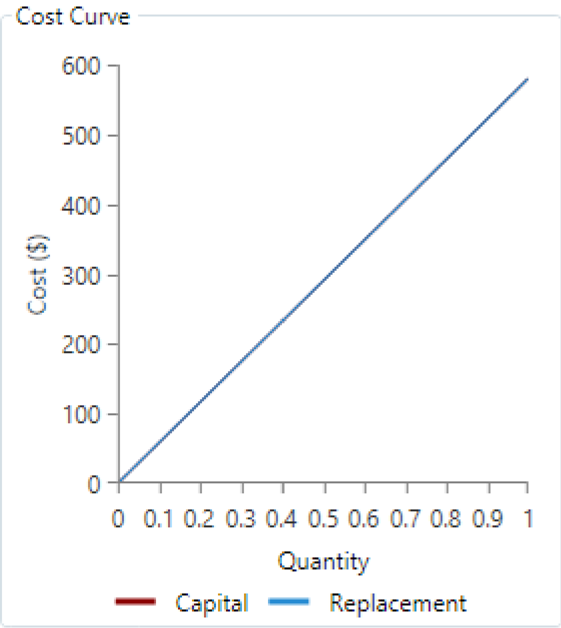
Figure 13: Mean Monthly Discharge of Msuwadzi River

4.4 Hybrid energy system configuration

The system design and sizing for this thesis followed the methodology of input consideration based on the load data and system design component selection. The hybrid system studied in this thesis is one combining solar PV and micro hydro with bank of batteries and a diesel generator during on demand scan for critical loads. Power conditioning units, such as converter, are also part of the supply system. The PV/ micro hydro hybrid system makes use of the solar PV and hydro turbine to produce electricity as the primary source to supply the load. The configuration of PV/micro hydro hybrid system was analysed for various PV array size and number of battery banks with including a diesel generator as a standby system. The key components of the hybrid system comprise of solar PV, hydro turbine, batteries and the converter.

4.4.1 PV sizing and cost

Choice of the required size of the PV panel depended on the peak load of 288.81kW. The HOMER software provides a number of options in the library which can be selected. After simulations are done and results are generated the system components sizing can always be adjusted. A 1 kW PV system was chosen for the initial simulation. The PV sizing can always be adjusted to suit the simulation and optimum result. A 1 kW solar panel installation and replacement costs are taken approximate as $580 and $ 580 respectively (**Figure 14 and figure 15**) (www.alibaba.com). The lifetime of the PV arrays are taken as 25 years.



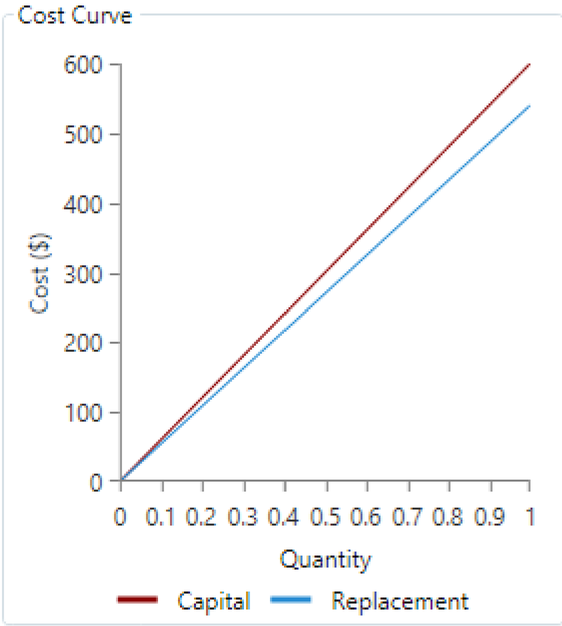


Figure 14 : Cost curve of PV.

Figure 15: cost curve of battery

4.4.2 Battery sizing and cost

Battery bank is utilised as a standby system and it additionally keeps up consistent voltage over the load. For battery we are utilising deep cycle battery made by Rolls Battery Engineering. The battery type recommended for using in solar PV system is deep cycle battery. Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. The battery should be large enough to store sufficient energy to operate the appliances at night and cloudy days. The nominal voltage of one battery is 6 V with nominal capacity if 1156 Ah and lifetime throughput 6,879.60 kWh. Cost of one battery is $600 with a replacement cost of $540 ("Surrette / Rolls 4 KS 25P Flooded Battery - Wholesale Solar", 2018).

4.4.3 Power converter sizing and cost

A power electronic converter is needed to maintain flow of energy between the ac and dc components. For a 1 kW system the installation and replacement costs are taken as $300 and $300, respectively (www.alibaba.com). Lifetime of a unit is considered to be 15 years with an efficiency of 90%. Consider for this hybrid system 1200 kW converter. The size can then be reduced or increased according to the result of simulation.

4.4.4 Diesel generator sizing and cost

The diesel generator is used to meet the peak loads and to charge the batteries in time of low resources (low flow rate and low solar irradiation).a 10kW diesel generator was chosen for the simulation. The diesel price in Malawi is at present US$1.10/L with the current conversion of 1US$ to 735 Malawian kwacha. The fuel has a heating value of 43.2MJ/kg and density of 820kg/m^3, the carbon content is 88% and sulphur content of 0.33%. The power conditioning units are dc-dc and ac-dc converters, with the sole purpose of matching the PV batteries voltages to that of the bus voltage at the dc bus.

4.4.5 Hydro turbine cost and sizing

The sizing of a small hydropower plant of the run-of-river type is very critical for the cost effectiveness of the investment. The primary criterion for the selection of the hydro turbine is its cost. For this research hydro turbines have been selected from different sources. In the selection of the turbine to be used the available head and the stream flow are considered. For this study the available head is 25m and design flow of 600litres/second (0.6m^3/s) based on the above mention criterion a cross flow turbines have been selected from turbine selection chart. This hydro turbine was obtained from hydro turbine website (www.alibaba.com) ("Hydropower system cost to operate - Renewables first", 2018). The design flow for sizing equipment was 500 litres per second, the flow rate with 80% permanency, with equipment having efficiency of 80%. Implementation costs of the hydroelectric power plant were estimated at US$ 120,000. The life time was estimated at 25 years. The operation and maintenance as well as replacement costs of a plant equipped with pumps as turbines are approximately equal to the implementation cost.

4.5 Optimisation and modelling results

The optimum configuration and components sizes that meet load requirements at the lowest costs are found by using HOMER sizing tool. The inputs treated by the software describe the solar and hydro resource availability; the load power and energy demand and the hybrid system component (PV array, hydro, battery and converter) costs are illustrated in the section 4.1. The system's simulation were performed for each 8760 hours in a year and the main economic output of the system configuration is based on the net present cost, displayed under the heading total NPC.

4.6 System control parameters, economic inputs and constraints

4.6.1 Dispatch strategy

Dispatch strategy is a set of rules used to control the operation of the generator(s) and the storage bank whenever there is insufficient renewable energy to supply the load. HOMER models two types of dispatch strategies namely; cycle-charging and load following. In load following mode, the diesel generator does not charge batteries whereas in cycle-charging mode it does. Both scenarios were modelled in this study.

4.6.2 Technical and economic inputs and constraints

HOMER software inputs for the economic analysis includes the nominal discount rate, expected inflation rate, the project life time in years, system fixed capital costs, and system fixed operation and maintenance costs and the capacity shortage penalty. According to the reserve bank of Malawi the nominal overall inflation rate for the year 2018 is 9.70%. The discount rate was modelled at 10% for 25 years project life time. Techno-economic model was developed using the HOMER software. The results of the carried out simulations are presented in the following paragraphs along with their discussion. A discussion on the validity of these results and the simulation model is also included in the second part of this section. Schematic overview of the designed simulated hybrid system is shown in figure 15.

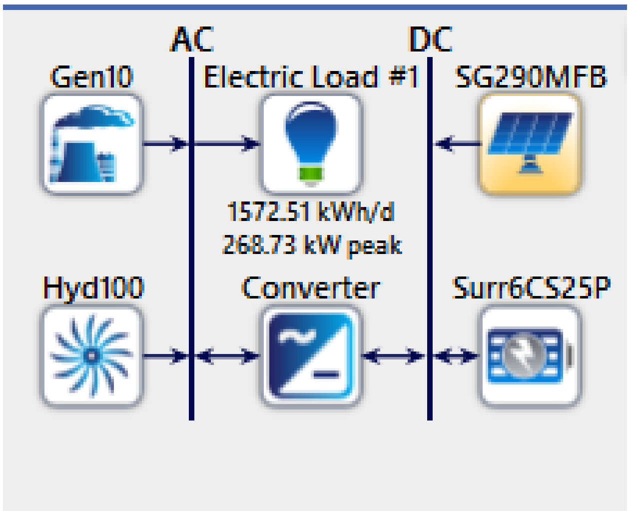


Figure 16: Schematic diagram of the simulated system.

