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Submitted by

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Design of Stand-Alone Solar-Wind-hydro based Hybrid Power System: Case of rural village in Malawi.

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

Prof Zaki Sari (Supervisor). Signature**:** ____________________________

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Dedication

This thesis is dedicated to my parents for their support and encouragement.

Abstract

Malawi has current electrification rate of less than 10% for a population of 18 million connected to the grid. The electricity generation company in Malawi (EGENCO) is greatly affected by low water levels making it difficult to satisfy the existing demand of electricity. This makes it difficult for Malawi to extend its National electricity grid. Thus, the aim of the study is to design stand-alone hybrid renewable energy system which is economically and technically feasible with focus on hydropower, wind, solar and battery bank within Dwangwa area. The study area is estimated to have 420 households, commercial and public service load with primary load demand of 5,556.31 kWh/day and peak load of 302.93 kW. River discharge data were collected from ministry of irrigation and water development while solar and wind data were collected from NASA. HOMER modeling tool was used to design a stand-alone system. From simulation results, the best design flow for Dwangwa river is 159 L/s at elevation of 100 metres and the best hybrid system combination was hydropower-wind-solar-battery and converter. The whole hybrid system initial capital cost was $2,662,638 while Net present cost (NPC) and levelized cost of energy (LCOE) were $3,597,197 and $0.134/kWh respectively. However, the cost of electricity in Malawi on the grid is K88.02/kWh ($0.11/kWh) which makes the system expensive. Therefore, the study has shown that the hybrid system is not economically viable. However, Government intervention can help to make the system monetarily acceptable and viable.

Keywords: Design, stand-alone, Solar, wind, hydropower, battery, converter, load, HOMER, simulation, hybrid, elevation, NPC, LCOE, grid,

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Nomenclature

$	United States Dollar.
$/MWh	Dollar per megawatt-hour
$\dot{m}$	mass flow rate.
A	rotor swept area.
AC	Alternating Current.
Ah	Ampere-hour.
AM	Air Mass.
C_p	power coefficient
COE	Cost of Energy.
DC	Dirrect Current.
EoT	Equation of Time.
ESCOM	Electricity Supply Corporation of Malawi.
FF	Fill factor.
g	gravitational acceleration.
G10	Generic 10kW wind turbine.
GHI	Global horizontal irradiation.
GMT	Greenwhich Mean Time.
H_{eff}	effective head.
HRA	Hour angle.
HRES	hybrid renewable energy system
hrs/yr	Hours per year.
Hyd10	Generic 10kW hydropower turbine.
I_{sc}	Short circuit current.
K	Boltzmann's constant.
kW	Kilo-Watt.
kWh	Kilo-Watt-hour.
kWh	Kilo-watt-hour.
kWh/year	Kilo-Watt-hour per year.

L/s	Litres per second.
LST	Local Solar Time.
LT	Local time.
m/s	metres per second.
MERA	Malawi Energy Regulatory Authourity.
MJ	Mega-joule.
MPPT	Maximum power point tracking.
η	Efficiency.
NASA	National Aeronautics and Space Administration (United States of America
NPC	Net Present Cost.
O&M	Operation and maintenance.
PV	Photovoltaic.
q	Electronic charge.
TV	Television.
Voc	Open circuit voltage.
V-I	Volttage-Current
W	Watt.
WHO	World Health Organisation.
α	empirical wind shear exponent.
δ	Declination
λ	Tip speed ratio.
ρ	Density
ρ_w	Density of water
φ	Latitude
Φ	Azimuth angle.
W/m^2	Watt per square metre

1. Chapter One: Introduction

1.1.Background and motivation

Electricity in Malawi is largely dominated by hydroelectric power which is mainly located in the Shire river. Since they mainly depend on one river which is facing a lot of climatic conditions then the country is also facing a lot of power outages due to water levels. Currently, less than 10% of the population of 18 million is connected to the electricity grid (The International Trade Administration, 2019). 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, candles and paraffin. For cooking, most of the 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, Bobby, & 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.

Therefore, this proposed hybrid system is aimed at sizing a hybrid renewable energy system (HRES) to design a system that minimises the necessary cost as much as possible to ensure its affordability for rural electrification.

1.2.Review of Related Works

The road map for Africa encourages rural electrification because Africa is home to the largest unelectrified population in the world, with about 600 million people lacking access, expected to reach 700 million by 2030. Off-grid solutions, including mini-grids and stand-alone solutions, are necessary to complement centralised grid (Irena - International Renewable Energy Agency, 2014). Remote communities are commonly assessed based on the existent physical infrastructure. Thus, remote communities are those communities that are not connected to the electrical grid, not connected to the piped natural gas network, considered permanent or long-term settlements (e.g., 5 years or more), and have at least 10 inhabitants (Contreras Cordero, 2015).

Electricity demand is increasing and cannot be fulfilled by non-renewable energy sources alone. Renewable energy sources such as micro hydro, solar and wind are environmental friendly. Currently, renewable energy sources are emerging options to fulfill the energy demand, but unreliable due to the stochastic nature of their occurrence. Hybrid renewable energy system (HRES) combines two or more renewable energy sources like small hydro, wind turbine and solar system (Khare, Nema, & Baredar, 2016). Technological advancements in renewables and increasing prices of petroleum products has made hybrid renewable energy systems more promising for remote areas (Abdelaziz, Eltamaly, & Ali, 2018).

Rural areas are usually difficult to access and it is therefore important to design a renewable energy system that is reliable and requires little maintenance. The main challenge with one energy source such as solar photovoltaics is during the night and when there is no sun. This also applies to wind turbine technology which does not generate electricity when there is no wind. Therefore, if more than one independent source is employed for energy generation, for example a combination PV panels and wind turbines, the energy demand generation can be split between these two sources and therefore the system depends less on one intermittent energy source. This improves energy supply security (Coppez, 2011).

Many studies have shown that different combinations of renewable systems are possible and are economically viable. Since most common hybrid systems are associated with two systems then combining all the three systems (wind, hydro and solar) the output is expected to be much greater than the two stage hybrid systems (Agarkar & Barve, 2011).

1.3.Research gap

The hybrid systems installed in Malawi are currently solar and wind which were installed in six different locations (Gobede, 2011). However, very little has been done on solar, wind and hydroelectric hybrid system. HOMER as an optimization tool for this study, has indicated different results from different studies because the results depend on location, load demands and its applications as well as different climatic data. Every hybrid power system has to be designed in a different way for the site based on specific conditions of the location such as climatic data, number of households, service centers and consumer load profiles.

This thesis intends to employ the same software to design and optimize the off grid hybrid power system for rural electrification. Solar, wind and hydroelectric hybrid systems have not yet been implemented and very limited studies of this type of system has been conducted in Malawi and Africa at large. Therefore, this thesis differs from the rest of the studies in terms of load demand, application, climatic data and location.

1.4.Research questions and the working hypothesis

Research question

- What are the available renewable energy resources potential in selected area in Malawi?
- What is the electricity load or power consumption of the selected area?
- What is the optimal combination of solar PV, wind and micro hydro hybrid renewable energy system to meet the energy demand?
- What are the economic (cost of energy $/MWh), social (impact on life of people), environmental (green gas house emissions reductions) and technical feasibility of installation of a hybrid PV, wind and hydro energy system in a rural community of Malawi?

Working Hypothesis

It is economically, socially, environmentally and technically feasible to install a hybrid renewable energy system for rural electrification in Malawi.

1.5.Methodology

1.5.1. Site identification

In the first phase we start by identifying a rural village in Malawi specifically in Dwangwa area. The main factor to consider is availability of wind and hydropower potentials. Otherwise solar potential is available across the country.

1.5.2. Collection and literature survey

The data for the study will be sourced from the following sources:

- ✓ Collection of flow rate, gross head for compensation flow, elevations for the plant design from the Government department
- ✓ Site visiting for understanding the topography for small hydropower, PV and wind energy electro-mechanical equipment installation places
- ✓ Site visiting for understanding the resettling village location and the under study population situations.
- ✓ Collection of wind and solar data from NASA and department of meteorological services.

1.5.3. Input data for the site load

The load profile for the site will be plotted using the actual activities of the community. Load estimate is a very important factor to consider for the sizing of the hybrid system. The possibility of investment for the proposed project for rural area is determined by the load size. This implies that the possible detailed load estimate is required in consideration for the effects of the multipurpose use of the power. In order to avoid the unforeseen load of the area, allowance load will be added making the community present load far lower than what it has been estimated.

The electrical load of rural villages in Malawi can be assumed to be composed of lighting, radio, TV set, water pumps, health center, primary school, and flour mill. The proposed project will also take in account pumps for small-scaled irrigation and restaurant. Since most people in rural areas use biomass for cooking, there is deforestation which has negative impact on the environment. Thus, cooking electrical load will be considered in the load estimate to prevent careless cutting down of trees.

The other loads that will be considered here are public service loads, pumps for portable water supply and small scaled-irrigation and some other commercial services. But the load of the school and clinic laboratories and workshops are estimated in lump sum.

Data Analysis and Feasibility Study

The flow rate and head of the river data collected from the site and data from NASA about the wind speed and solar radiation for the site will be used for analysis. The optimization and sensitivity analysis for the hybrid system under study will be carried out using HOMER software based on the data provided for each energy resource and financial costs. HOMER simulation provides graphical results that help identify market opportunities and barriers for each technology. Thus, HOMER indicate the energy cost or NPC for the hybrid models in a particular region. The two-dimensional sensitivity analysis will be carried out with the two sensitive variables, PV cost and Wind turbine cost, to get a better optimized system. It also helps determine how different conventional, renewables and hybrid systems interact with end users. Furthermore, data for wind and solar are collected from different sources.

1.6.Possible obstacles

Rural electrification has other challenges other than technical challenges. This means that when developing a project for electricity solution in rural area other factors must be taken into account. These factors may include social factors, for instance, the adoption and acceptance the designed electricity for the community; economic factors, for instance, the financial status of people determines the repayment of the system or membership fees to be collected from community members.

Another limitation to the implementation of rural electrification project is to consider the growth of the community once the electricity has been installed. This growth as well as growth in industry and functions of the community will increase the load to be supplied to the community. Therefore, all these factors are important for rural electrification, however more research should be done. A surplus of 5% is added onto all load data received for designing the system to ensure that there is room for growth of the community, but no further areas of growth have been included or accounted for.

1.7.Relevance of the study

Wind turbine and solar PV has been considered in most rural electrification research publications and projects. Since hydroelectricity alone is also considered a mature technology for electricity generation. Thus, the combination of the three sources will make it more reliable with vast rural applications. Therefore, the scope of this thesis is to optimise the size of a hybrid renewable energy system (HRES) to be used in a rural area using hydroelectricity turbine, solar PV panels and wind turbines.

1.8.Chapter outline

The first part of the thesis will begin with an Abstract. This will be followed by Introduction, Background and Statement of the Problem. The Situation of the Study Area and The Proposed Site will be discussed. The first part will be finished with aim and objective of the Project, proposed methodology and related works.

Chapter one will cover introduction and background of the thesis. This consist of some review of Related Work, research gap, Research questions and the working hypothesis.

Chapter two will cover literature review. The first part will discuss about in detail solar energy. Solar energy will be discussed in the following dimensions; solar photovoltaic power potential, solar energy and radiation, solar PV power system, solar photovoltaic cell technology, electrical characteristics and system components. then we will also discuss solar energy, solar energy potential, PV Application in Malawi. The second part will consist of wind power potential where power extraction principle from Wind and wind speed distribution will be discussed. Furthermore, types and blade Aerodynamics will be discussed. Turbine components, power output and power control mechanisms will also be discussed. Finally, wind potential and application in Malawi will be discussed. The third part will begin by discussing the hydropower potential, main hydropower components, principles of hydropower plants and classification of hydropower plants. Furthermore, types and selecting of hydraulic turbines, hydropower potential and application in Malawi will also be discussed.

Chapter three will comprise of load estimation for proposed site through load estimation for residential, pumps, public services and commercial applications. Chapter four will consist of hybrid system optimization methodology and HOMER for the optimization methodology will be discussed while chapter five will comprise of simulation results and discussion. Finally, Chapter six will be comprised of conclusions, recommendation and suggestion for Future Work. The rest of the thesis will contain bibliography and appendices.

2. Chapter Two: Literature review

2.1. Solar energy

2.1.1. The solar resource

Sun behaves perfectly as a blackbody and it is the source of the solar radiation that reaches the Earth. Earth's surface is called photosphere which has temperature of about 6000 K (Jager, Isabella, Smets, H., M., & Zeman, 2014). According to Ingebrigtsen (2017), satellite measurement of solar radiation at the top of the Earth's atmosphere is $1366 \pm 7\ W/\mathrm{m}^2$. This value slightly changes due to solar activity, however, it is relatively constant. On the other hand, the radiation that reaches the Earth's surface is influenced by many factors.

The atmospheric effects such as absorption and scattering reduces the amount of radiation received on the Earth's surface. Local variations in the atmosphere also affect the received radiation. This include water vapour, clouds and gases in the atmosphere (pollution). Finally, latitude of the location and yearly season and also time of the day influence on the amount of the solar radiation on the Earth's surface. These variations affects the overall power received, the spectral content of light and the angle from which light is incident on the surface (Honsberg & Bowden, 2015). The angle from which light is incident on the surface determines the path length through which the radiation travels in the atmosphere. The position of the Earth in relation to the sun in the sky influences the path length and is known as air mass (AM) (M. Sengupta et al., 2017). Solar radiation is attenuated as it travels through atmosphere of the Earth. Thus, to determine solar irradiance under clear sky conditions, the distance that the sunlight travels is considered. This distance is shortest when the sun is at the zenith (perpendicular to the point) (Jager et al., 2014).

Mathematically, optical air mass is the ratio of an actual path length of the sunlight to the minimal distance. When the sun is at its zenith, the optical air mass is unity and the spectrum is called the air mass 1 (AM1) spectrum. When the Sun is at an angle with zenith, the air mass is given by:

$$AM = \frac{Y}{X} = \frac{1}{Cos\ \theta}$$

Where X, Y and θ are shown in Figure 1. The angle between X and Y is called zenith angle (Honsberg & Bowden, 2015).