4.6.3 Results obtained in simulation

The results panel shows overall and categorized list of configurations available based on the input data earlier introduced to HOMER and ordered according to the lowest NPC. The categorized table presented the least cost effective combinations from among all components setup, whereas, the overall optimization results displayed all of the affordable system combinations based on their NPC. Power systems are selected after simulation based on primarily minimum net present cost. On top of these parameters less cost of energy, high renewable fraction, low capacity shortage and low excess electricity generation could be used for comparison of power generating schemes in order to check their technical feasibility. For this thesis NPC and the levelised cost of energy (LCOE) was used as criteria to determine the feasibility of the system.

Export...

Optimization Results

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

Architecture						Cost					System	
SG290M (kW)	Gen10 (kW)	Surr6CS:	Hyd10C (kW)	Conver (kW)	Disp	COE ($)	NPC ($)	Operating cc ($/yr)	Initial cap ($)	O&M ($/yr)	Ren Fr (%)	Cap S (%
181		333	39.2	222	CC	$0.0833	$855,251	$20,326	$491,653	$11,910	100	0.0998
186	10.0	300	39.2	227	LF	$0.0836	$857,793	$21,061	$481,050	$11,800	99.9	0.0930

Figure 17: Categorized optimisation result

From the optimal simulation result table the most financially savvy framework, i.e. the system with the lowest net present cost, is the PV micro hydro battery converter configuration with a net present cost of $855,251 and the cost of energy (COE) is cost 0.0833$/kWh, this is less than the current grid price of Malawi 0.099$/kWh (MERA 2018), and renewable resources fraction is 100% from this we can easily observe that the total portion of energy production is from renewable energy sources. The dispatch strategy for the configuration follows cycle charging. This setup could be a good choice for implementation because the system is almost from renewable energy sources. Figure 21 shows the monthly average electrical production of this system.

Export...

Optimization Results

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

Architecture						Cost					System	
SG290M (kW)	Gen10 (kW)	Surr6CS	Hyd10C (kW)	Conver (kW)	Disp	COE ($)	NPC ($)	Operatinç ($/yr	Initial car ($)	O&M ($/yr)	Ren Fr (%)	Cap S (%
189		332	39.2	215	LF	$0.0835	$856,641	$20,318	$493,187	$11,965	100	0.0788
189		332	39.2	215	CC	$0.0835	$856,641	$20,318	$493,187	$11,965	100	0.0788
182		336	39.2	223	LF	$0.0835	$857,193	$20,301	$494,036	$11,932	100	0.0868
182		336	39.2	223	CC	$0.0835	$857,193	$20,301	$494,036	$11,932	100	0.0868
182		334	39.2	225	LF	$0.0835	$857,350	$20,340	$493,496	$11,923	100	0.0880
182		334	39.2	225	CC	$0.0835	$857,350	$20,340	$493,496	$11,923	100	0.0880
186	10.0	300	39.2	227	LF	$0.0836	$857,793	$21,061	$481,050	$11,800	99.9	0.0930
193		323	39.2	217	LF	$0.0836	$858,059	$20,528	$490,845	$11,954	100	0.0774
193		323	39.2	217	CC	$0.0836	$858,059	$20,528	$490,845	$11,954	100	0.0774
190	10.0	301	39.2	222	LF	$0.0836	$858,122	$21,011	$482,266	$11,831	99.9	0.0762
175		357	39.2	218	LF	$0.0837	$858,680	$19,989	$501,101	$11,979	100	0.0792
175		357	39.2	218	CC	$0.0837	$858,680	$19,989	$501,101	$11,979	100	0.0792
187	10.0	305	39.2	226	LF	$0.0837	$858,702	$20,941	$484,098	$11,828	99.9	0.0757
181		353	39.2	215	LF	$0.0837	$859,464	$20,039	$500,999	$12,006	100	0.0639
181		353	39.2	215	CC	$0.0837	$859,464	$20,039	$500,999	$12,006	100	0.0639
191		311	39.2	230	LF	$0.0838	$859,915	$20,867	$486,643	$11,880	100	0.0979

Figure 18: Extract of Overall optimization Result

The figure below shows cost summary of the most feasible configuration by components. While the figure 19 shows among the components the battery Surrette has the highest cost seconded by the generic hydro turbine which has a net cost of about $300,000. Table 11 shows the breakdown of the total cost of a component with its associated cost the sum of the capital, replacement cost, operation and maintenance and salvage cost. System converter has lowest total cost of all the system components.

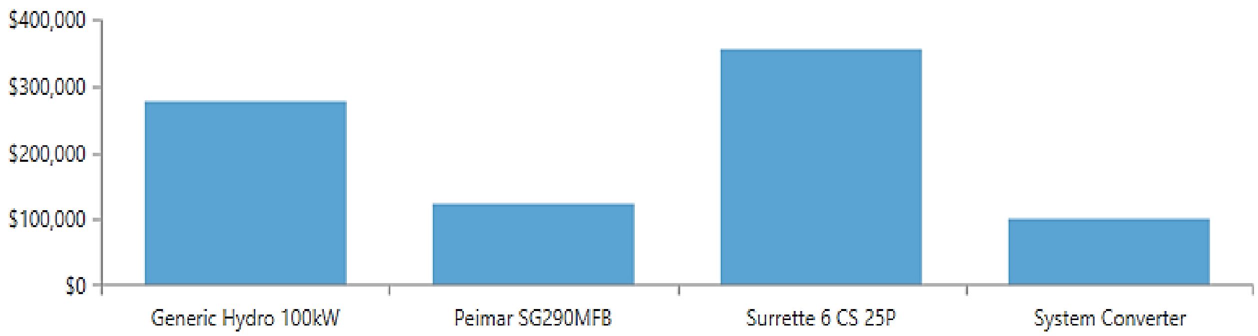


Figure 19: cost summary by net present cost of the components

Table below shows the total annual energy production by a simulated PV-micro hydro battery modelled hybrid system for Mtambanyama area.

Table 11: Cost summary of the hybrid power generation system.

Component	Capital	Replacement	O&M ($)	Salvage	Totals
Generic Hydro	$120,000.00	$0.00	$157,327.95	$0.00	$277,327.95
Peimar SG290MFB	$105,160.08	$0.00	$25,946.75	$8,873.79	$122,233.04
Surrette 6 CS 25P	$199,800.00	$127,637.63	$29,784.09	$1,301.39	$355,920.32
System Converter	$66,692.76	$44,332.71	$0.00	$11,255.55	$99,769.92
System	$491,652.85	$171,970.34	$213,058.78	$21,430.7	$855,251.24

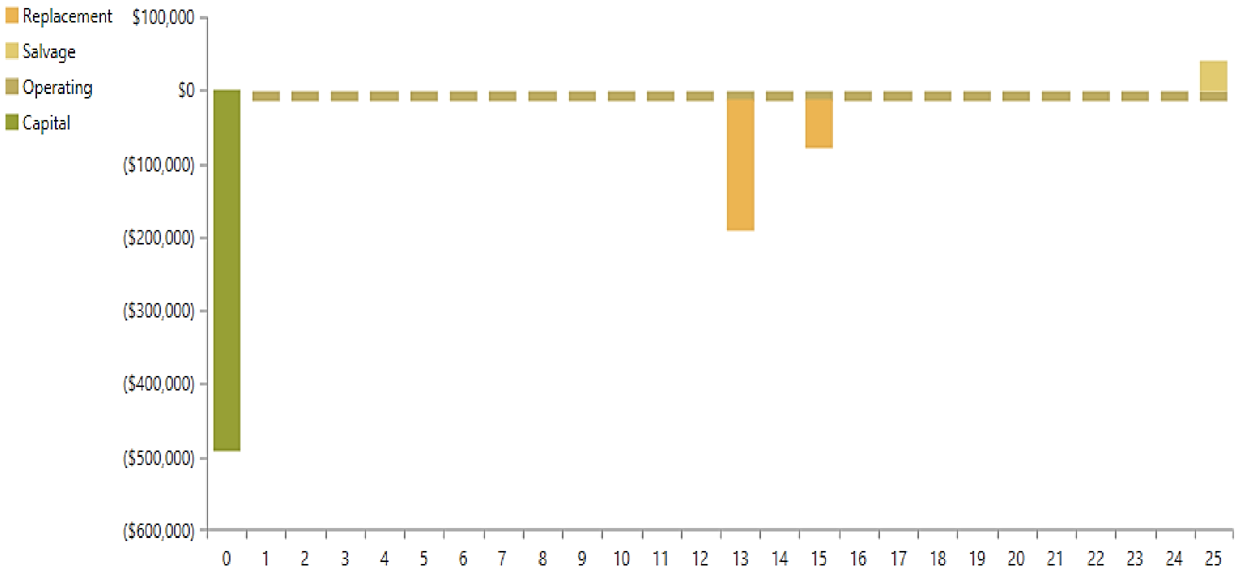


Figure 20: Yearly cash flow summaries by cost type.

1.1.1 Electrical energy production and consumption

Table 12 shows the total annual energy production by a simulated PV-micro hydro battery modelled hybrid system for Mtambanyama area.

Table 12: Annual energy production by a simulated PV-hydro battery system Mtambanyama

Technology	Production	
	kWh/year	Per cent of total production
P- SG290MFB (PV)	290,517	39.9
Hydro	438,272	60.1
Total	728,788	100

The percentage of energy production of the hybrid system is shown in figure 21. The major part of the energy originates from hydropower which is 60.1% and 39.9% offer is PV panels. Based on the optimisation result the most feasible hybrid configuration is 35kW PV, 94.2kW hydropower, 80 surrattCS25P battery and 70kW inverter and 52.2 rectifiers. The net NPC of the hybrid system is $855,251 and the Levelized cost of energy for the hybrid system is 0.0833$/kWh.

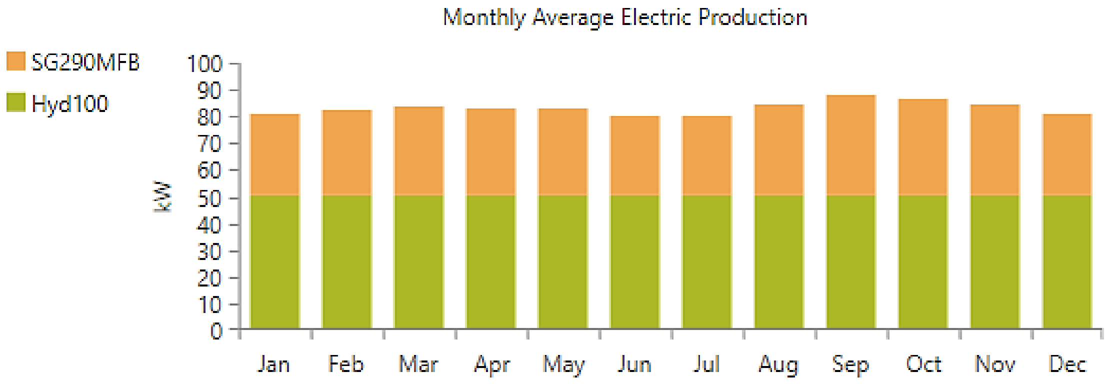


Figure 21: Monthly energy production and system architecture of the most feasible system configuration

1.1.1 Excess electricity and unmet electricity load

Table below shows the total excess electricity produced compared with the total unmet electricity load for the PV-hydro battery modelled hybrid system for Mtambanyama area.

Table 13: Excess electricity and unmet electricity load

Quantity	Production	
	kWh/yr	Per cent of total
Excess electricity	104,909	14.4
Unmet electricity load	302	0.0526
Capacity shortage	573	0.0998

As it was seen in Table 13, 104, 909 kWh i.e. 14 per cent of the produced energy was in excess of the electricity demand and would need to be curtailed. Figure 22 shows a chart of expected excess electricity by the energy system on each day of the year.

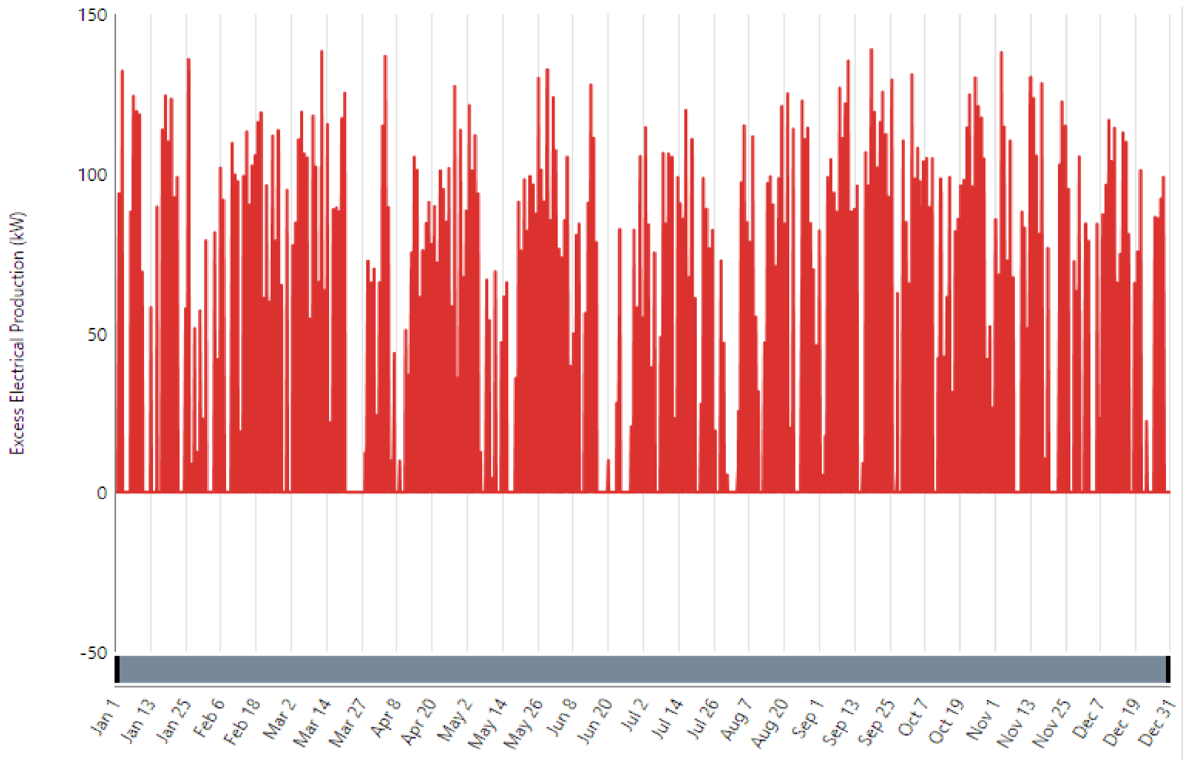


Figure 22: Expected excess power by a model PV-micro hydro system for Mtambanyama Installed capacity of the model system

It can be seen from Figure 22 that the excess electricity is likely to exceed 100 kW at any time of excess power. The total energy production from the solar panels and hydro turbine are 290,517kWh/yr. and 438,272 respectively representing a total annual production of 728,788kW/yr. It must be noted that the only load we have in the system is the AC load which is consuming 573,664kWh/yr representing a 100% consumption fraction. On the same note it must also be noted that 104,909 of excess electricity is produced representing 14.4% of the total energy produced while the total unmet electric load is 302kWh/yr representing 0.0525 which is very small and which can always be compensated by the backup generator.

The configuration presented has a 100% renewable energy fraction as such it is a very good system as it is environmental friendly and it will also help to offset the carbon emitted by other sources of energy. The configuration if implemented will also achieve 1,724 maximum renewable energy penetrations.

4.6.4 Performance of the PV array

Table 15 shows the predicted performance indicators and power output respectively for the PV component of the modelled hybrid system for Mtambanyama area.

Table 14: Performance indicator for a model PV component of the hybrid system

Quantity	Value	Units
Rated Capacity	181	kW
Mean Output	33.2	kW
Mean Output	796	kWh/d
Capacity Factor	18.3	%
Total Production	290,517	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	169	kW
PV Penetration	50.6	%
Hours of Operation	4,373	hrs/yr
Levelized Cost	0.0235	$/kWh

It can be observed from the illustrated table 15 above that the PV would operate with a capacity factor of 18.3%. With an installed capacity of 181 kW, the PV array could achieve a maximum power output of 169 kW. The Levelized cost of energy is 0.0235 per kWh shown above is based on the total cost of the components. This is the LCOE for the installed costs of the PV panels alone without accounting for auxiliary equipment for interconnection.