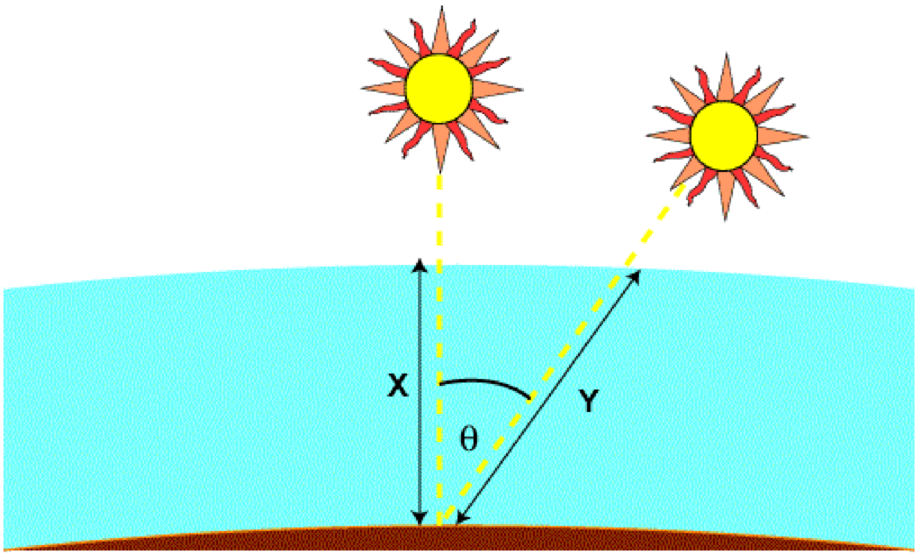


Figure 1: Determining AM. (Honsberg & Bowden, 2015)

The presence of particles in the atmosphere, such as clouds, results in scattering and absorption of the portion of the incident radiation. The extent of scattering and absorption depends on the physical properties of the molecules and particles in the atmosphere. Hence, the longer the path through the atmosphere, the more scattering occurs (M. Sengupta et al., 2017). Topography simply means earth's surface appearance, height and surface features. This contribute to surface Albedo effects and hence affect solar radiation energy potential for a specific location. For instance, surface albedo value for a calm sea surface is 2%, pine forest is 6%, green grass is 8%, clayey desert is 29% while Snow is 85%. In general, forests and wet surfaces have low values as compared to snow covered surfaces and deserts have high albedo values (Sen, 2008).

Radiation is classified into two: direct and diffuse. Direct radiation is defined as radiation that reaches the surface without being scattered or absorbed, while diffuse radiation is the one with no specific direction. Additionally, reflected light is considered as a third component of the solar radiation (M. Sengupta et al., 2017).

2.1.2. Calculating the solar path

The Earth revolves around the sun and there are geometric relationships between the sun and Earth. This affects the amount and intensity of solar radiation reaching the Earth's surface (Sen, 2008).

Figure 2 shows the geometric relationship of the Earth with respect to the Sun and its effects for different seasons in both hemispheres.

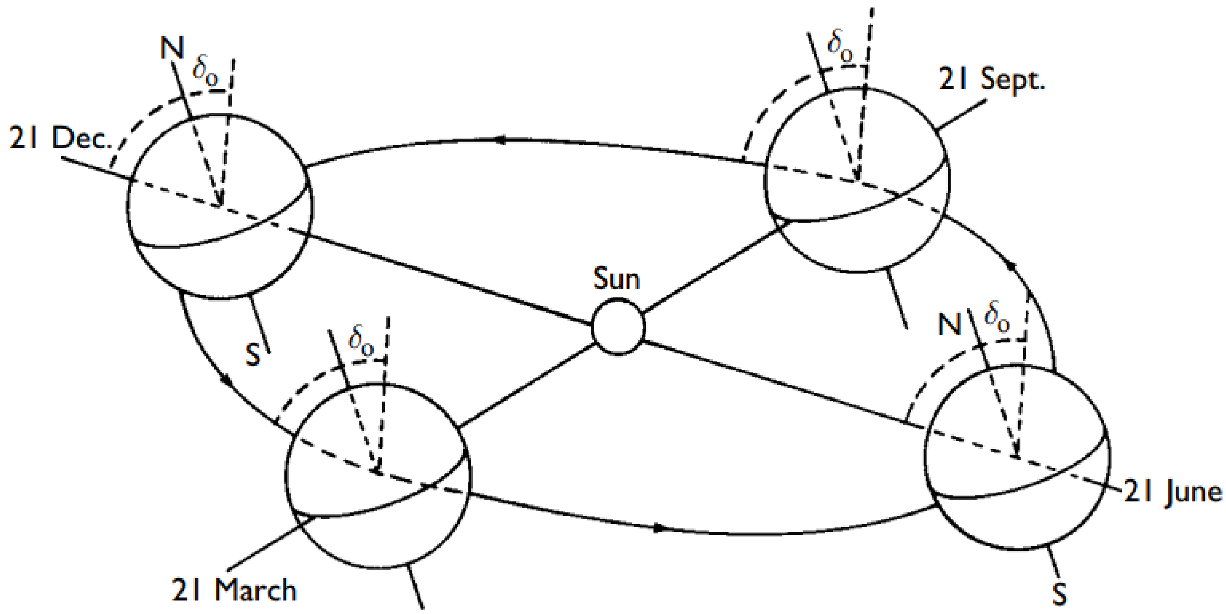


Figure 2: The Earth revolving around the Sun, as viewed from a point obliquely above the orbital (Twidell & Weir, 2006)

The Earth orbits the Sun once per year and the direction of its axis remains fixed in space with the angle of $\delta_0 = 23.45^o$ away from the normal to the plane of revolution. The angle between the Sun's direction and the equatorial plane is called the **declination $\boldsymbol{\delta}$**, relating to seasonal changes. Thus, this variability has the largest effect in a longer time interval (hours or days) and in particular during sunrise and sunset (Twidell & Weir, 2006).

The declination $\boldsymbol{\delta}$ varies smoothly from $+\delta_0 = +23.45^o$ at the midsummer in the northern hemisphere, to $-\delta_0 = -23.45^o$ at northern midwinter. Mathematically,

$$\delta = \delta_0 \sin\left[\frac{360^{\circ}(284 + n)}{365}\right]$$

Where n is the day in the year (n = 1 on 1 January). The leap year error is not considered in practice (Sen, 2008).

Another important parameter to consider in solar energy production is variation in the length of the day. The equation below shows the number of hours, N, between sunrise and sunset given the latitude, ϕ, and declination, δ.

$$N = \frac{2}{15} cos^{-1}(-\tan\phi \tan\delta)$$

According to Ingebrigtsen (2017), the two parameters that are important in describing solar path are elevation angle α (The angle between the incident sunlight and the horizontal) and Azimuth angle Φ (The angle horizontal direction from which the sunlight is coming.

Twelve noon local solar time (LST) is when the sun is highest in the sky while local time (LT) is usually different from LST. This is because of eccentricity of the Earth's orbit and human adjustments such as time zones and daylight savings. Thus, LST can be adjusted as follows in hours (Honsberg & Bowden, 2015),

$$LST = LT + \frac{1}{15}\lambda_{long} - \Delta T_{GMT} + EoT$$

Where λ_{long} is the longitude, $\Delta T_{GMT}$is the difference between the Local Time (LT) and the Greenwhich Mean Time (GMT) in hours while EoT is the Equation of Time which is the empirical equation which takes into account the eccentricity of the Earth. Thus, the approximation to within ½ minute is:

$$EoT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

Where

$$B = \frac{360}{365}(d)(-81)$$

Where B is in degrees and d is the number of days since the start of the year (Honsberg & Bowden, 2015).

The calculated LST can be converted from hours to the number of degrees the Sun moves by the following equation:

$$HRA = 15^{o}(LST - 12)$$

Where HRA is the hour angle and it is zero at solar noon and ranges from -180^o to 180^o. Thus, the sun moves 15^o each hour. Therefore, the elevation of the angle is then calculated as follows:

$$\propto = sin^{-1}(\sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(HRA))$$

Where ϕ is the latitude of a particular location and δ is the declination angle. The declination angle which is the tilt of the Earth varies from -23.45^o in December solstice to $+23.45^o$ in June solstice and to -23.45^o in December solstice again. The declination angle is zero in March and September which is twice a year.

According to Honsberg and Bowden (2015), Azimuth angle Φ is calculated using the following equation:

$$\Phi = cos^{-1}\left(\frac{\sin(\delta)\cos(\phi) - \cos(\delta)\sin(\phi)\cos(HRA)}{\cos(\alpha)}\right)$$

Where ϕ is the latitude and azimuth angle of 0^o represents north. The above equation only gives the correct azimuth in the solar morning so that:

$Azimuth = Azi$, for LST <12 or HRA < 0

$Azimuth = 360^o - Azi$, for LST > 12 or HRA > 0

2.1.3. Structure of a photovoltaic (PV) cell

Photovoltaic cells are manufactured from semiconductors, thus, materials that conduct when supplied with energy (photon) they get excited to a higher energy level in the atoms of the material. A semiconductor can be p-doped or n-doped which are then combined to form a p-n junction hence the same method used in the formation of solar cell. Electrons are majority charge carriers in an n-doped material and the holes are minority charge carrier and vice versa in a p-doped material. In a p-n junction, an electric field exists from the n-side to the p-side hence a drift current of electrons to the n-side and holes to the p-side (Jager et al., 2014). Near the junction of those two layers, the electron moves into the electron-hole from n-type layer thereby creating a depletion zone so that the electrons fill the holes. Figure 3 is the schematic representation of a solar cell, showing the n-type and p-type layers, with a close-up view of the depletion zone around the junction between the n-type and p-type layers.

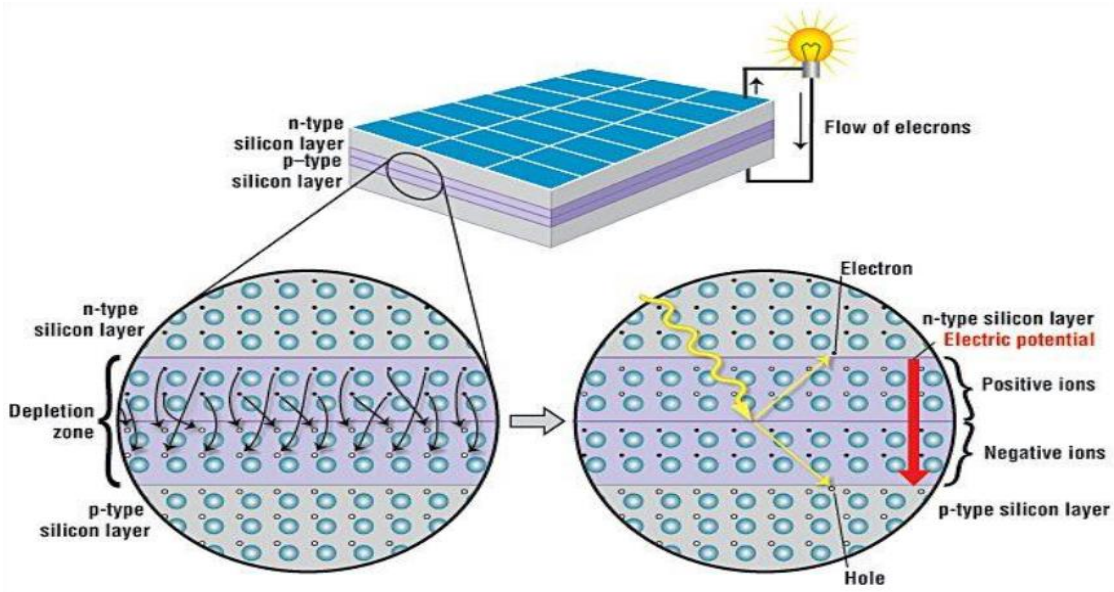


Figure 3: Schematic representation of a solar cell, showing the n-type and p-type layers. (American Chemical Society, 2014)

The process of photovoltaic conversion of solar energy is done in solar cells and it is done in two steps. The first step involves absorption of sunlight by solar cells which result in generation of an electron-hole pair. These electrons and holes are then separated by the structure of the solar cell thereby the electrons to the negative terminal and the holes to the positive terminal (Rao & Shrivastava, 2016). When light photons strike on a solar cell, photons that possess energy higher than the band gap of the semiconductor material such as silicon gives an opportunity to excite the electron to the higher energy level to generate electricity (Jager et al., 2014).

American Chemical Society, (2014) explained that when the sunlight strikes a solar cell, electrons are ejected and travel from the n-type layer to the p-type layer by crossing the depletion zone and then travel through the external wire back of the n-type layer hence creating a flow of electricity. The antireflective layers between the metal grid lines helps to reduce reflection of light hence more absorption.

2.1.4. Efficiency and power of PV cells

A single diode model of solar cell has a current source which represents a light-generated current in parallel with a diode. The photon current is directly proportional to the solar radiations. Figure

4 shows solar cell model when the light is not illuminated, a dark current is flown into the circuit similar to the diode.

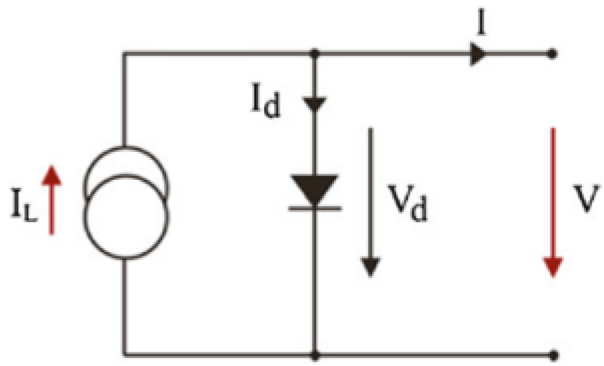


Figure 4: Single diode model of photovoltaic. (Kumar, Richhariya, & Sharma, 2015)

The equation for a single diode model of solar photovoltaic is given as (Kumar, Richhariya, & Sharma, 2015):

$$I = I_L - I_R\left[e^{(qV/mkT)} - 1\right]$$

Where

I is the cell output current,

I_L is the light-generated current or photocurrent,

I_R is the reverse bias saturation current of diode,

q is the electron charge,

V is the terminal voltage,

m is the diode ideality factor,

k is the Boltzmann's constant ($1.38 \times 10^{-23} J/°K$), and

T is the cell temperature

Short-circuit current, I_{sc} and open-circuit voltage, V_{oc} are the important characteristics of a photovoltaic cell. At the constant junction temperature, when the terminal of solar cell is short-circuited, the short-circuit current, I_{sc} is given as follows:

For V = 0, $I_{sc} = I = I_L$

At the constant junction temperature, when the terminal of the solar cell is open-circuited, the open-circuit voltage V_{oc} is given as follows:

For I = 0, $V = V_{oc}$

This implies that the cell output power is given by:

$$P = V\left[I_{sc} - I_R e^{(qV/mkT)} - 1\right]$$

The following are important definitions related to the modeling of solar cell.

a) Open circuit voltage (V_{oc})

This is maximum voltage available from a solar cell which occurs when current is zero. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The curve in figure 5 shows open-circuit voltage.