4.6.5 Performance of hydro turbine

Based on the simulation results shown in Table 15, the modelled hydro turbines would operate at a capacity factor of 128 per cent with a mean output of 50 kW. The mean wind power penetration would be 76.4 per cent. The Levelised cost of energy for the wind turbines would be US$0.354 per kWh. This is the LCOE for the installed costs of the turbines alone without accounting for auxiliary equipment for interconnection. The LCOE shown in Table 15 can be used as general merit factors for the economic viability of PV and wind energy on Mtambanyama area. Thus, based on turbine costs and PV array costs, the LCOE for hydro power could be 5 times higher than the LCOE for PV, indicating that PV is generally a favourable technology for Mtambanyama community.

Table 15: performance indicator for a model hydro turbine component of the hybrid system

Quantity	Value	Units
Nominal Capacity	39.2	kW
Mean output	50.0	kW
Capacity factor	128	%
Total Production	438,272	kWh/yr

Quantity	Value	Units
Minimum output	50.0	kW
Maximum output	50.0	kW
Hydro penetration	76.4	%
Hours of operation	8,760	hrs/yr
Levelized Cost	0.0354	$/kWh

The minimum and maximum output the hydro turbine are both 50kW, while the hydro turbine 8760 hours which is a full year, and has a nominal capacity of 39.2kW while the average output for the hydro turbine is 50.0kW with a capacity factor of 128%. Figure 22 shows the average energy production from the hydro turbine.

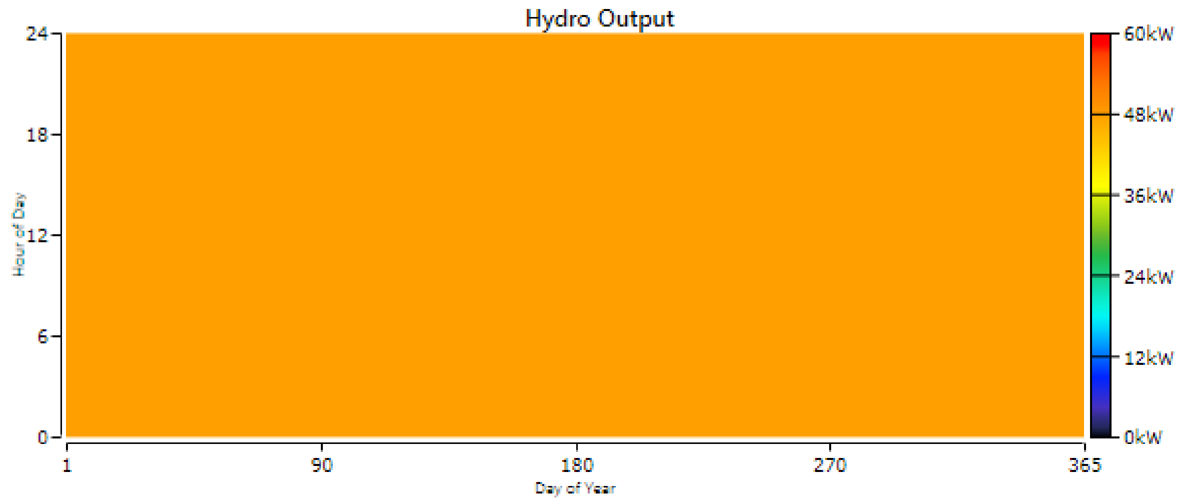


Figure 23: Average energy production from the hydro turbine

4.6.6 Battery bank performance

Figure 17 shows the predicted variation in battery bank state of charge; and Table 16 shows a summary of performance indicators for the modelled battery storage.

Table 16: Simulated performance indicators for battery bank

Quantity	Value	Units
Batteries	333	qty.
String Size	1.00	batteries
Strings in Parallel	333	strings
Bus Voltage	6.00	V

Quantity	Value	Units
Autonomy	21.1	hr
Storage Wear Cost	0.0878	$/kWh
Nominal Capacity	2,301	kWh
Usable Nominal Capacity	1,380	kWh
Lifetime Throughput	2,290,907	kWh
Expected Life	12.6	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	202,107	kWh/yr
Energy Out	162,752	kWh/yr
Storage Depletion	1,193	kWh/yr
Losses	40,547	kWh/yr
Annual Throughput	181,963	kWh/yr

The system architecture contains 333 batteries with a string size of 1.00 per battery and 333 strings in parallel and Bus a voltage of 6.00V. The battery sizing has autonomy of 21.1 hours with a nominal capacity of 2301kWh and a lifetime throughput of 2,290,907 kWh and the expected life time of 12.6 years.

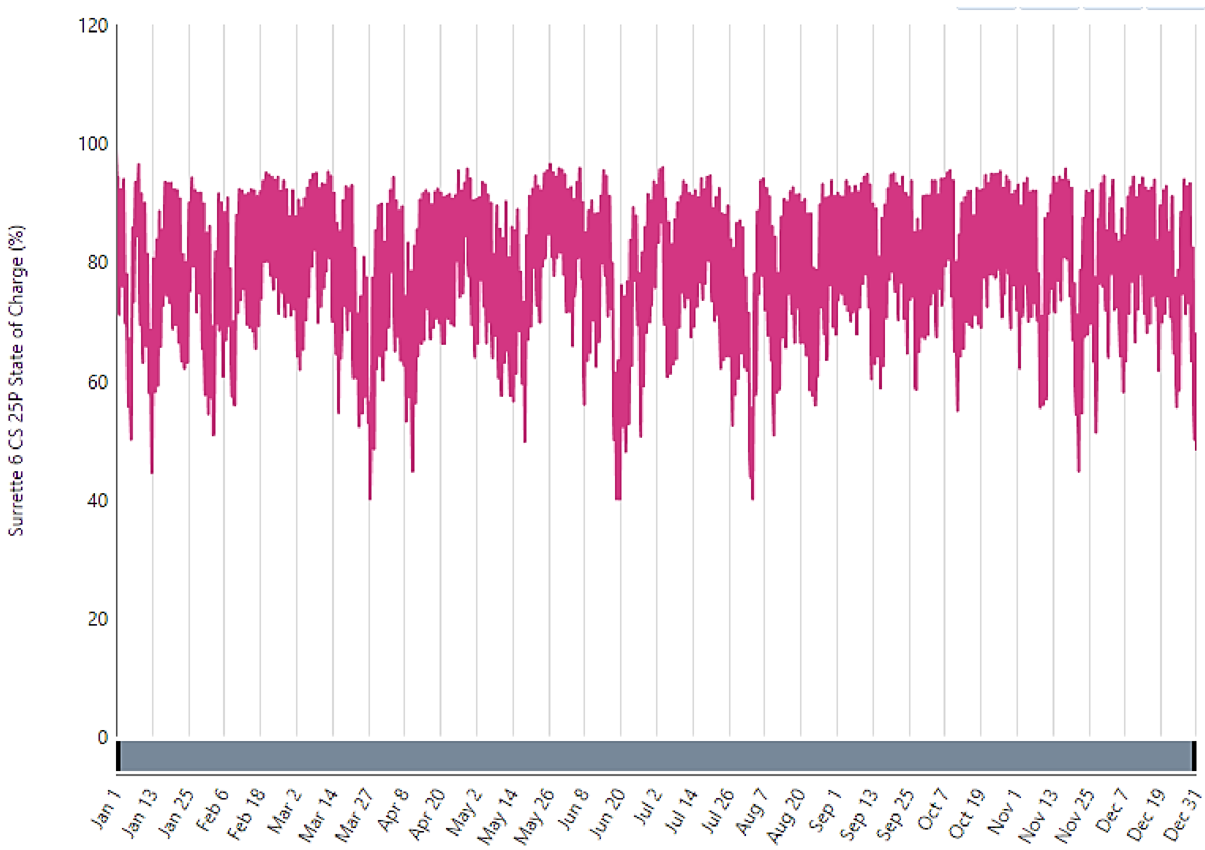


Figure 24: Simulated variation of battery bank state of charge for the model PV-wind-diesel-battery system for Mtambanyama

It can be seen from Figure 24 that the battery bank state of charge would vary between 40 and just over 90 per cent. In Table 16, it can be shown that the battery bank efficiency is 80 percent i.e. 20 percent losses. However, the important parameter in the table is the expected life of the battery. The results show that the battery bank would need changing about every 12.6 years i.e. within twelve years of system operation, there would need to be enough funds for replacement of the batteries needless to mention about the logistics which will have to be started probably months or a year before the actual dates of battery replacement.

4.7 Sensitivity analysis

Sensitivity analysis can be done by entering multiple values for a particular input variable. HOMER repeats its optimization process for each value of the variable and lets you see how the results are affected. An input variable for which you have specified multiple values is called a sensitivity variable. Sensitivity analysis helps in exploring the effect of the changes in the available resource and economic condition. Four sensitivity parameters were considered in this study, namely: solar radiation, river flow rate, and diesel price. The sensitivity values entered for each of these parameters are presented in Table 18.

Homer simulates the entire system with respect to each sensitivity variable specified. Figure 25 and 26 shows the optimal system type (OST) sensitivity results for three different scenarios namely; variation in hydro flow rate and solar radiation with varying diesel prices, variation in hydro flow rate and diesel price with constant solar radiation and finally, variation in solar radiation and diesel price with constant flow rate.

Table 17: Sensitivity variable values

Diesel fuel price ($)	Hydro capital cost ($)	Hydro flow rate (L/s)	Solar radiation (kW/m^2)
0.8	120,000	700	3.0
0.9	100,000	400	5.0
1.1	95,000	300	6.5
1.2	90,000	200	7.5

4.8 Sensitivity results

This model shows how micro-hydro systems integrate with Photovoltaic system and battery in a stand-alone application. Sensitivity analysis was carried out and Figure 7.7 shows the variation of stream flow against global solar radiation at fixed diesel price, the most cost effective set up for a particular set of hydro and battery is also included.

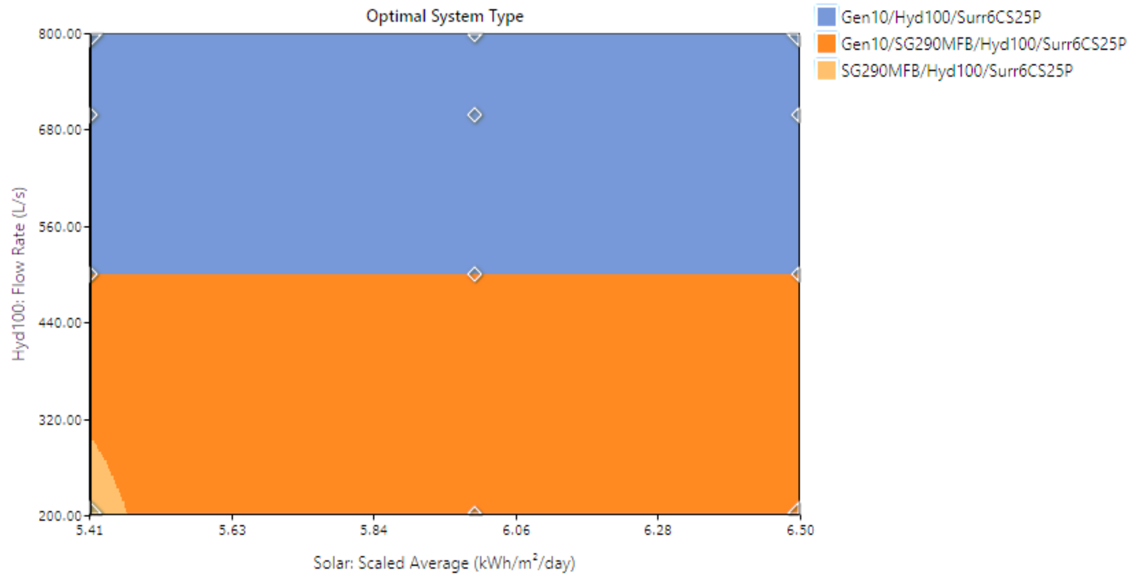


Figure 25: Sensitivity of stream flow and global radiation with some NPC

In this Figure, it can be seen that the hydropower plays big role in supplying energy to the community. At this point, it must be known that this is not due to poor solar radiation; rather it is because mean flow rate of the river is high enough to generate electricity. From Figure 25, It is observed that for a stream flow lies above 495 litre/second HOMER suggests

Gen/hydro/ battery/ systems is favourable while for stream flow between 495 litre/second and 300 litre/second PV/hydro/Gene/battery is the most favourable configuration. But For a steam flow greater 495, litres/second and if solar radiation is ample Homer Combines Gen/Hydro/PV/ Battery as the best alternative.

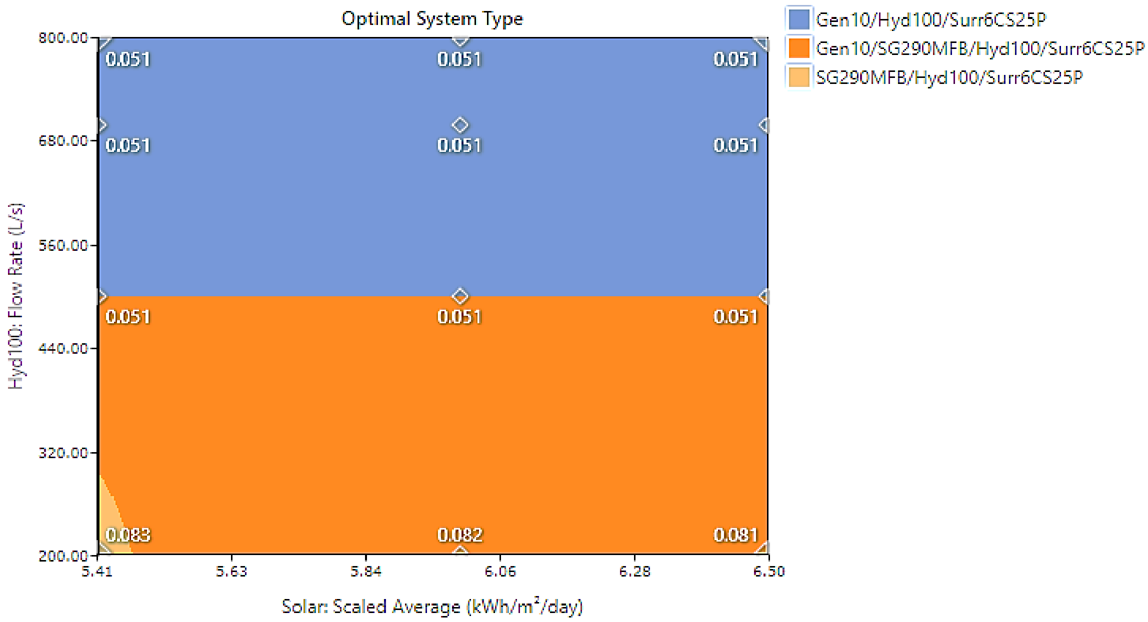


Figure 26: Sensitivity of stream flow and global radiation superimposed with the cost of energy (LCOE)

It can be observed that the Levelized cost of energy LCOE decreases with increasing flow rate and with increasing solar radiation. It is further observed from these figures that the superimposed LCOE reduces as the global radiation increases, whereas the reverse is the case for the increase in diesel price. This simply because generating electricity using hydro power is relatively cheaper than using a diesel genset. In addition to that it also means there enough water which can run the turbines all year long. It must also be noted that the average energy production from the hydro power remains constant. This is because the sizing of the turbine was commensurate with total load demand of the area as such a turbine of 100kW was picked to supply the load.

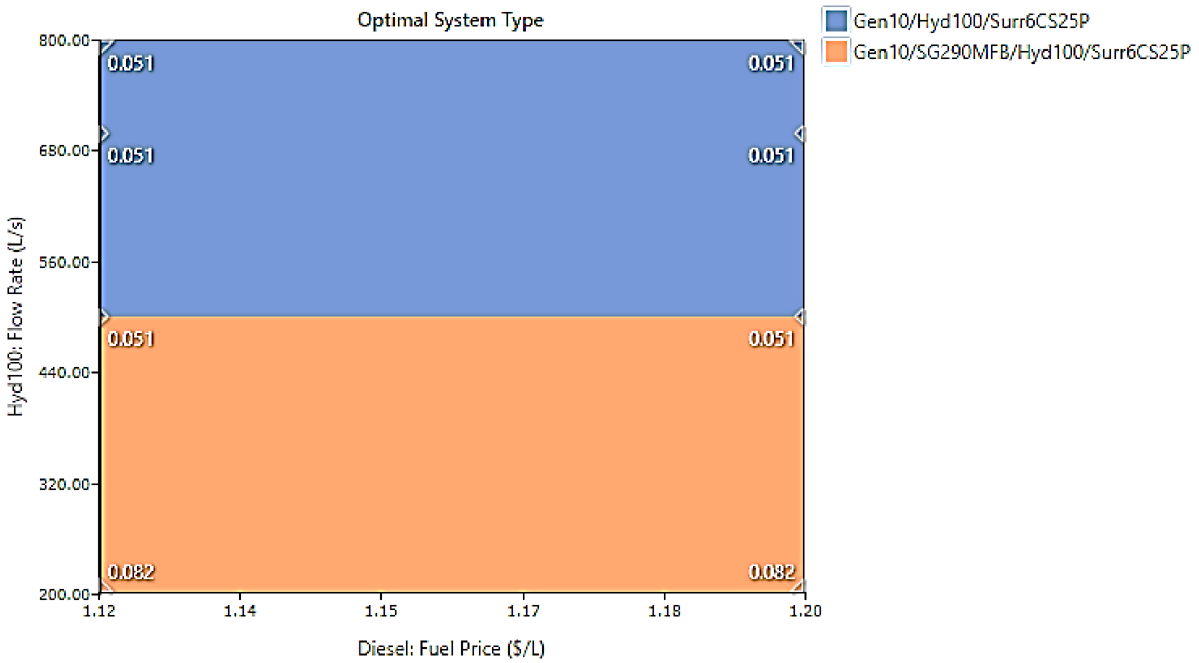


Figure 27: Sensitivity of stream flow and diesel price superimposed with the cost of energy (LCOE)

From the graph it can also be seen even the diesel prices are changing the LCOE relatively remains the same at 8.2 cent per kilowatt when flow rate is 200, but just doubling the flow rate we see that LCOE is 5.1 cent per kilowatt.