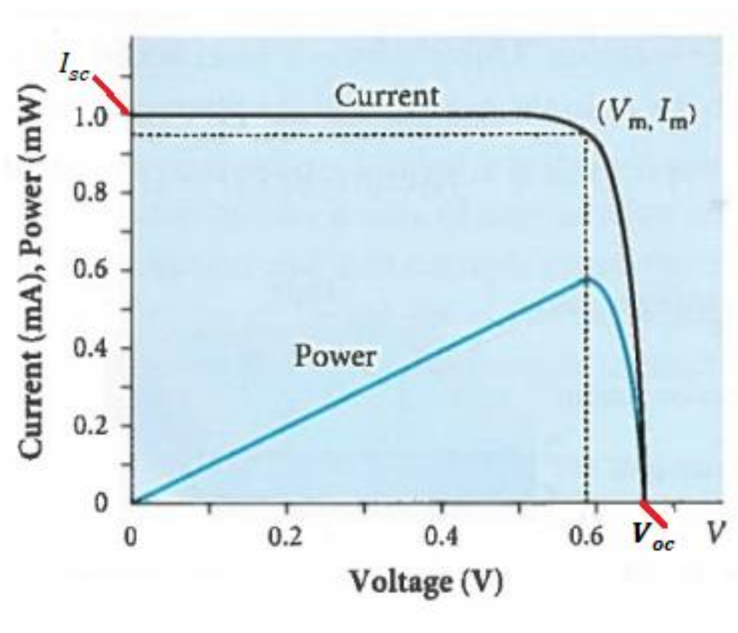


Figure 5: I-V curve of a solar cell showing the open-circuit voltage. (Honsberg & Bowden, 2015)

The open-circuit voltage decreases with increase in temperature and depends on the solar irradiance. The open-circuit voltage can be expressed by the equation (Kumar et al., 2015):

$$V_{oc} = V_T ln\left[\left(\frac{I_{sc}}{I_o}\right) + 1\right]$$

b) Short-circuit current (I_{sc})

Short-circuit current is calculated at short-circuiting terminals of the solar cell. It increases slightly with increasing temperature and is directly proportional to the incident optical power. Under the short-circuit condition of the solar cell, the voltage across the terminal is zero and the impedance offered is very low. The short-circuit current can be expressed as follows (Kumar et al., 2015):

$$I_{sc} = I + I_o[exp(V/V_T)] - 1$$

c) Fill factor (FF)

The fill factor is the ratio between the maximum actual power (maximum value of voltage, V_m and current, I_m) generated by the solar cell and the product of open-circuit voltage and short-circuit current (Jager et al., 2014; Kumar et al., 2015).

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}$$

d) The maximum power

The maximum power is defined as power that can be delivered by the modules/ array to the load. This can also be used to determine the performance of a PV system. The maximum power can be obtained from fill factor, open-circuit voltage and short-circuit current (Kumar et al., 2015).

e) Efficiency (ɳ)

Efficiency is defined as the ratio of electrical power that the solar cell delivers to the load to the optical power incident on it. The incident optical power is normally specified as the solar power on the surface of the Earth which is $1\, mW/mm^2$. The efficiency equation can be written as (Kumar et al., 2015):

$$ɳ = \frac{FFV_{oc}I_{sc}}{solar\ power}$$

2.1.5. Effects of temperature on solar cell output

The operation of solar cell depends on temperature as shown in figure 6 where there is effect on voltage versus current characteristic. Increase in temperature result increase is short-circuit current while open-circuit voltage decreases hence decrease in the maximum power output of the solar as well as efficiency (Luta, 2014).

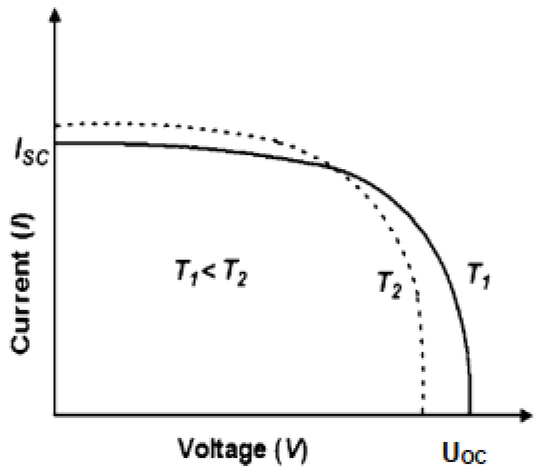


Figure 6: Effect of temperature in I-V solar cell curve. (Luta, 2014)

2.1.6. Photovoltaic systems

Modules and arrays

A solar PV module is formed by connecting several single PV cells. A typical solar cell produces less than 3 watts at approximately 0.5 volts d.c. thus, to obtain enough power and voltage rating for high power applications, solar cells are connected in series and parallel configurations (Honsberg & Bowden, 2015). The solar cells are enclosed in different materials that act to protect the cells and electrical connections between them from the rough outdoor environment. Figure 7 shows connection of single solar cells to form a module and connection of a single module to form aa array. The module output can be ranging from a few watts to hundreds where as an array output power can range from hundreds of watts to Megawatts (Luta, 2014).

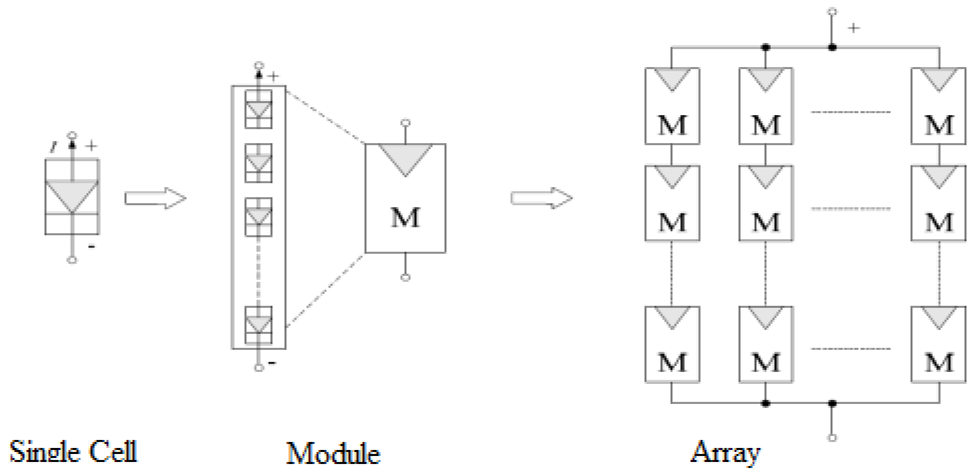


Figure 7: Solar cell, module and array. (Luta, 2014)

Howell (2014) stated that for a grid-connected systems a module typical consist of 60 to 72 cells. In order to increase voltage in a module or array, cells or identical modules are connected in series while current remains constant. On the other hand, to increase current in a module or array, cells or identical modules are connected in parallel while voltage remains constant. Thus, a combination of series and parallel arrays or modules are built to meet the required power (Howell, 2014).

Mismatch and shading

Mismatch losses are due to interconnection of solar cells or modules which do not have identical properties or which experience different conditions from one another. This is a serious problem in PV modules and arrays because the PV module output under worst case conditions may be determined by the solar cell with the lowest output. For example, when one solar cell is shaded while the remainder in the module are not shaded then the power generated by the unshaded solar cells can be dissipated by the lower performance cell rather than delivering to the load. This may damage the entire module due to highly localized power dissipation and the resultant local heating (Honsberg & Bowden, 2019). Some of the well-known causes of large mismatches are differences in either the short-circuit current or open-circuit voltage. The impact of the mismatch depends on both the circuit configuration and on the type of mismatch (Ingebrigtsen, 2017).

2.1.7. Methods for increasing the efficiency of PV cells and modules

Maximum power point tracking (MPPT)

Solar modules are moved throughout the day in order to track the movement of the sun hence increased direct solar radiation received and absorbed by the solar cells. The tracking system can either be vertical single-axis, where movement is possible in the east-west direction, horizontal single-axis, where the tilt of the modules can change or two axis, where variation of both the east-west direction and tilt is possible (Finan, 2013).

Several methods of tracking the maximum power point (MPP) exist, these include: constant voltage, open and short circuit method, perturb and observe method, incremental conductance algorithm, fuzzy logic and artificial neutral networks (Morales, 2010).

The constant voltage is the method that uses the voltage of MPP and sets this as the voltage reference for the output of the PV system. A voltage regulator is then used to keep the output voltage as close to MPP voltage as possible hence the system operates close to the MPP. The open and short circuit method uses PV curves provided by the manufacturers to determine MPP current and voltage and then find the characteristics for the PV module. The voltage and current can be monitored and adjusted in the simulations to ensure MPP voltage at that point. Perturb and observe (P&O) MPPT method uses trial and error in the controller in order to adjust the reference output power of the inverter up fractionally and monitors the output power of the system. Increase in power makes the controller adjust the reference output fractionally upwards and again monitor the output. This will continue thereby maintaining the MPP (Jager et al., 2014).

Incremental conductance uses the principle that when the derivative of the PV output power divided by the derivative of the output voltage approaches zero then the maximum output power is achieved. The controller finds the output power and voltage and then voltage is adjusted slowly until the derivatives approach zero (Malki, 2011).

Bifacial modules

Conventional photovoltaics panels are monofacial which are defined as panels through which their electrical power output is from the direct and diffuse radiation captured on the front side of the module only. In comparison with bifacial modules, they utilize light captured on both the front and back sides of the modules into electrical power. This method of capturing radiation from both sides improves PV system energy capture (Brearley, 2017).

The radiation received by the back surface originates from diffusive and reflective components of the solar radiation. The reflective radiation can either be reflected from the ground or from objects in near the modules. The albedo (whiteness) of the surface determines the amount of radiation reflected from the ground. This could be light-coloured stone, reflective paint, foil or even grass. However, the uptake of the bifacial technology has been inhibited by the difficulty in predicting performance with a level of certainty. In 2015, bifacial modules contributed 5% market share and in the effort to increase the share, test facilities are in operation around the world particularly in Japan and New Mexico (Hackbarth, 2019).

2.1.8. Solar energy in Malawi

2.1.8.1. Solar resource in Malawi

Solar energy is in abundant supply in Malawi which can be one of the possible solution for the electricity problem. Again, solar can easily be deployed to rural areas hence reduced cost as compared to grid extension. Malawi has quite high levels of solar energy in the range of $1200\,W/m^2$ and $1900\,W/m^2$ received in most parts of the country. This solar energy is high enough for the development of solar thermal and photovoltaic energy projects. The estimated solar irradiation potential for photovoltaic and solar-thermal applications is at $21.1\,MJ/m^2/day$ (Kaunda, 2013).

According to Taulo et al., (2015), the country receives about 2138 to 3087 hours of sunshine and $2133\,KWh/m^2/year$. The global solar radiation on a horizontal surface has a minimum value of $4.3\,KWh/m^2/day$ and maximum of $7\,KWh/m^2/day$. In Malawi, maximum irradiation of $6.5\ to\ 7.0\,KWh/m^2/day$ are received in September to October whereas the minimum irradiation of $4.3\ to\ 4.6\,KWh/m^2/day$ are received in January to February or June to July depending on the location.

Many parts of Malawi receive 8 to 12 hours of sunshine per day of $244\,W/m^2$ hence the potential for using solar for electricity generation is very high. The total estimated solar energy potential over the total geographical area of $94,280\,km^2$ for Malawi is calculated to be $356{,}284{,}837\,MWh/year$ (Taulo et al., 2015). The figure 8 shows the solar resource map showing areas of higher potential (SOLARGIS, 2018).

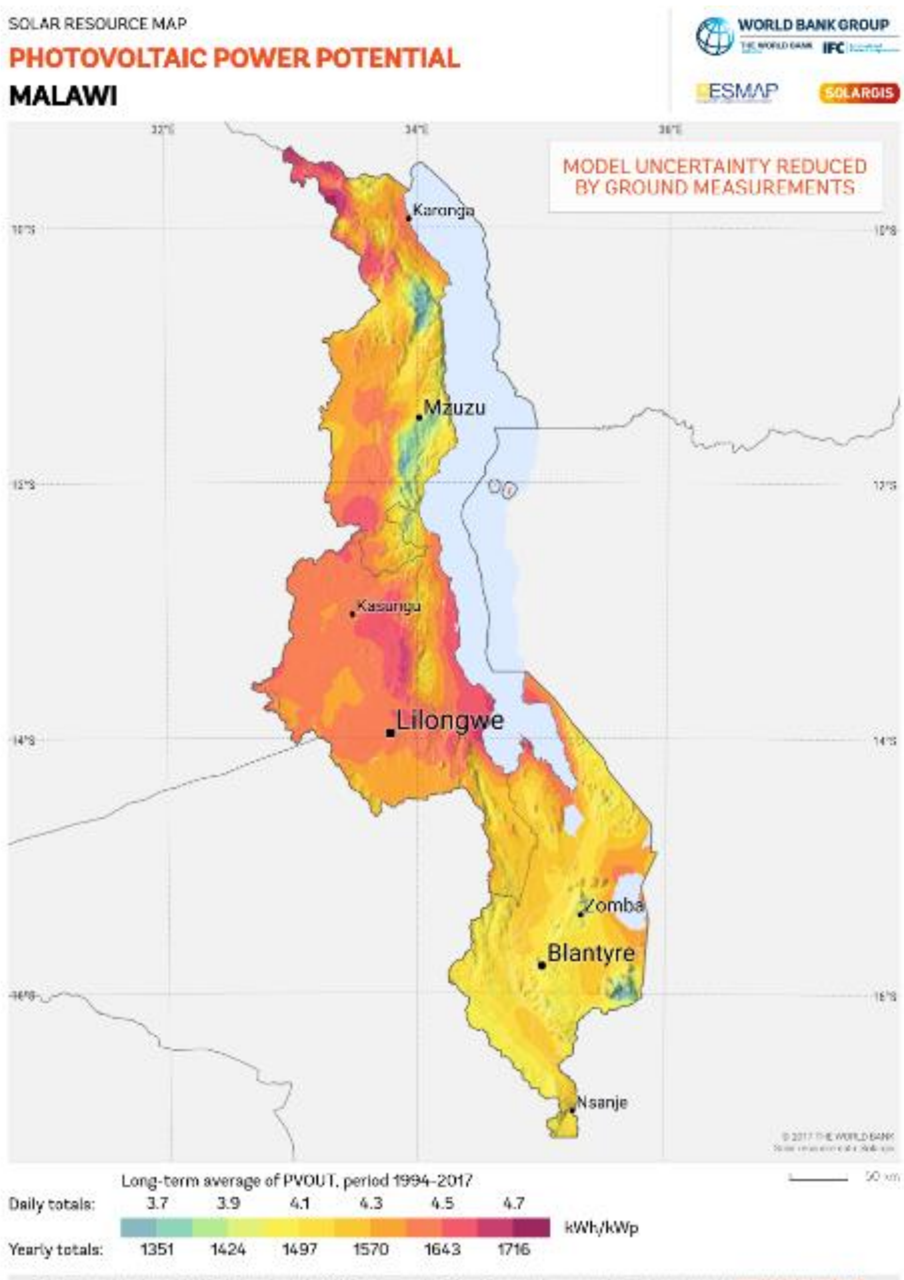


Figure 8: Solar resource map for Malawi (SOLARGIS, 2018).

Solar energy deploying in Malawi is growing in small scales particularly for household application. Solar water heaters have been locally manufactured for domestic purposes. The total amount of installed solar water heaters in the country is estimated to have reached approximately 4, 855 square meters. On the other hand, photovoltaics is also increasing in the day to day application such as lighting, water pumping, telecommunication, refrigeration and other home use application. More recently, 870 kWp solar photovoltaic plant has been commissioned at Lilongwe International Airport which is the biggest solar power plant in Malawi today (Taulo et al., 2015).