Chapter 5: Conclusion and Recommendation

5 Introduction

This study main objective was to assess the techno-economic feasibility of a PV-micro hydro standalone hybrid renewable energy system for rural electrification. What has been accomplished in this work is firstly the determination of solar and micro hydro energy potentials of the study area located in Mtambanyama community. Hydro flow rate showed huge variations in intensity at times, thus making it less reliable as a continuous source of energy for power generation. A well-designed power generation system combining both solar and hydro energy can be more consistent and economical.

5.1 Conclusion

From the results, the hydro energy potential of Nsuwazi River is considerably lower. However it can be concluded that, generally speaking, although the potential may not be sufficient for a large, independent system hydro system, the analysis has shown that hydro energy from the river is viable option if intergrated with other energy systems such as PV, wind and diesel generator and batteries. Regarding solar energy potential of Mtambanyama area, the findings were that the area demonstrated the availability of extensive utilisable solar energy.

Based on the renewable energy potential of the study area, a feasibility study for a standalone electric power supply system for a model community of 400 households in a village was modelled. Finally Off-grid having a combination of (PV/Micro-Hydro/Battery) hybrid system was found to be technically and economically feasible. The developed system is composed of 60.1% of hydro power and 39.1% is from solar photovoltaic technology. From economic point of view, the levelised cost of energy from the simulated project which is cost competitive with 0.0845$/kWh, this is less than the current grid price of Malawi 0.099$/kWh (MERA 2018). From the environmental point of view, the project renewable energy fraction of the project is 100% which implies all the energy is obtained from renewable energy resources. This project will promote clean and contribute to the reduction of pollutant emission released to the environment.

Thus the government, non-governmental organizations and private sectors should make combined efforts to improve the quality of life of the communities living in rural areas. This present proposal can bring about improvement in the standard of living and increase in the economic activities among the rural dweller in the location where the hybrid system is situated, as the excess electricity generated from such hybrid system can serve to supply dump loads (water pumping and street lighting, etc.). Finally, the results of the findings from the sensitivity analysis carried out, as well as information gained from the entire study can be applied in the design, execution, or development of HRES for any applications in other locations in the country having similar geographical coordinate as the site considered in this study.

Studies of this nature be transferred and implemented also in other parts of the country, to determine the feasibility for implementation of hybrid projects using renewables elsewhere in Malawi; and the Mtambanyama project should be implemented in a pilot phase, so that later on it can be replicated to other regions of the country that yet have not been covered by the national grid authority EDM; Future socio-economic analysis must be made to evaluate the possibility so that the rural communities should pay the regular EDM electricity tariff (0.1 USD/kWh) and the remaining production cost (LCOE) inferred by renewable energy generation should be subsidized by the Government.

5.2 Recommendations

The following recommendations are made out of this research; some of them are directed to other researchers while the others are directed to decision makers. Based on these findings, the following recommendations are proposed:

Malawi has a huge potential of renewable energy resources, which can be used for the rural electrification through min off gird system. There are, however many challenges like low purchasing capacity of the rural community, unfavourable conditions towards utilisation of renewable energies, absence of awareness how to use these resources. Thus the government, non-governmental organisations and private sectors should make combined efforts to improve the low rate of electrification in Malawi.

The Implementation for this hybrid system in the village can serve as a pilot system for the whole country. This will build for more research, study and analysis. As far as the environmental aspects are concerned, this kind of hybrid energy system has to be wide spread in order to cover the energy demands of rural communities, and in that support Malawian government Green Economic Police as well way to help reduce the greenhouse gases emission and the deforestation of the environment in general.

The study had limitations in analyzing recent river discharge data because of its unavailability at department of irrigation and water development. Awareness campaigns should be conducted to sensitize authorities on the importance of this data so that proper funding should be channeled towards capturing of this data. The study recommends both solar radiation and river flow rate data measurement be taken regularly for all the potential sites in the whole country.

The study done is on one randomly selected village of Mtambanyama in Thyolo district and it does not cover all around Thyolo district. Future researchers should extend such a research work in other potential sites and make the rural people beneficial with renewable energy resource. Another study should be done to assess the willingness to pay for the power by the community before the project is implemented.

In spite of the huge hydroelectric potential of Malawi, sever power cuts in recent years have a heavy impact on the country's economy. Standalone small hydro and standalone PV/micro hydro hybrid system recommended to be built in for the future application to crate sustainable energy supply of the country.

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Appendix 1: Expenditure report

A. DESCRIPTION OF FUNDED ACTIVITIES

1. A total of 100 questionnaires were prepared and printed for the load survey
2. Four copies of the dissertation were printed and presented for the thesis defence. The thesis document contained 88 pages. A total of 352 pages were printed.
3. The unit cost for the printing is also shown inside the table.
4. Three currencies were used as some expenses were made while still in Algeria,
5. The receipts and invoices for various purchases are attached at the end of the document.
6. The N/A represents the money which was budgeted but not incurred during the course of the master thesis.

Expenditure report					
EXPENSES	**Unit cost**	**Quantity**	**MT Budget**	**Granted**	**Actual Expenses**
Itemize all expenses for MT and internship			*What was budgeted($)*	*Money spend in Kwacha and dinars*	*Actual/ expenses in dollars*
Resource & load demand survey					
Production of questionnaires	K330	100	$75.00	K33,500.00	$45.58
Software data analysis tool					
Flow rate, Biomass, Wind data	3	N/A	$150.00	N/A	N/A
HOMER Monthly subscription	$185	5 Months	$750.00	$925.00	$925.00
GPS hiring/ hydro equipment	$30	2 days	N/A	$30.00	$30.00
Travel and logistics					
1. flight to Malawi for internship and research	$1200.00	Return ticket	$1400.00	127,820.00	$1183.51
2. Transport Algiers to Tlemcen	DZ4,750.00	Return ticket	N/A	DZ9,500.00	$88.00
3. Taxi hiring to and fro	K25,000	8 days	$250.00	K200,000.00	$272.10
4. Fuel for preliminary visit @ hydro site.	K65,000.00	2 days	N/A	K65,000.00	$88.00
Documentation and consumables					
Internet	K50,000.00	2	$200.00	K100,000.00	$136.05
Binding and Printing	K15,000.00	4	$50.00	K60,000.00	$81.63
GRAND TOTAL – ALL EXPENSES					$2850.00
	Amount of grant funds that remain unspent				$ 0.00

Appendix 2: questionnaire for the households and trading centre

QUESTIONNAIRE NO.		Date :	
Name of location : Mtambanyama			
Name of Institution: household		Name of interviewer:	
NO	QUESTIONS AND INSTRUCTIONS	**RESPONSE**	**CD**
1.	Who is the head of the household?	Male headed household	1
		Female headed household	2
		Child headed household	3
		Elderly headed household	4
2.	What do you do for your living?	Small scale farming	1
		Large scale farming	2
		Business	3
		Employed	4
		Other (specify):	5
3.	What is your average household income (estimate per day or month or year)		
4.	How many people live in this house?	One to three	1
		Four to six	2
		More than six	3
5.	How many rooms does the house have?		
6.	Tick the electrical appliances you have/If not, state the aappliances you need	Radio	1
		TV	2
		Refrigerator	3
		phone	4
		Other (specify	5
7.	Please specify what is used for the following applications, i.e.:		
	1. Lighting		
	2. Water pumping		
	3. Refrigeration		
	4. Radios		
	5. Cello phone charging		

	6. Ventilation and fans	
	7. Other applications	

8.	Please specify the times in a day the following appliances are used?			
	Type	Number	Usage time(hour, min)	When during the day are they used?
	Lamps			
	Radio			
	DVD			
	Computer			
	Refrigerator			
	Iron			
	Water pump			

8.	Have you at any time been looking at the possibilities for using alternative energy sources, such as solar thermal for hot water production, solar PV for lighting or other alternatives? Please specify.		

Appendix 3: questionnaire for the school and health centre

QUESTIONNAIRE NO.		Date :	
Name of location : Mtambanyama			
Name of institution: School		Name of interviewer:	
NO	**QUESTIONS AND INSTRUCTIONS**	**RESPONSE**	**CD**
1.	What's the total number of students		
2.	What's the total number of girls		
3.	What's the total number of boys?		
4.	What's the total number of staff?		
5.	Opening hours? Evenings?		
6.	How old is the building?		
7.	How many classrooms does the school have?		
8.	How many lamps needed in each?		
9.	Is the school closed during the weekend and holidays?		
10.	Tick the electrical appliances you have.	Radio	1
		TV	2

		Refrigerator	3
		phone	4
		Other (specify	5
11.	If not, state the appliances you need and When do you expect to have them?		
12.	Do the staff stay in during the holidays		
13.	Please specify what is used for the following applications, i.e.:		
	1. Lighting		
	2. Water pumping		
	3. Refrigeration		
	4. Radios		
	5. Cello phone charging		
	6. Ventilation and fans		
	7. Air conditioning(if any)		
	8. Other applications		

9.	Please specify the times in a day the following appliances are used?			
	Type	Number (quantity)	Usage time(hour, min)	When during the day are they used?
	Lamps			
	Radio			
	DVD			
	Computer			
	Refrigerator			
	Electric kettle			

14.	Hot water in the kitchen?		
15.	Is there any hot water production? If yes please specify how it is heated and how it is distributed?		

16.	Have you at any time been looking at the possibilities for using alternative energy sources, such as solar thermal for hot water production, solar PV for lighting or other alternatives? Please specify.		

QUESTIONNAIRE NO.		Date :	
Name of location : Mtambanyama			
Name of institution: Health centre		Name of interviewer:	
NO	**QUESTIONS AND INSTRUCTIONS**	**RESPONSE**	**CD**
1.	Type of hospital		
2.	What's the total number of beds		
3.	What is the total number of staff?		
4.	Does the staff lives within the hospital campus? If yes, state how many		
5.	Opening hours? Evenings?		
6.	How old is the building?		
7.	How many rooms or wards does the school have?		
8.	How many lamps needed in each?		
9.	Is the school closed during the weekend and holidays?		
10.	Tick the electrical appliances you have/ state the appliances you plan to have?	Radio	1
		TV	2
		Refrigerator	3
		phone	4
		Other (specify	5
11.	Please specify what is used for the following applications, i.e.:		
	10. Lighting		
	11. Water pumping		
	12. Refrigeration		
	13. Radios		
	14. Cello phone charging		

	15. Ventilation and fans		
	16. Air conditioning(if any)		
	17. Other applications		

9.	Please specify the times in a day the following appliances are used?			
	Type	Number	Usage time(hour, min)	When during the day are they used?
	Lamps			
	Radio			
	DVD			
	Computer			
	Refrigerator			
	Iron			
	Water pump			
	Phone charging			
	Television			
	Sterilization equipment			
	Other hospital equipment			
	Other appliances			

12.	Have you at any time been looking at the possibilities for using alternative energy sources, such as solar thermal for hot water production, solar PV for lighting or other alternatives? Please specify		
13.	Is there any hot water production? If yes please specify how it is heated and how it is distributed?		
14.	Any hot water in the staff houses?		

Appendix 4: Bartlett's Table for determining sample size for educational research

Population size	Sample size					
	Continuous data (margin of error = .03)			Categorical data (margin of error = .05)		
	alpha=.10 t=1.65	alpha=.05 t=1.96	alpha=.01 t=2.58	p=.50 t=1.65	p=.50 t=1.96	p=.50 t=2.58
100	46	55	68	74	80	87
200	59	75	102	116	132	154
300	65	85	123	143	169	207
400	69	92	137	162	196	250
500	72	96	147	176	218	286
600	73	100	155	187	235	316
700	75	102	161	196	249	341
800	76	104	166	203	260	363
900	76	105	170	209	270	382
1,000	77	106	173	213	278	399
1,500	79	110	183	230	306	461
2,000	83	112	189	239	323	499
4,000	83	119	198	254	351	570
6,000	83	119	209	259	362	598
8,000	83	119	209	262	367	613
10,000	83	119	209	264	370	623

Appendix 5: Electrical needs for Mtambanyama health centre

Energy Need	Location	Quantity	Power Rating	Operating Times
lighting	1 ward	4	20	08:00-17:00
	1 office	3	20	08:00-17:00
	reception	1	20	08:00-17:00
	laboratory	2	20	08:00-17:00
	corridors	3	20	08:00-17:00
	outdoor light	4	100	18:00-06:00
Radio	reception	1	80	08:00-17:00
refrigeration	drug/vaccine refrigerator	2	225	00:00-00:00
equipment	microscopes	2	25	08:00-12:00 13:00-17:00
	Blood chemical analyser	2	88	08:00-12:00 13:00-17:00
	Examination lamp (AFC)		60	08:00-12:00 13:00-17:00
	radio communication	1	5	00:00-00:00
	Outlet for Phone charging	4	6	00:00-00:00

Appendix 6: Calculated electricity demand for health centre

Hour of the day	Lighting	Cooking	Refrigeration	Radio/TV	Total Power (Kw)
00:00-01:00	0.4	0	0.45	0	0.85
01:00-02:00	0.4	0	0.45	0	0.85
02:00-03:00	0.4	0	0.45	0	0.85
03:00-04:00	0.4	0	0.45	0	0.85
04:00-05:00	0.4	0	0.45	0	0.85
05:00-06:00	0.4	0	0.45	0	0.85
06:00-07:00	0	0	0.45	0	0.45
07:00-08:00	0	0	0.45	0	0.45
08:00-09:00	0.182	0	0.45	0.255	0.887
09:00-10:00	0.182	0	0.45	0.255	0.887
10:00-11:00	0.182	0	0.45	0.255	0.887
11:00-12:00	0.182	0	0.45	0.255	0.887
12:00-13:00	0.182	0	0.45	0	0.632
13:00-14:00	0.182	0	0.45	0.255	0.887
14:00-15:00	0.182	0	0.45	0.255	0.887
15:00-16:00	0.182	0	0.45	0.255	0.887
16:00-17:00	0.182	0	0.45	0.255	0.887
17:00-18:00	0.4	0	0.45	0	0.85
18:00-19:00	0.4	0	0.45	0	0.85
19:00-20:00	0.4	0	0.45	0	0.85
20:00-21:00	0.4	0	0.45	0	0.85
21:00-22:00	0.4	0	0.45	0	0.85
22:00-23:00	0.4	0	0.45	0	0.85
23:00-00:00	0.4	0	0.45	0	0.85

Appendix 7: Electrical needs for Mtambanyama Primary school

Energy need	Service item	number of service item	Quantity	Assumed power rating of appliance	Total number of hours	Operating times

	offices	3	2	20	12	6:00-18:00
	administration	1	2	20	12	6:00-18:00
	Library	1	3	20	8	08:00-12:00 13:00-17:00
	staff room	1	4	20	12	18:00-20:00
	security/outdoor	33	2	100	12	18:00-6:00
	store rooms	1	2	20	N/A	N/A
Lighting	classrooms	20	3	20	12	18:00-20:00
Phone charging	staff room	45	4	10	12	7:30-5:00
TV	staff room	1	1	200	12	6:00-18:00
Satellite decoder	staff room		1	100	12	6:00-18:00
Computer	offices	3	1	200	8	7:30-17:00
Printer	administration	1	1	185	4	N/A
Refrigeration	staff room	1	1	250	24	00:00-00:00
cooking	Kitchen	1	1	1100	2	08:00-09:00 12:00-13:00
electric jug	Kitchen	1	1	1400	1	09:00-10:00