2.2. Wind energy

2.2.1. The wind resource

Wind is one of the exploitable forms of renewable energy which is available in most parts of the world. Wind blows from the region of higher atmospheric pressure to one of the lower atmospheric pressure. The difference in pressure is caused by two reasons. The first reason is the fact that the earth's surface is not heated uniformly by the sun and another reason is the earth's rotation (Bhadra et al., 2017).

The earth's equatorial regions receiving more solar energy than the polar regions hence a large-scale convection currents are created in the atmosphere. Meteorologists estimate that about 1% of the incoming radiation is converted to wind energy. The amount of solar radiation received in ten days has enough energy equivalent to the world's entire fossil fuel reserve. This implies that the wind resource is extremely large (Siraj & Maulana, 2016). Another force that is important for the global wind pattern is the centrifugal force. The isobars in the atmosphere are curved and the consequence of this that a parcel moving parallel to the isobars experience a centrifugal force outwards from the curve. The balance between the pressure force, Coriolis force and centrifugal force results in a wind called gradient wind, parallel to the curved isobars (Ingebrigtsen, 2017).

Ingebrigtsen (2017), further explained that the wind patterns on earth's surface vary from location to location due to friction between the earth's surface and the wind itself. The friction force is directed in the opposite direction of the air flow and acts near the surface, diminishing at higher altitudes.

Thus, with the progress in technical and economical aspect of wind energy, it can contribute substantially in global energy share. However, it is important to remember that the topology and landscape along with local temperature changes and other local phenomena will have a considerable effect on this idealized model. This shows that local and short-term wind conditions are difficult to predict hence more detailed assessment are required to quantify the resource in a particular area (Siraj & Maulana, 2016).

Power in the Wind

Wind is defined as air in motion. Since air has mass and it is estimated that the weight of air is a little more than one kilogram per cubic metre, then wind contains kinetic energy. This power can be turned into electric power, heat or mechanical work by wind power plants (WPP) (Joshua & Tore, 2015). Consider a cylinder in space of cross-section A and wind is passing through it at a speed V, then the rate of kinetic energy passing at any section will be (Siraj & Maulana, 2016):

$$Power = \frac{1}{2}\dot{m}\,V^2 = \frac{1}{2}(\rho AV)V^2$$

Where $\dot{m}$ is mass flow rate, ρ is the density of air ($1.225\ kg/m^3$ at sea level). If a wind turbine is placed inside it and part of this power is transferred to this wind turbine then the power output P, from the wind turbine is given by the expression (Siraj & Maulana, 2016):

$$P = \frac{1}{2}C_p\rho AV^3$$

Where C_p is the power coefficient, that is part of kinetic energy from the wind is transferred to turbine, A is the rotor swept area.

2.2.2. Vertical wind speed profile

Generally, for any given location, wind speed increase with height. However, the roughness of the terrain determines how large this increase of wind speed will be with height. For a wind power plant, it is the wind speed at the hub height that is of interest. Therefore, the height of the hub varies for different models and manufacturers (Joshua & Tore, 2015). The figure 9 shows how different roughness of the terrain affect the increase in wind speed (Ingebrigtsen, 2017).

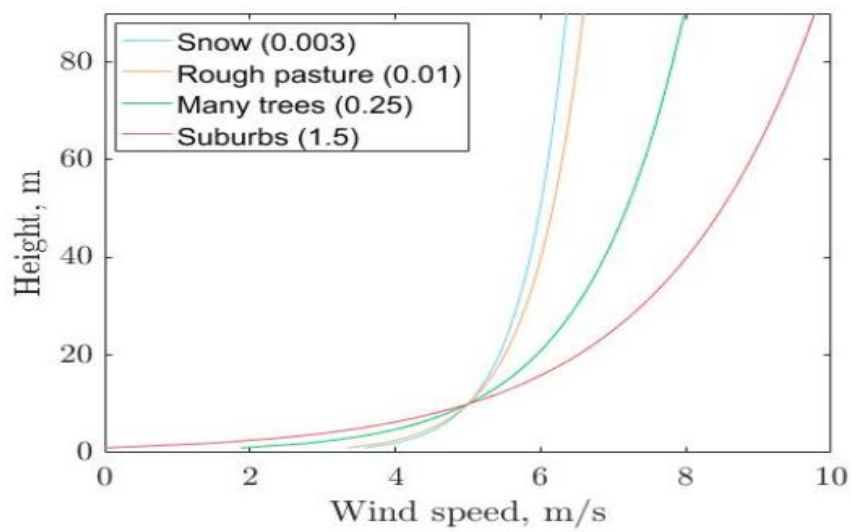


Figure 9: Plot of the logarithmic vertical wind speed profile with different roughness. (Ingebrigtsen, 2017)

Available wind data usually represents a different height than the hub height. Thus, wind speed at the hub can be derived in a number of ways from the theoretical fluid mechanics and empirical research. Assumptions in the derivation is that the pressure is independent of height and the pressure gradient is very small near the surface and that the surface is smooth (Joshua & Tore, 2015).

A ***power law*** for vertical profiles of steady wind is commonly used in wind energy for defining vertical wind profiles. If the heights at which measurements have been performed do not match the hub height of a wind turbine, then it necessary to extrapolate the available wind speeds to the turbine hub height. The basic equation of the wind shear power law is (Siraj & Maulana, 2016):

$$V = V_r \left(\frac{z}{z_r}\right)^{\alpha}$$

Where

V = wind velocity at elevation z

V_r = wind speed at higher elevation z_r

α = empirical wind shear exponent

Log law is another method of extrapolation at a certain height by using the log law. The increase of wind speed with height in the lowest 100m can be described by the logarithmic expression (Manwell, 2003):

$$V \approx V_{ref} \cdot \frac{ln\left(\frac{Z}{Z_o}\right)}{ln\left(\frac{Z_{ref}}{Z_o}\right)}$$

Where

V = velocity to be calculated at height z

Z = height above ground level for velocity V

V_{ref} = known velocity at height z_{ref}

z_{ref} = reference height where V_{ref} is known

z_o = roughness length in the current wind direction.

The characterization of the roughness of the terrain on the ground, called the roughness length for different landscapes are given in the table 1 (Manwell, 2003):

Table 1: Roughness length in the current wind direction according to the European Wind Atlas. (Manwell, 2003)

Roughness Class	**Roughness Length (m)**	**Landscape Type**
0	0.0002	Water surface
0.2	0.0005	Inlet water
0.5	0.0024	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approximately 1250 metres

2	0.1	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approximately 500 metres
2.5	0.2	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approximately 250 metres
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	Larger cities with tall buildings
4	1.6	Very large cities with tall buildings and skyscrapers

2.2.3. Betz limit and power coefficient

The Betz limit is the theoretical maximum efficiency for a wind turbine, estimated by a German physicist Albert Benz in 1919. He found out that the maximum value is 59.3%, meaning that at most only 59.3% of the kinetic energy from wind can be extracted to spin the turbine for electricity generation (Afework, Hanania, Stenhouse, & Donev, 2018). The figure 10 demonstrate the Betz limit (REUK, 2006).

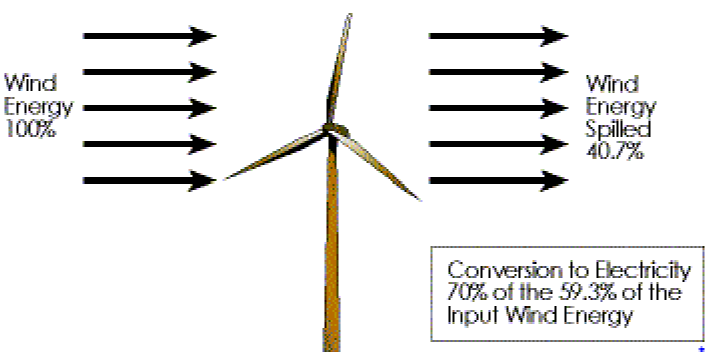


Figure 10: Demonstration of the Betz limit. (REUK, 2006)

Realistically, efficiencies of the wind turbine ranges between 35% and 45%. Since wind turbine extract energy from the wind passing through it, then in order to acquire 100% efficiency of energy extraction then the wind has to be blocked completely. However, this is impossible since if the wind is stopped completely, the air would not move out of the way to the back of the turbine, thereby preventing further air from coming in causing the turbine to stop spinning (Afework et al., 2018).

Power coefficient

Power coefficient represents a fraction of the power in the wind that the rotor can extract. This is usually used to evaluate wind turbine performance for a particular wind turbine. The equation below defines the power coefficient (Manwell, 2003):

$$C_p(\lambda, \alpha) = \frac{P_t}{P_V} = \frac{Power\ of\ the\ wind\ turbine}{Power\ of\ the\ wind}$$

The value of the power coefficient varies with the wind speed, the rotational speed of the wind and the pitch angle of the rotor.

Calculation of Tip Speed Ratio

The tip speed ratio for wind turbines is the ratio of the translational speed at the tip of the turbine blade to the actual velocity of the wind. Tip speed ratio, $\lambda = \text{Tip speed}/wind\ speed$ (Vlab.amrita.edu, 2013).

$$\lambda = \frac{\omega * r}{\mathrm{V}}$$

where

ω is the rotational speed in radians per second,

r is the rotor radius in meters, and

V is the wind speed in meters per second

Figure 11 gives an illustration tip speed ratio against power coefficient (Vlab.amrita.edu, 2013).

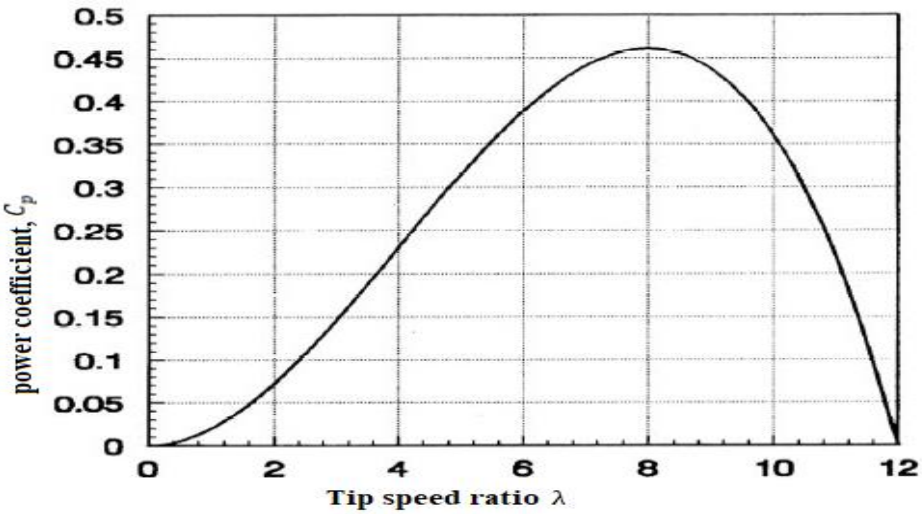


Figure 11:The graph of tip speed ratio against power coefficient. (Vlab.amrita.edu, 2013)

2.2.4. Operating and controlling the wind turbine

The operation of a wind turbine requires certain control systems. For instance, a horizontal-axis wind turbines have to face the wind all the time. When the winds are very high, it is desirable to reduce the drive train loads and protect the generator and the power electronic equipment from overloading, by limiting the turbine power to the rated value up to the furling speed (Bhadra et al., 2017).

Wind turbines have four different types of control mechanics which include: pitch angle control, stall control, power electronic control and yaw control. The pitch angle control is responsible for changing the blades angle in relation to the variation of the wind speed. This is used to increase the power output by ensuring that the turbine operate at the rated speed and protection of the machine during turbulent weather conditions (Bhadra et al., 2017).

For stall control to limit the power output at high winds is applied to constant-pitch turbine driving induction generators connected to the network. The rotor speed is fixed by the network, allowing only 1–4% variation. Increase in wind speed result in increase in the angle of attack for a blade running at a near constant speed. For power electronic control, it incorporates a power electronic interface between the generator and the load or the grid, the electrical power delivered by the generator to the load can be dynamically controlled (Bhadra et al., 2017; Siraj & Maulana, 2016)

For yaw control, it is responsible for orienting the turbine continuously along the direction of wind flow. In small turbine this is achieved with a tail-vane while in large turbines, this is achieved using motorized control system activated either by fan-tail or centralized system for detection of a wind direction. The yaw system is also used for speed control whereby turning the rotor away from high winds hence reducing mechanical power (Bhadra et al., 2017; Siraj & Maulana, 2016).

Control strategy of a wind turbine

According to Bhadra et al. (2017), every wind turbine is designed to operate at different speed control strategies. Thus, there exist five different ranges of wind speed as shown in figure 12:

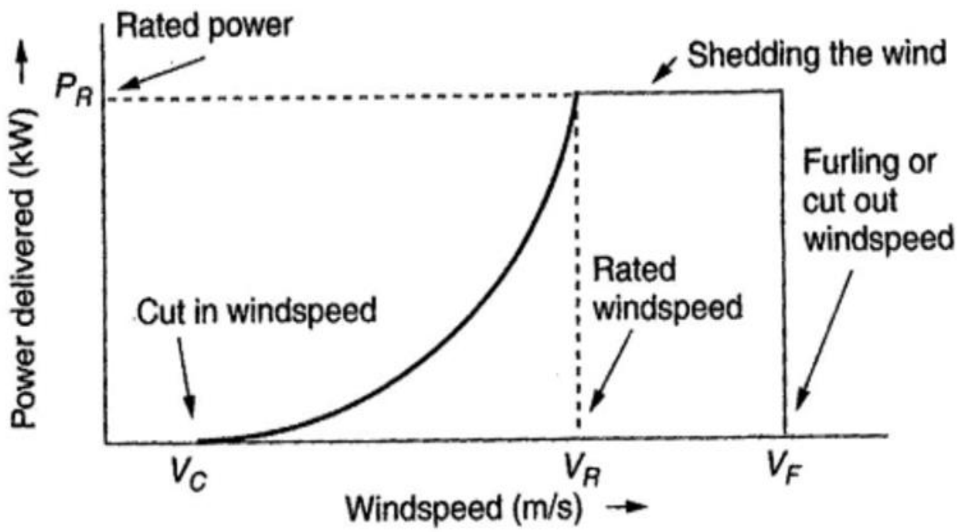


Figure 12: typical power versus wind speed characteristics of variable speed wind turbine

Bhadra et al. (2017) further explained each of the region of the graph with respect to the required control mechanisms:

1. Below a cut-in speed, the machine does not produce power. The rotor may have sufficient starting torque and it may start rotating below this wind speed. However, power is not extracted and the rotor rotates freely. In many modern designs the rotor starts rotating at the cut-in wind speed.
2. At normal wind speed, the machine extract maximum power from the wind. In order to maintain power extracted, the rotational speed has to be changed continuously in proportion to the wind speed.

3. At high wind speeds, the rotor speed is limited to a maximum value depending on the design limit of the mechanical components. In this region, the C_p is lower than the maximum and the power output is not proportional to the cube of the wind speed.
4. At even higher wind speeds, the power output is kept constant at the maximum value allowed by the electrical components.
5. At cut-out of furling wind speed, the power generation is shut down and the rotation stopped to protect the machine from being damaged.