Appendix 8: Calculated electricity demand for Mtambanyama Primary school

Hour of the day	Lighting	Cooking	Refrigeration	Computer, TV/radio (kW)	Total power (kW)
00:00-01:00	6.6	0	0.25	0	6.85
01:00-02:00	6.6	0	0.25	0	6.85
02:00-03:00	6.6	0	0.25	0	6.85
03:00-04:00	6.6	0	0.25	0	6.85
04:00-05:00	6.6	0	0.25	0	6.85
05:00-06:00	6.6	0	0.25	0	6.85
06:00-07:00	0	0	0.25	0	0.25
07:00-08:00	0	0	0.25	1.54	1.79
08:00-09:00	0	1.1	0.25	1.54	2.89
09:00-10:00	0	1.4	0.25	1.54	3.19
10:00-11:00	0	0	0.25	1.54	1.79
11:00-12:00	0	1.1	0.25	1.54	2.89
12:00-13:00	0	0	0.25	1.54	1.79
13:00-14:00	0	0	0.25	1.54	1.79
14:00-15:00	0	0	0.25	1.54	1.79
15:00-16:00	0	0	0.25	1.54	1.79
16:00-17:00	0	0	0.25	1.54	1.79
17:00-18:00	7.48	0	0.25	1.54	9.27
18:00-19:00	7.48	0	0.25	1.54	9.27
19:00-20:00	6.6	0	0.25	0	6.85
20:00-21:00	6.6	0	0.25	0	6.85
21:00-22:00	6.6	0	0.25	0	6.85
22:00-23:00	6.6	0	0.25	0	6.85
23:00-00:00	6.6	0	0.25	0	6.85

Appendix 9: Electrical needs for Mtambanyama Trading centre

	Load	Service Item	Number Of Service Item	Quantity	Power Rating	Operating Times
Commercial	Lighting	Grocery	20	1 Room	15	18:00-21:00

				1 Security	100	18:00-06:00
		Local Small Bar	2	4 Room	15	18:00-21:00
				1 Security	100	18:00-06:00
		Female Salon	2	1 Room	15	08:00-12:00 13:00-17:00
				1 Security	100	18:00-06:00
		Barber Shop	2	1 Room	20	09:00-21:00
				1 Security	20	18:00-06:00
Public	Lighting	Church	1	8 Rooms And Hall	20	N/A
				3 Security	100	18:00-06:00
		Mosque	1	8 Room And Hall	20	N/A
				2 Security	100	18:00-06:00
		Police Unit	1	10 Room And Hall	20	18:00-06:00
				2 Security	100	18:00-06:00
	Refrigeration	Local Small Bar	2	2 Room	225	00:00-00:00
		Police Unit	1	1 Room And Hall	225	18:00-06:00
Commercial	Radio	Grocery	20	1 Radio	50	06:00-21:00
		Local Small Bar	2	1 Radio	100	10:00-22:00
				1 TV	200	10:00-22:00
		Female Salon	2	1 Radio	50	08:00-17:00
		Barber Shop	2	1 Radio	50	09:00-21:00
		Police Unit	1	1 Radio	100	8:00-05:00

Appendix 10: Calculated electricity demand for trading centre

Hour of the day	**Lighting**	**Refrigeration**	**TV/radio (kW)**	**Total power (kW)**
00:00-01:00	2.94	1.125	0	4.065
01:00-02:00				4.065
02:00-03:00	2.94	1.125	0	4.065
03:00-04:00	2.94	1.125	0	4.065
04:00-05:00	2.94	1.125	0	4.065
05:00-06:00	2.44	1.125	0	3.565
06:00-07:00	0	1.125	1	2.125
07:00-08:00	0	1.125	1	2.125
08:00-09:00	0	1.125	1.2	2.325

09:00-10:00	0	1.125	1.3	2.425
10:00-11:00	0	1.125	1.9	3.025
11:00-12:00	0	1.125	1.9	3.025
12:00-13:00	0	1.125	1.9	3.025
13:00-14:00	0	1.125	1.9	3.025
14:00-15:00	0	1.125	1.9	3.025
15:00-16:00	0	1.125	1.9	3.025
16:00-17:00	0	1.125	1.9	3.025
17:00-18:00	0	1.125	1.7	2.825
18:00-19:00	3.4	1.125	1.7	6.225
19:00-20:00	3.4	1.125	0.3	4.825
20:00-21:00	3.4	1.125	1.7	6.225
21:00-22:00	3.4	1.125	0.7	5.225
22:00-23:00	2.94	1.125	0	4.065
23:00-00:00	2.94	1.125	0	4.065

Appendix 11: Electrical needs for Mtambanyama Households

Energy need	Service item	Quantity	Total number of houses	Total quantity	Assumed power rating of appliance	Operating times
lighting	Rooms	4	400	1600	15	18:00-21:00
	security lights	2	400	800	100	18:00-06:00
	Living room	1	400	400	15	6:00-18:00
	Living room	1	400	400	15	6:00-18:00
radio	Living room	1	400	400	50	6:30-22:00
TV	Living room	1	80	80	50	6:30-22:00
cello-charging	N/A	2	80	160	50	22:00-05:00
refrigerator	Living room	1	24	24	275	00:00-00:00
hot Plate		1	30	30	1100	06;00-07:00 18:00-19:00
electric kettle	Kitchen	3	80	240	1400	06:00-07:00

Appendix ten: Calculated electricity demand for Households

Hour of the day	Lighting	cooking	Refrigeration	TV/radio (kW)	Total power (kW)
00:00-01:00	80	0	6.6	0	86.6
01:00-02:00	80	0	6.6	0	86.6
02:00-03:00	80	0	6.6	0	86.6
03:00-04:00	80	0	6.6	0	86.6
04:00-05:00	80	0	6.6	0	86.6
05:00-06:00	80	0	6.6	0	86.6
06:00-07:00	0	33	6.6	20	59.6
07:00-08:00	0	0	6.6	20	26.6
08:00-09:00	0	0	6.6	20	26.6
09:00-10:00	0	0	6.6	20	26.6
10:00-11:00	0	0	6.6	20	26.6
11:00-12:00	0	33	6.6	20	59.6
12:00-13:00	0	33	6.6	20	59.6
13:00-14:00	0	0	6.6	20	26.6
14:00-15:00	0	0	6.6	20	26.6
15:00-16:00	0	0	6.6	20	26.6
16:00-17:00	0	0	6.6	20	26.6
17:00-18:00	0	0	6.6	20	26.6
18:00-19:00	104	33	6.6	20	163.6
19:00-20:00	78	33	6.6	20	137.6
20:00-21:00	78	0	6.6	20	104.6

21:00-22:00	80	0	6.6	20	106.6
22:00-23:00	80	0	6.6	0	86.6

Appendix 12: CDSS

Energy need	Service item	number of service item	Quantity	Assumed power rating	Total number of hours	Operating times
Lighting	Offices	2	2	20	12	6:00-18:00
	Administration	1	2	20	12	6:00-18:00
	Library	1	3	20	8	08:00-12:00 13:00-17:00
	Staff Room	1	4	20	12	18:00-20:00
	Security/Outdoor	7	2	100	12	18:00-6:00
	Store Rooms	1	2	20	N/A	N/A
	Classrooms	4	3	20	12	18:00-20:00
Phone charging	Staff Room	20	4	10	12	7:30-17:00
TV	Staff Room	1	1	200	12	7:30-17:00
Satellite decoder	Staff Room		1	100	12	7:30-17:00
Computer	Offices	3	1	200	8	7:30-17:00
Printer	Administration	1	1	185	4	7:30-17:00
Refrigeration	Staff Room	1	1	250	24	00:00-00:00
electric jug	Kitchen	1	1	1400	1	09:00-10:00

Appendix 13: Calculated electricity demand for CDSS

Hour of the day	Lighting	Refrigeration	TV/radio (kW)	hot water((electric jug)	Total power (kW)
00:00-01:00	1.4	0.25	0	0	1.65
01:00-02:00	1.4	0.25	0	0	1.65
02:00-03:00	1.4	0.25	0	0	1.65
03:00-04:00	1.4	0.25	0	0	1.65
04:00-05:00	1.4	0.25	0	0	1.65
05:00-06:00	1.4	0.25	0	0	1.65
06:00-07:00	0.2	0.25	0	0	0.45
07:00-08:00	0.2	0.25	1.785	0	2.235
08:00-09:00	0.26	0.25	1.785	0	2.295
09:00-10:00	0.26	0.25	1.785	1.4	3.695
10:00-11:00	0.26	0.25	1.785	0	2.295

11:00-12:00	0.26	0.25	1.785	0	2.295
12:00-13:00	0.26	0.25	1.785	0	2.295
13:00-14:00	0.26	0.25	1.785	0	2.295
14:00-15:00	0.26	0.25	1.785	0	2.295
15:00-16:00	0.26	0.25	1.785	0	2.295
16:00-17:00	0.26	0.25	1.785	0	2.295
17:00-18:00	0.26	0.25	0	0	0.51
18:00-19:00	1.4	0.25	0	0	1.65
19:00-20:00	1.4	0.25	0	0	1.65
20:00-21:00	1.4	0.25	0	0	1.65
21:00-22:00	1.4	0.25	0	0	1.65
22:00-23:00	1.4	0.25	0	0	1.65
23:00-00:00	1.4	0.25	0	0	1.65