The last three control regimes can be realized with yaw control, pitch angle control (if these are installed) and the eddy-current or mechanical brakes (Siraj & Maulana, 2016).

The mechanical brakes

The mechanical brakes are used in the event of load tripping or accidental disconnection of the electrical load. This is done to prevent the rotor speed increasing dangerously thereby preventing the machine from mechanical destruction of the motor. Sometimes the mechanical brake can be applied when other braking mechanisms have failed to apply. The mechanical brake is also required for stalling the turbines in gusty winds (Bhadra et al., 2017; Siraj & Maulana, 2016).

2.2.5. Wind farm

Wind farm is defined as a concentrated groups of wind turbines that are electrically and commercially tied together (Manwell, McGowan, & Rogers, 2009). The development of wind farm is advantageous since profitable wind resources are limited to distinct geographical areas, multiple turbines increases the total wind energy produced. Again, economically, concentration of repair equipment and spare parts reduces costs. Figure 13 shows a typical example of a wind farm array (Manwell et al., 2009):

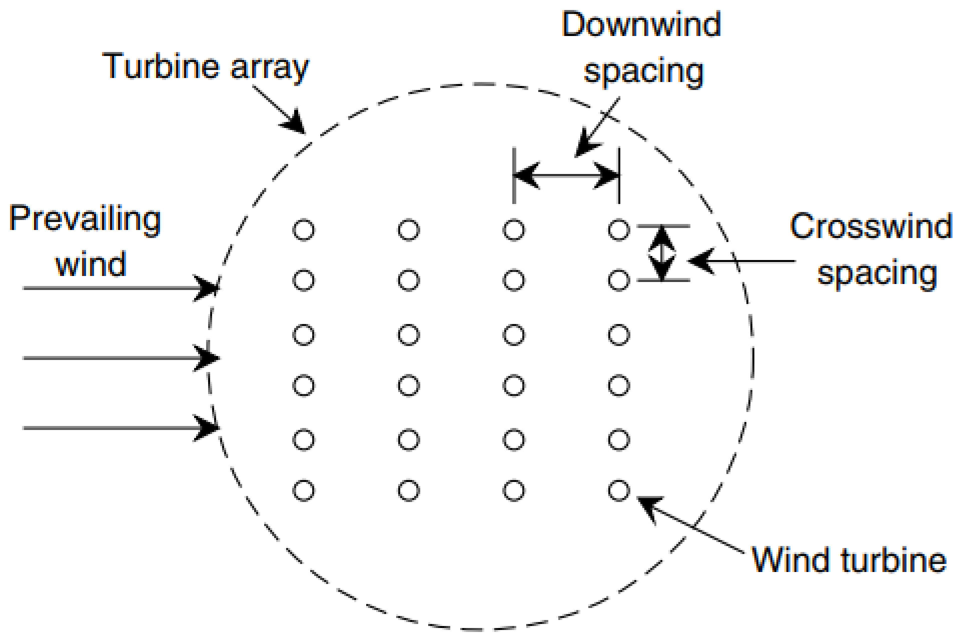


Figure 13: Wind farm array schematic. (Manwell et al., 2009)

However, wind farms have technical issues that arise due to the close spacing of the multiple wind turbines. The most important technical issue is due to wind turbine array spacing. This is commonly brought about by where to locate and how close the space is between wind turbines. This is due to variations in the wind resource across a wind farm as a result of terrain effects. In addition, the extraction of energy by the wind turbines that are upwind of the other turbines resulting in lower wind speeds at the downwind turbines and increased turbulence. Therefore, necessary steps to determine the proper spacing and positioning wind turbines have to be taken into account when developing a wind farm (Joshua & Tore, 2015; Manwell et al., 2009).

2.2.6. Wind energy in Malawi

Malawi has quite a good number of areas with mean speeds above 5 m/s throughout the year (Gamula, Hui, & Peng, 2013). For instance, Malawi's lakeshore areas have good wind speeds that can be utilized for electricity generation and it was estimated that with serious investment the country had the potential to meet its energy demand within 15 years.

Wind energy has been applied on a small scale is Malawi such as to supply water for both livestock and irrigation. Although it seems like the wind speeds are moderate to low, a typically in the range of 2.0 – 7.0 m/s (Taulo et al., 2015). The paper has already stated that wind speeds also increase with height of the hub, then most areas of Malawi have data for wind speeds at lower hub height. For instance, Dedza has some areas of reasonable wind resource of 4 m/s at 18m hub height. Therefore, individual site assessment for each proposed site would be required to determine the actual wind data (Frame, Eales, Dauenhauer, Kambombo, & Kamanga, 2017).

2.3.Hydroelectric power

Water power is produced through the combination of head and flow. For a hydro system, water is diverted from a stream into a pipeline where it is carried downhill and through the turbine. The vertical drop, known as head, creates pressure at the bottom end of the pipeline. Then water with more pressure exiting from the end of the pipe creates the force that drives the turbine. Thus, the more the water flow or larger head, the more power is produced hence head and flow are the most important things for the development of the hydropower plant (New, 2004). Figure 14 illustrate a typical example of hydropower plant.

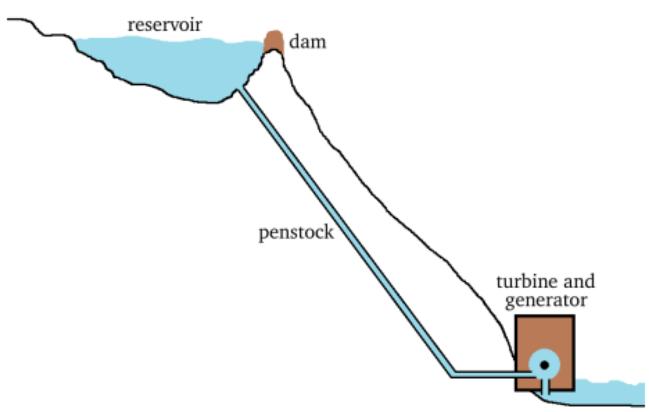


Figure 14: A typical hydropower plant. (Ingebrigtsen, 2017)

2.3.1. Available power of a dam

The theoretical power output available from a water reservoir at height H with volumetric flow rate Q (in m^3/s) out from the reservoir is given by (Ingebrigtsen, 2017):

$$P_{theoretical} = \rho_w g H Q$$

Where

g is the gravitational acceleration ($g \approx 9.81\ m/s^2$)

ρ_w is the density of water ($\rho_w \approx 1000\ kg/m^3$)

This is the power that is available theoretically but some energy will be lost in the penstock due to friction. Some energy will also be lost as the water flows through the turbine due to friction. This can be represented by a loss of head. Then the resultant head is then called the effective head.

2.3.2. Efficiency of hydro power plants

A hydropower plant can be 100% efficient, then the maximum possible power delivered after losses is given by the equation (Ingebrigtsen, 2017):

$$P = \eta_t \rho_w g H_{eff} Q$$

Where

η_t is the efficiency of the turbine

$H_{eff} = H - h_f$ is the effective head

2.3.3. Classification and types of hydropower plants

The type hydropower plant for a particular location depends on the characteristics of that site, it is site specific. However, hydropower plants can be classified according to the following parameters: size or installed capacity, head availability, operation regime and purpose of plant structures.

a. Classification by size

Hydropower plants can be classified with respect to installed capacity. This classification is widely accepted by may vary among countries. The following are the classification by size (New, 2004):

Micro hydropower plants (Below 0.1 MW): This type of plant can supply electricity for an isolated industry or a small remote community. They are usually stand-alone, not connected to the grid and they are always run-off-river type. A small water storage tank maybe constructed so that generation is guaranteed for a minimum of one day (New, 2004).

Small hydropower plants (0.1 MW to 10 MW): These power plants usually utilize low discharge, commonly constructed on run-of-river and commonly connected to the grid. In some countries, small hydropower plant has capacity of 30 MW to 35 MW (New, 2004).

Medium hydropower plant (10 MW to 100 MW): This type of plant can either be of run-of-river or storage type and they are almost always feed into the grid. A dam may be constructed to create a head pond. However, the equipment and materials is similar to that of a large hydropower plant (New, 2004).

Large hydropower plant (Above 100 MW): this type of a plant is always connected to a large grid. Since a hydropower plants is site specific then, large hydropower plant can be run-of-river or storage type (New, 2004).

b. Classification by head size

Hydropower plants have different heads depending on the site of that particular plant. The following are classification based on head size:

1. High head (greater than 100 m)
2. Medium head (30 m to 100 m)
3. Low head (less than 30 m)

Classification of hydropower plants based on the head may be inconsistent with respect to power capacity. Since power capacity is proportional to the product of available flow and head then, even a plant with high head might be classified as micro or small hydropower plant. Usually, mountainous terrain provides conditions necessary to create high head or medium head plant. On the other hand, lowland areas with wide river valleys can be feasible for low head plant and are mostly run-of-river types (New, 2004).

c. Classification by operation

Hydropower plants can also be classified based on the type of operation. The following are classifications by type of operation:

Run-of-river plants*:* This type of plant generate electricity by immediate use of the inflow and they are usually with no storage capacity or limited storage, which limits peak power operation to a few hours. The figure 15 shows a typical example of run-of-river type (New, 2004).

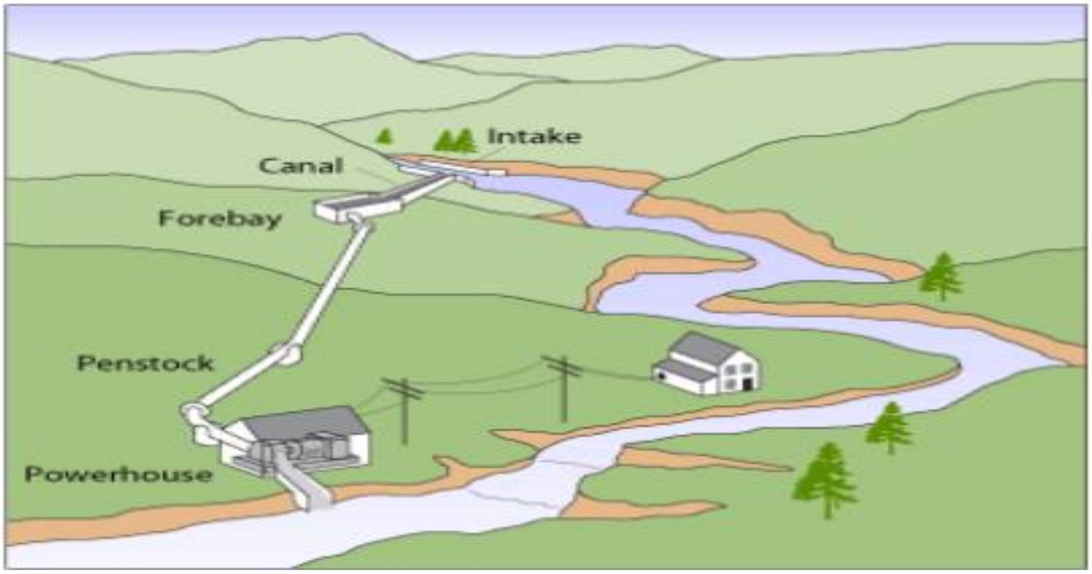


Figure 15: Run-of-the-river Schematic. (Peschka, 2015)

Storage type plant*:* This plant is characterized by water impoundment upstream of a dam structure thereby creating a reservoir in which water is stored during high flow season and used for generation during low-flow season. Figure 16 is the typical example of a storage type plant. This ensures constant generation of electricity regardless of natural fluctuations in water availability due to weather and seasonal variations (New, 2004).

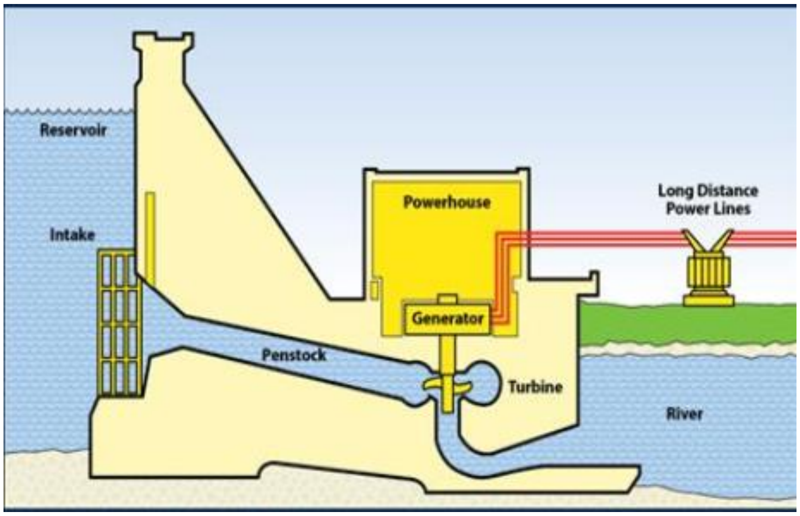


Figure 16: Schematic of a Hydroelectric Dam. (The Colorado Energy Office, 2013)

Pumped storage plants*:* These are plants that store water by pumping it from a lower reservoir or a river to a higher reservoir. Water is pumped during off-pick hours by reversing turbine operation to make more water available for generation during peak demand hours. This process uses 20% or more of the energy generated for water pumping when the water is released (New, 2004).

d. Classification by purpose

This implies that a hydropower plant can be a single or multi-purpose scheme. A single purpose power plant is constructed only for electricity generation while a multi-purpose scheme provide water for other uses by people or industries and other developmental activities. The following are additional functions of a hydropower scheme: flood protection where water storage reduces the impact of floods, drought mitigation measure, water supply to the community, irrigation for agriculture and other uses such as fishing, tourism and recreation (New, 2004).

2.3.4. Turbine selection for hydropower plant

The site characteristics are the most important factors to consider when choosing a turbine for electricity generation. The two main parameters that are considered include available head and flow. Turbines can be classified as impulse and reaction turbine.

i. Impulse turbines

This type of turbine is more efficient for high heads. The most used impulse turbine is ***Pelton turbine***. It is made up of a runner blades shaped like a double spoon and one or more nozzles. The kinetic energy of the jet from the nozzle is converted to rotational mechanical energy by hitting the runner blades. Each nozzle is comprised of a movable needle to control its discharge. Horizontal-shaft turbine has maximum of two nozzles while a vertical-shaft turbine has a maximum of six nozzles. Each nozzle has a deflector which is triggered when a load rejection occurs thereby deflecting the jet to control overpressure in the penstock and prevent runner over speed. Pelton turbine operates in the air (New, 2004).

The ***Turgo turbine*** is similar to the Pelton turbine and the only difference is the angle at which the jet strikes the runner plane which is about 20^o. Thus, water can enter at one side of the runner and exit on the other side so the flow rate is not limited by the discharged fluid interference with the incoming jet. This makes a Turgo turbine diameter smaller than that of a Pelton turbine with equivalent power (New, 2004).

The ***crossflow turbine*** has a drum-like rotor with a solid disk at each end gutter-shaped slats joining the two disks. Water flows transversely through the turbine, entering at the edge and emerging on the opposite side thereby generating additional energy (New, 2004).

ii. Reaction turbines

This turbine uses the water flow to generate hydrodynamic lift forces that propel the runner blades. The turbine's runner always functions within a completely water-filled casing. The reaction turbine has a draft tube below the runner through which water is discharged. The draft tube decelerates the water discharge and reduces static pressure below the runner hence increasing the effective head (New, 2004).

The ***propeller turbine*** is an axial-flow turbine with a propeller-like runner and three to six runner blades depending on the designed head. To increase the efficiency, the water must have some swirl before entering the turbine runner. The runner absorbs the swirl and the water flow that emerges goes straight into the draft tube. A set of guide vanes and housing the runner in a snail shell are some of the methods used to swirl the water (New, 2004). Figure 17 shows a propeller turbine positioning.

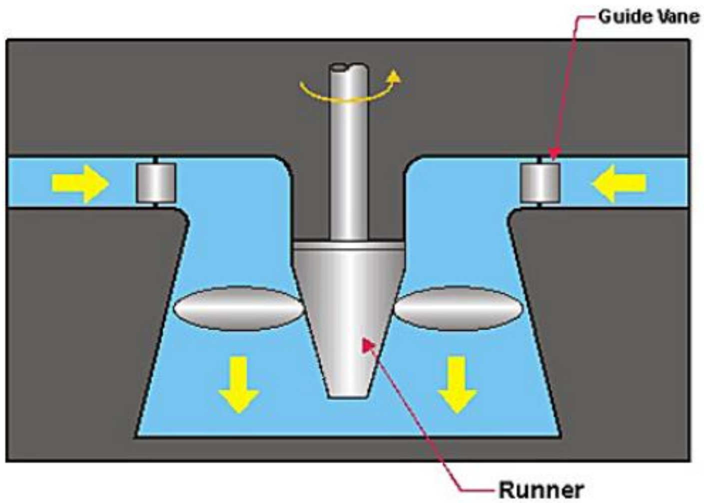


Figure 17: Propeller turbine positioning.

The ***Kaplan turbine*** is a type of propeller turbine with adjustable runner blades as well. This equipment responsible for adjusting the turbine blades improves the efficiency over a wide range of flow. However, this is expensive, thus, increases the cost of machine. Double regulation of turbines is a feature widely used for river installations with significant flow variation throughout the year (New, 2004).

Bulb turbine is a name derived from the shape of the upstream watertight casting in which the generator is enclosed. They are usually implemented in low-head hydropower schemes with high output. These turbines are used in power plants with head up to 30 m and offer reduced size and costs compared to vertical Kaplan turbines due to the almost horizontal water passage in the draft tube which requires a smaller excavation (New, 2004).

Francis turbines were originally designed as a low-head machine which are installed in an open chamber without a spiral casing. However, for the same head and flow conditions, the propeller machines are more compact and faster running. The figure 18 shows the schematic of a Francis turbine (New, 2004):

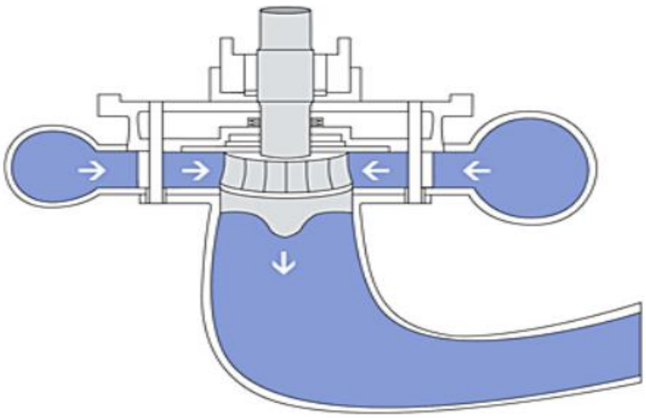


Figure 18: Francis turbine with spiral casing

Therefore, the selection of a turbine is site specific and depending on the head and flow of that particular site, then different turbines can be selected using the figure 19 below.

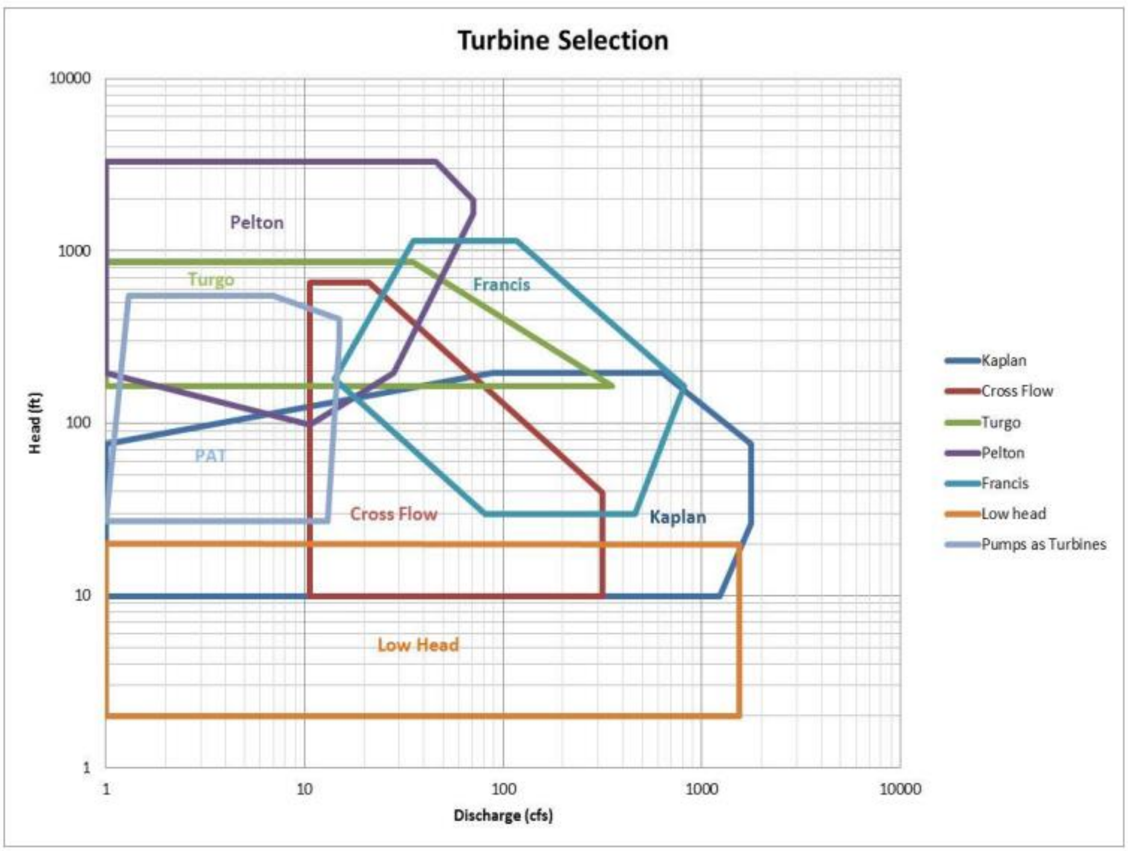


Figure 19: Turbine Selection Chart

Turbine efficiency

The turbine efficiencies can be summarized as follows: The Pelton and Kaplan turbines retain very high efficiencies when operating below designed flow and operate well under partload conditions. Cross-flow and Francis turbine efficiencies drop more sharply if run at below half their normal flow. This is why they are usually used in run-of-river plant schemes with constant flow. The figure 20 shows typical turbine efficiencies by type (New, 2004):

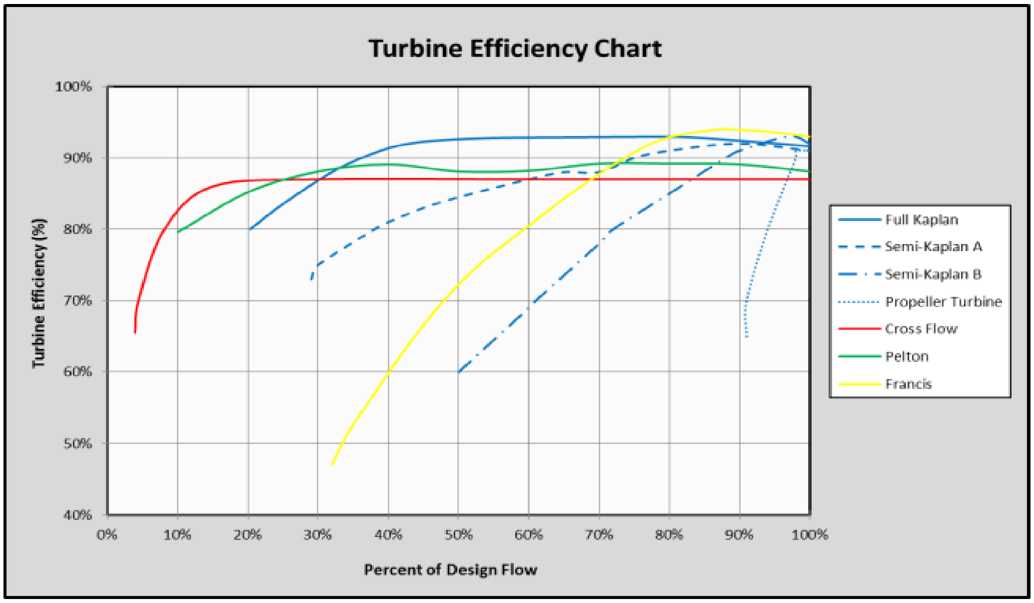


Figure 20: Typical turbine efficiencies by type

2.3.5. Hydroelectric power energy in Malawi

Malawi has abundant water resources in form of lakes, rivers and aquifers which can fully be utilized for electricity generation. The trends of annual mean flows in most rivers has generally remained constant for past years excluding random fluctuations which is due to annual rainfall variations (Kaunda, 2013). The northern region of Malawi has more perennial rivers than other parts of the country as shown in the figure. This can make the hydropower plant sustainable and reliable as water can be available in the river throughout the year.

The most important rivers in Malawi include: Shire, Bua, Dwangwa, North Rukuru, South Rukuru, Rumphi, Songwe, Wovwe, Lufira, Dwambazi, Luweya and Ruo. These rivers show that Malawi can generate electricity from these rivers in order to satisfy the current electricity demand. For small hydropower plant installations, technically small streams can be diverted from the main river for such purpose with respect to the topography of the site (Kaunda, 2013). Figure 21 shows the topography and river systems of Malawi:

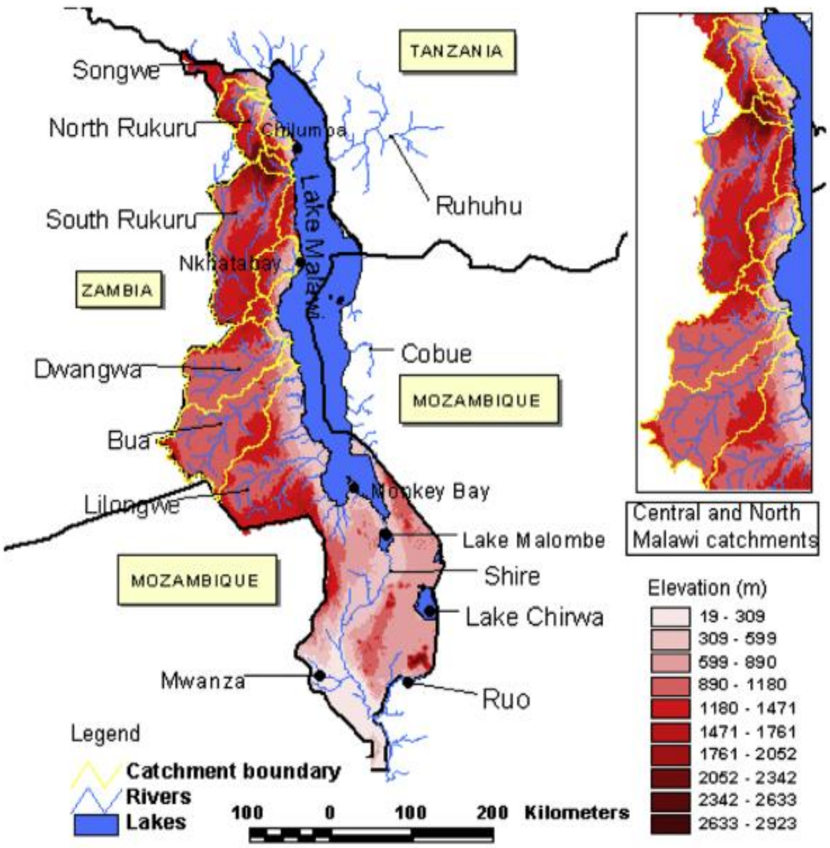


Figure 21: The topography and river systems of Malawi. (Kaunda, 2013)

Table 2: Malawi's small-scale hydropower potential sites and their characteristics as identified by the System Development and Operation Study Project. (Government of Malawi, 1997)

Name of hydro-scheme	Location (District)	Estimated parameters					
		Net head (m)	Mean flow (m^3/s)	Load factor (%)	Catchment area (km^2)	Firm power (kW)	Energy output (MWh/a)
Kaseye	Chitipa	28	1.29	30	560	150	394
Kalenje1	Chitipa	122	1.08	30	80	230	604
Chambo	Chitipa	100	0.6	30	117	6	16
Mbalizi	Chitipa	187	0.98	30	270	30	79
Kalenje2	Chitipa	63	1.08	30	80	120	315
Upstream Lufira	Karonga	67	3.2	30	806	130	340
Lufira	Karonga	135	10.6	30	1380	940	2470
North Rukuru	Chitipa	132	11.9	30	1610	2250	5913
North Rukuru2	Karonga	75	11.0	30	1310	1070	2810
North Rukuru3	Karonga	83	6.35	30	698	670	1760
Wovwe	Karonga	194	3.01	30	140	1400	3680
Chisenga	Chitipa	15–20	0.1	30	4	15	39
Kakasu	Chitipa	10–30	0.1	30	8	15	39
Hewe	Rumphi	25–30	0.2	30	37	45	118
Ntchenachena	Rumphi	10–30	0.2	30	18	30	78
Murwezi	Nkhatabay	10–15	0.05	30	7	5	13
Zulunkhuni	Nkhataby	50–60	0.15	30	80	50	131
Sasasa	Nkhatabay (Usisya)	20–30	0.1	30	85	20	52
Ngapani	Mangochi	5–15	0.05	30	48	5	13
Mtemankhokwe	Mangochi	20–30	0.1	30	24	25	65
Nswadzi	Thyolo	5–15	1	30	380	75	197
Choyoti	Rumphi	30–40	0.2	30	13	60	157
Total estimated small-scale hydroelectric potential						**7345**	**19,283**

2.3.6. Installed hydropower capacity and challenges

An estimation of 95% of Malawi's electricity generation is mainly from hydro with Shire river as the main source of the hydro-electricity (ESCOM, 2015). According to ESCOM (2015), the maximum generation capacity for hydro-electricity is 351 MW. Estimates indicate that shortage of capacity frequently exceeds 60 MW or over 17% of peak demand in Malawi. There are no reserve margin and a stressed system, the reliability and quality of electricity supply is poor (The International Trade Administration, 2019). Thus, a considerable investment in electricity generation is necessary to improve security and regularity in supply and meet a growing demand.

However, the hydropower generation is facing so many challenges in Malawi which include old machinery and reduced water levels. During summer season, electricity generation maybe reduced by up to 40% due to declining water levels. Therefore, ESCOM generate an average of 200 MW out 351 MW. Hence increased load shedding periods (ESCOM, 2015).

2.4.Hybrid system

A hybrid system is a combination of one or more resources of renewable energy such as solar, wind, micro/ mini-hydropower and biomass with other technologies like batteries and diesel generator. The renewable energy hybrid system offers clean, efficient and sustainable power for off-grid rural electrification (Tesfaye, 2014). Agarkar & Barve (2011) found out that combination of solar-wind, wind- hydro and solar-hydro yields more power. Hence combination of the three system should yield more power too.

Wind and solar resources are highly variable and varies in time intervals from seasons to minutes and even seconds. These resources are very difficult to predict for the near future hence a hybrid system can be more advantageous due to combined energy systems. This enables production of an amount of energy in accordance with the consumption (Ibrahim, Khair, & Ansari, 2015). Another great advantage of hybrid systems is that some of the different energy sources can complement each other such as solar and wind (Ingebrigtsen, 2017).

The combination of hydropower system to other renewable energy system such as wind and solar can be more advantageous even during peak load hours. For instance, if pumped hydro is incorporated to the system, wind and solar can be used in water pumping during off peak hours. This can help to satisfy the energy need during peak hours (Ingebrigtsen, 2017).

Advantages of hybrid renewable energy systems

According to Srivastava and Banerjee (2015), hybrid renewable energy systems makes use of a variety of primary energy sources and is applicable for rural electrification where grid extension is not possible or uneconomic. The author further said that power generation of hybrid energy systems, its stability, reliability and efficiency will be high because many sources of primary energy are involved. Running cost of thermal plant and atomic plant is high. Majority of the renewable source based electricity generation has minimum running cost also abundant in nature.

Limitations of hybrid renewable energy systems include the following:

Intermittent nature of renewable energy sources: Renewable energy sources such as wind and solar are usually variable and intermittent. This means that using this type of energy sources in a hybrid power generation system requires extensive backup generation or energy storage capacity in order to eliminate the effects of their variable and intermittent nature (Haruni, 2013).

Maximum power extraction: The V-I characteristics voltages of different energy sources when connected together, one will be superior to other hence difficult to extract maximum power for a constant load (Srivastava & Banerjee, 2015).

Stochastic Nature of sources: Renewable energy resources are site specific with different amounts. Thus the design of power converters and controllers has to be matched with the requirement. Complexities in matching voltage and frequency level of these sources and V-I characteristics depends on atmospheric condition, which is varying time to time. Forecasting of these sources is not accurate (Haruni, 2013).

Power Quality issues: In hybrid renewable energy systems the use of power electronics converters are involved in power conditioning from source to user. Therefore, harmonics are usually generated due to harmonic components in the transmission which causes disturbances to the load or power distribution system (Srivastava & Banerjee, 2015).

Hybrid Energy Systems as a solution for overcoming drawbacks

If two or three types of renewable energy generation systems are combined into one hybrid power generating system their drawbacks can be avoided partially/completely, depending on the control units. As the one or more drawbacks can be overcome by the other, as in northern hemisphere it is generally seen that in windy days the solar power is limited and vice versa and in summer and rainy season the biomass plant can operate in a full flagged so the power generation can be maintained in the above stated condition. The cost of solar panel can be subsided by using glass lenses, mirrors to heat up a fluid, that can rotate the common turbine used by wind and other sources.

2.4.1. Hybrid system in Malawi

As the world is researching and trying to install hybrid renewable energy systems, Malawi has not been left behind as it has already installed solar-wind hybrid systems. Malawi has installed six solar-wind hybrid systems. This project which was funded by the Government of Malawi in 2007 covered the following districts: Nkhata Bay, Mzimba, Nkhotakota, Ntcheu, Chiradzulu and thyolo (Kaunda, 2013; Phiri, 2014).

2.5. Connection to the grid

2.5.1. Metering and Rate arrangements for Grid-Connected Systems

The existence of a grid-connected system, when your system generates more electricity than you can use at that time, the electricity can be exported to the grid for your utility to use elsewhere. However, it is not the scope of this thesis but a good way to go for countries to increase injection of renewable energy into the grid. The metering arrangements you are likely to come across include: Net-metering arrangement and Net purchase and sale arrangement (U.S. Department of energy, 2019).

2.5.2. Existing grid, challenges and options

A hybrid system just like any other source of energy, there are several conditions that must be fulfilled before it is injected into the grid, the following are some of the conditions (Ingebrigtsen, 2017):

i. Voltage regulation: the voltage injected into the grid should be approximately constant.
ii. Synchronization: the frequency, the phase angle and the magnitude of the voltage waveform injected to the grid must have the same values as what is specified for the grid.
iii. Response to voltage and frequency disturbance: if there are disturbances in the voltage or frequency, mechanisms should be put in place to stabilize these at the appropriate level again.
iv. Disconnection for faults and fault-ride-through: if the voltage, frequency or current becomes larger or smaller than what is recommended, then the energy source should be disconnected from the grid. However, if there is only a small disturbance that lasts only for a very short time interval, there should be a ride-through of this fault.
v. Minimizing harmonics: the alternating current injected to the grid is sinusoidal, and then harmonic distortion will occur due to power electronic components. Harmonics have a frequency that is a multiple of the frequency wanted into the grid, and should be minimized.

vi. Power regulation: power electronics used in the interface between the energy source and the grid produce both reactive and active power, and the ratio of these must be controlled.

2.6. Types of Energy storage

Renewable energy resources do not provide constant supply of energy, for instance, solar and wind power are available when sun and wind are available. However, constant supply of energy is needed for steady function of our equipment hence energy storage mechanism must be used in our hybrid system. This ensures that excess energy produced is stored for later use. Energy can be stored using chemical method (battery or hydrogen), as electrical energy (capacitors), as potential energy (pumped hydro or compressed air) or as mechanical energy (flywheels). The most important characteristics that are used to determine the storage technology include; energy storage capacity, charge and discharge rates, lifetime, efficiency and energy density (Bahta, 2013).

Bahta (2013) summarized selection criteria based on the advantages and disadvantages of different energy storage types in table 3.

Table 3: : Advantages and disadvantages of energy storage types

Energy Storage Types	**Advantages**	**Constraints**
Lead-acid batteries	Market availability , moderate costs, high performance over cost ratio	Limited lifetime
Li-Ion batteries	compacted size	less experienced with use in electric grids
Na-S batteries	high round-trip efficiency	only for larger electricity systems, corrosive
Flywheels	Modular, low maintenance	Expensive
Pumped Hydro	Technically proven, low costs	Very large scale
CAES	Moderate costs	Very large scale, uses natural gas

Hydrogen	compatible with fuel cells	Low round-trip efficiency, expensive
Flow batteries	Can be fully discharged	Still under development, higher costs

3. Chapter Three: Load estimation for the proposed site

3.1.Domestic load estimation

In this thesis work, one household is assumed to have low energy saver bulbs, sound system or radio, TV set, mobile phones and refrigerator. An individual household was assumed to have 5 bulbs of 20W and 2 bulbs of 60W for security lights, 3 bulbs for bedroom lighting and living room and dining room with a bulb each. Each household has 1 sound system with rated capacity 95W and a TV set with rated capacity of 100W. A refrigerator has rated capacity of 200W and each household was assumed to have 2 phone chargers with rated capacity of 7W. The table 4 gives the summary of the estimated power for a single household with their operating times and then transformed into 420 households.

Table 4: Household load estimation

Household load estimation					
Energy need	**Use**	**Quantity**	**Rated power (W)**	**Operating times**	**Total power = 420 households (kW)**
lighting	3 Bedrooms	3	20	18:00-21:00 04:00-07:00	**25.2**
	security lights	2	60	18:00-06:00	**50.4**
	Living room	1	20	18:00-23:00 06:00-07:00	**8.4**
	Dinning	1	20	18:00-23:00 06:00-07:00	**8.4**
Sound system	Living room	1	95	07:00-23:00	**39.9**
TV set	Living room	1	100	07:00-23:00	**42**
cello-charging	N/A	2	7	22:00-05:00	**5.88**
refrigerator	Kitchen	1	200	00:00-00:00	**84**

The selected appliances were considered based on low energy saving technologies in order to minimize the size of the power plant hence manageable by the community.

3.2. Commercial Load estimation

Dwangwa region is close to the lake (Lake Malawi) and is one of the touristic places in Malawi hence a small hotel with 20 rooms was considered. Dwangwa region is usually associated with high temperatures hence each room has a fan which was assumed to be operative throughout the year. Eight restaurants were also considered for fast food and four local bars. Malawi's staple food is Nsima which is prepared from maize flour hence one flour milling machine was considered for the community. One bakery was also considered since breakfast in Malawi usually contains bread.

Other commercial load which were considered for the community include: ten grocery shops, each shop is assumed to have a refrigerator and bulbs, 6 female saloon and four barber shops where each shop is assumed to have internal and security bulb. Three butchery shops were also considered where each shop is assumed to have a refrigerator, internal and security bulb. The last business activity which was considered is a welding shop. The Appendix A gives the summary of the estimated power for all assumed business activities with their operating times.

3.3. Water supply and irrigation load estimation

This thesis paper is considering energy demand estimated for pumps for three applications. This include water collection, water distribution and irrigation pumps. The water collection pump is intended for pumping water from the well to the storage while distribution pump is intended for water distribution.

According to World Health Organisation (WHO), the minimum water requirement for every individual for consumption is 20 litres per day. However, this amount varies from region to region hence some regions consume more e.g. Egypt while others consume less e.g. other African countries (Ingebrigtsen, 2017; WHO, 2019). In this thesis paper, it has been assumed 200 litres per day for each household and 90, 000 litres per day for health centers and schools in the study area. Thus, the collecting pump is intended to collect water from the well into the storage and it will have 70 m^3/hr flow rate and 16.15 kW capacities. The distribution pump is assumed to flow rate of 1.6 m3/hr and capacity of 0.45 kW. One pump for water collection and two pumps for distribution purpose were proposed. On the other hand, two pumps for irrigation purpose were also proposed with rated capacity of 7.7 kW. The table 5 shows the water supply and irrigation load with their time of operation.

Table 5: Water pumping and irrigation activities load estimation

Water pumping and Irrigation activities					
Activity	**Use**	**Quantity**	**Rated power (W)**	**Operating times**	**Total power (kW)**
Water pumping	Collecting water	1	16150	00:00-05:00	**16.15**
	2 Distribution pumps	2	16650	06:00-18:00	**33.3**
Irrigation	2 Irrigation pumps	2	7700	06:00-09:00 15:00-20:00	**15.4**

3.4. Public service and tourist office load

This is composed of local administration and tourist office, police unit, church, mosque, schools and hospital (Health centre). The local administration office is a government office responsible for public services and tourist protection and guidance within the community. The load was assumed to comprise of office lights with capacity of 20W, security lights of 60W, TV set of 100W, 4 computers and 1 printer. Phone charging was assumed to be 15 chargers with rated capacity of 7W.

A police unit is comprised of security lights, internal lights,1 computer and 1 refrigerator of rated capacity 200W. A church and Mosque were all assumed to have security lights, internal lights, sound system with rated capacity of 50W and fans of 75W capacity. The table 6 gives the summary of the public services and tourist office load with their quantities and operation time.

Table 6: Local administration and tourist office load estimation

Local (District) Administration and Tourist office					
Activity	**Use**	**Quantity**	**Rated power (W)**	**Operating times**	**Total power (kW)**
Local (District)	Office lighting	15	20	07:00-16:00	**0.3**
	Reception lighting	2	20	07:00-16:00	**0.04**

Administration and Tourist office	security lights	4	60	18:00-06:00	**0.24**
	Phone charging	15	7	07:00-16:00	**0.105**
	TV set	1	100	09:00-16:00 18:00-21:00	**0.1**
	Computers	4	200	08:00-16:00	**0.8**
	Printer	1	100	N/A	**0.1**
Police Unit	Internal lights	4	20	18:00-06:00	**0.08**
	Security lights	2	60	18:00-06:00	**0.12**
	computer	1	200	08:00-17:00	**0.2**
	Refrigeration	1	200	00:00-00:00	**0.2**
Church	Internal lights	12	20	N/A	**0.24**
	Security lights	4	60	18:00-06:00	**0.24**
	Sound system	1	50	06:00-08:00	**0.05**
	fans	6	75	N/A	**0.45**
Mosque	Internal lights	8	20	N/A	**0.16**
	Security lights	2	60	18:00-06:00	**0.12**
	fans	4	75	N/A	**0.3**
	Sound system	1	50	06:00-08:00	**0.05**

3.5. School load estimation

The schools are important features of the community and in turn helps in the development of the country. Thus, the load for school was also considered where schools were categorized into three types; primary, day secondary school and boarding secondary school.

For the primary school, 16 classrooms were considered with administration building. Thus, lights, 1 computer and 1 printer were considered for primary school load. For community day secondary school, 8 classrooms were considered where bulbs were assumed to be available in all rooms and security bulbs. 4 phone charger and TV set were also considered in the staff room. 20 computers were also considered for computer laboratory and 1 office computer with a printer for administration purpose. A refrigerator and 1 electric jug with rated capacity of 1400W for coffee making.

A boarding secondary school with 12 classrooms, 20 hostels, staff room, Library, cafeteria, storerooms and 2 offices was considered. Bulbs in different quantities were assumed to be in every room and security lights. The school is assumed to have 20 computers for computer laboratory, 1 computer and 1 printer for administration. 2 refrigerators were also considered for the kitchen use and administration use. Electric cooker of 1500W and electric jug of 1400W were also consider for kitchen use. Appendix B-D give detailed loads for schools with their time of operation.

3.6.Healthy Centre load estimation

The healthy clinic within the community is equipped with simple equipment to handle minor illnesses. The rural electrification can also attract the construction of bigger hospitals in order to support other surrounding communities. Thus, three types of health centres were considered for Dwangwa area which include small healthy centre, medium healthy centre and higher clinic.

The load small healthy centre is comprised of 1 refrigerator, 2 microscopes, sterilize machine and other laboratory equipment.1 TV set was also included at the reception, a computer and a printer for office use and electric stove for water heating and fast food was also considered. Bulbs were also considered in different rooms at different quantities. The small healthy centre operates during the day time, thus, they starting working at 7:30 and finish at 16:30. Table 7 below gives a summary of the required load for the small healthy centre with their rated power and operating times. The medium healthy centre is assumed to operate the same way as small health centre but with an extension of 24-hour ward for maternity services. The higher clinic is a 24-hour hospital which operate to assist all kinds of illnesses. Appendix E- F gives summary of the assumed load and their operating time for medium healthy centre and higher clinic.

Table 7: Small healthy centre load estimation

Small healthy centre					
Appliances	**Use**	**Quantity**	**Rated power (W)**	**Time of use**	**Total power (kW)**
Equipments	Refrigerator	1	200	00:00-00:00	**0.2**
	Microscopes	2	25	08:00-12:00 13:00-17:00	**0.05**

	Sterilise machine	1	200	08:00-12:00 13:00-17:00	**0.2**
	Other lab. Equipments	1	300	08:00-12:00 13:00-17:00	**0.3**
TV set	Reception	1	100	08:00-17:00	**0.1**
Computer	Office	1	200	08:00-12:00 13:00-17:00	**0.2**
Printer	Office	1	100	08:00-12:00 13:00-17:00	**0.1**
Electric stove	Water heating/ fast food	1	1000	10:00-10:10 15:00-15:10	**1**
Fan	Office	1	75	08:00-12:00 13:00-17:00	**0.075**
	2 Wards	4	75	09:00-12:00 13:00-17:00	**0.3**
Lighting	2 wards	4	20	08:00-17:00	**0.08**
	Office	1	20	08:00-12:00 13:00-17:00	**0.02**
	Reception	2	20	08:00-17:00	**0.04**
	Laboratory	2	20	08:00-17:00	**0.04**
	Corridors	2	20	08:00-17:00	**0.04**
	Security lights	4	60	18:00-06:00	**0.24**

3.7. Summary of load estimation

The estimated total load for the whole community of study obtained from tables 3-6 and Appendix A-F with respect to the time of operation has been summarized in table 8 below. However, weekend load was also calculated and Appendix G shows the summary of weekend load for the study area.

Table 8: Summary of hourly total load estimation

From	To	Residential consumption	Pumps consumption	Public consumption	Commercial consumption	School consumption	Clinic consumption	Hourly Total consumption (kW)
0:00	1:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
1:00	2:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
2:00	3:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
3:00	4:00	140.28	16.2	0.92	17.32	0.96	3.56	179.19
4:00	5:00	165.48	16.2	0.92	17.32	0.96	3.48	204.31
5:00	6:00	159.6	0	0.92	16.88	0.96	3.48	181.84
6:00	7:00	126	48.7	0.65	3.6	0.6	1.8	181.35
7:00	8:00	165.9	48.7	0.645	8.6	7.2	1.8	232.841
8:00	9:00	165.9	48.7	1.745	28.7	12.1	8.87	265.991
9:00	10:00	165.9	33.3	1.745	28.7	12.4	8.87	250.9243
10:00	11:00	165.9	33.3	1.745	31.94	10.6	10.68	254.141
11:00	12:00	165.9	33.3	1.745	29.94	10.6	10.62	252.081
12:00	13:00	165.9	33.3	1.745	29.94	8.12	6.73	245.731
13:00	14:00	165.9	33.3	1.745	29.94	10.6	10.52	251.981
14:00	15:00	165.9	33.3	1.745	29.94	10.6	10.52	251.981
15:00	16:00	165.9	48.7	1.745	29.94	10.9	10.52	267.701
16:00	17:00	165.9	48.7	0.2	29.94	0.8	10.52	256.06
17:00	18:00	165.9	48.7	0.4	13.94	2.88	4.07	235.89
18:00	19:00	258.3	15.4	1.1	18.18	3.84	4.04	300.86
19:00	20:00	258.3	15.4	1.1	18.18	4.68	5.27	302.93
20:00	21:00	258.3	0	1.1	16.52	3.2	5.17	284.29
21:00	22:00	258.3	0	1	16.42	2.16	5.27	283.15
22:00	23:00	154.98	0	1	14.02	0.84	5.07	175.91
23:00	0:00	140.28	0	1	13.32	0.96	5.11	160.67
TOTAL		**4165.6**	**604**	**27.7**	**495**	**119**	**145.57**	**5556.31**

The proposed study site has a total daily consumption of 5,556.31 kWh with an exception of rainy season (December, January, February and March) where there is no irrigation. Thus, the annual energy consumption for the community is 2,028.05 MWh. Residential load has the highest energy demand of 75% of the total daily load. The figure 22 gives the power curve for community in a day.

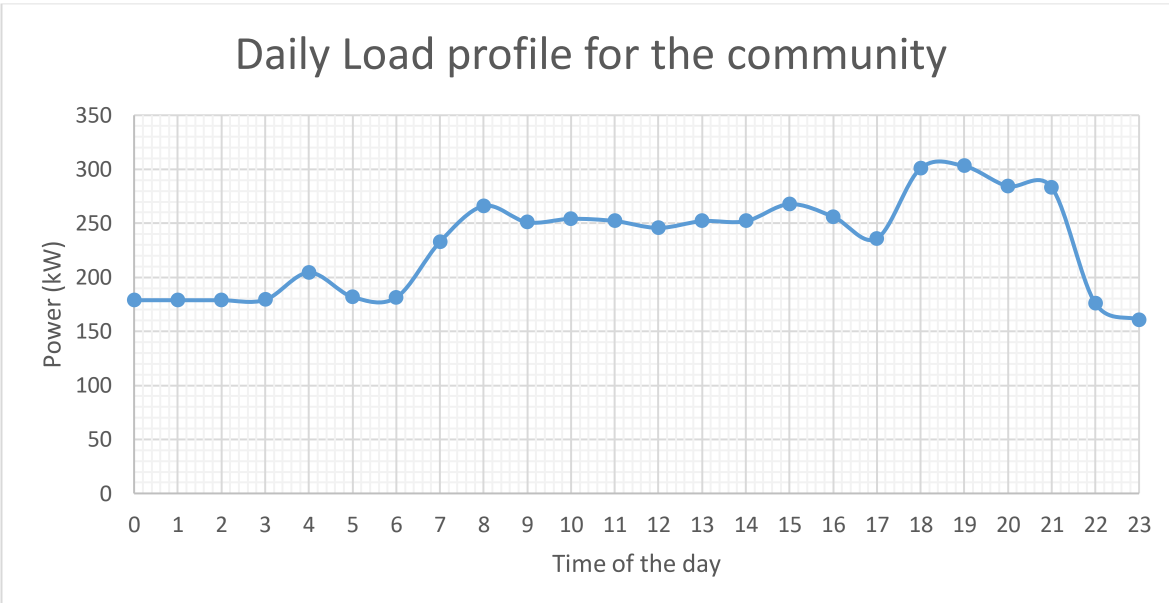


Figure 22: Daily load profile for the community

4. Chapter Four: Methodology

1.1.HOMER software description

The selection and sizing of components of most hybrid power systems has been done using HOMER software. HOMER is a user friendly software developed by Mistaya Engineering, Canada for the National Renewable Energy Laboratory (NREL) USA. It simplifies the evaluation task for design of both off-grid and grid-connected power systems for various applications (Bee, Geogre, & Ansari, 2016).

Power system design requires many decisions in order to configure a suitable system. These decisions include components to be included in the system, size of each component to use and many more. The large number of technology options and the variation in technology costs and availability of energy resources make these decisions difficult. Thus, optimization and sensitivity analysis algorithms using HOMER software make it easier to evaluate many possible system configurations (Ajao, Oladosu, & Popoola, 2011).Furthermore, HOMER allows the designer to compare many different design options based on their technical and economic aspects. Thus, HOMER simulates the operation of a system by making energy balance calculations and displays a list of configurations which are sorted by net present cost that can be compared to other system designs (Canales, Beluco, & Mendes, 2015; Magarappanavar & Koti, 2016).

1.2.Hybrid energy system configuration

The proposed renewable hybrid energy system expects to meet the load demand for the community comprised of 420 households with other community activities. Considering the availability of Dwangwa river, the renewable resources considered include hydropower, solar and wind. Battery was preferred than a diesel generator as a backup due to limited petroleum resources in Malawi. Energy storage systems are employed in the energy system due to the intermittent nature of the renewable sources. The AC load was the only type of load considered in this system design. Bidirectional converter was considered in the configuration which is responsible for changing voltage from AC to DC and DC to AC to enable charging of the battery all both sources and to supply DC power to AC load. All these components, hydro turbine, wind turbine, battery and PV panels, come in different sizes and quantities. The proposed system design showing arrangement of components for optimization and modeling of the system. Figure 23 display the schematic representation of HOMER simulation model of the proposed hybrid system architecture considered. Details of each component of the proposed power system and electricity load for the community has already been explained in this paper.

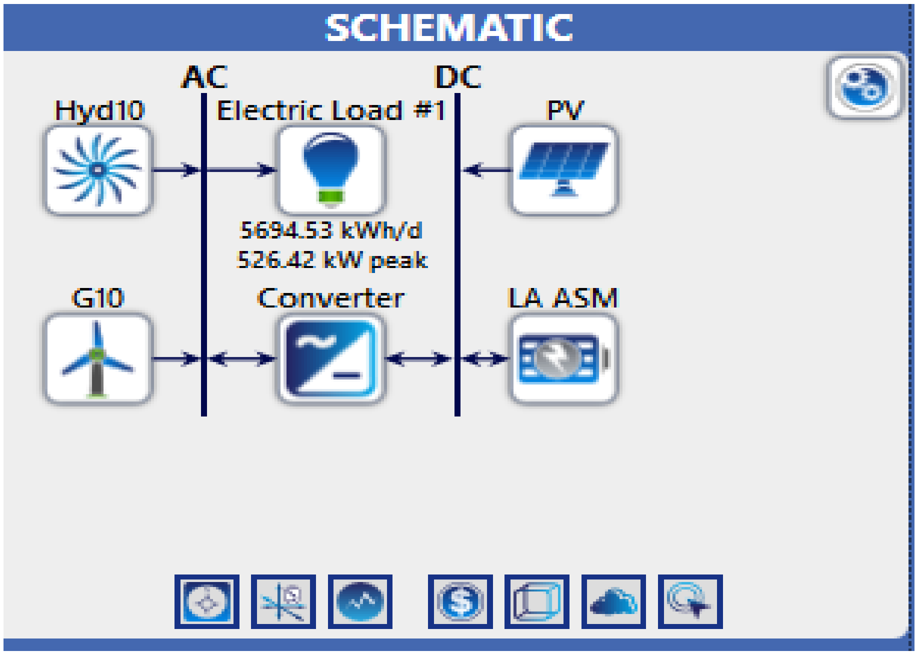


Figure 23: Configuration of the system in HOMER

1.3. Input load data for the community

The load profile of the study site has been presented in previous chapter and the estimated daily average energy demand is 5,556.31 kWh with daily noise of 10%. The study site has a peak load of 302.93 kW which occurs in the evening. Thus, solar PV alone cannot satisfy the load during the peak hour hence hybrid system can be the solution. The figure 24 shows the daily load distribution for the study site.

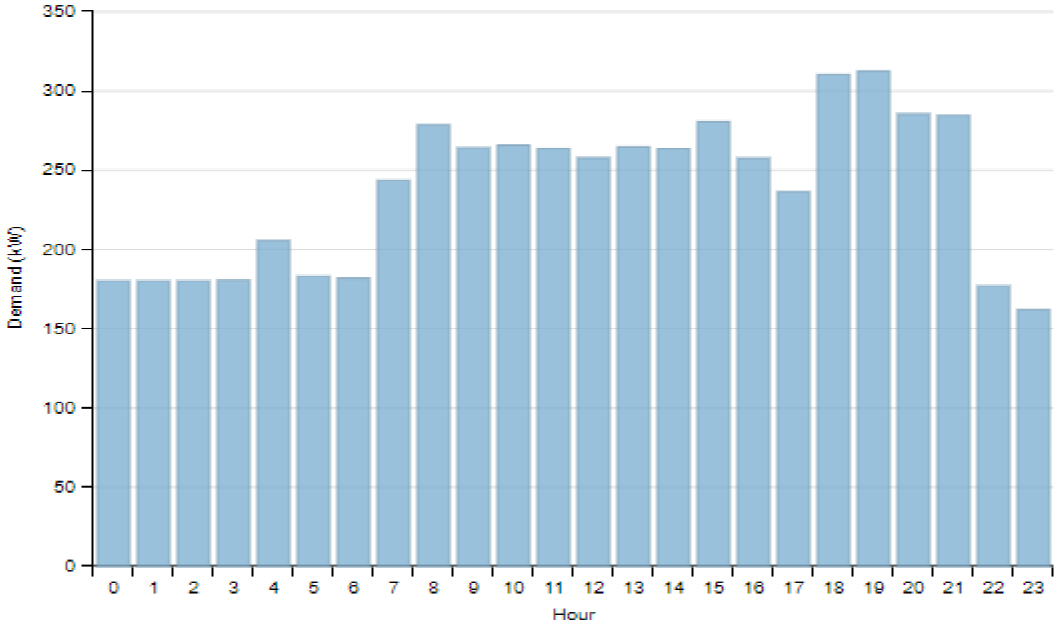


Figure 24: The daily load profile for the study site

Community load may not be constant throughout the due seasonal changes which result in affecting irrigation load and cooling load. The figure 25 displays the seasonal profile for the community.

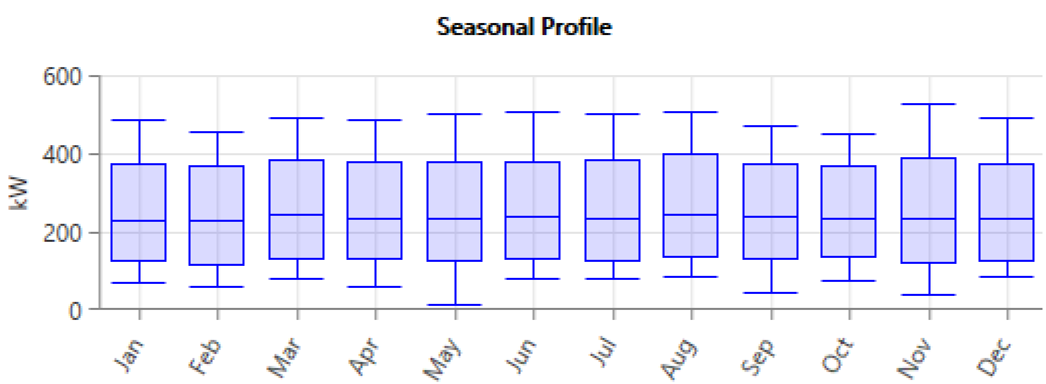


Figure 25: Seasonal load profile for the study site

1.4.Input data for solar PV power system in Dwangwa

The solar resource data for Dwangwa, Malawi was obtained from NASA Surface meteorology and solar energy database. The approximate location to the study site used is 12˚31.1′S and 34˚7.8′E The monthly averaged value for Global horizontal radiation were obtained for a period of 22 years from July, 1983 to June, 2005. Figure 26 shows Dwangwa's daily radiation in $kWh/m^2/day$ and their clearness index which ranges from 0 to 1 for the whole year.

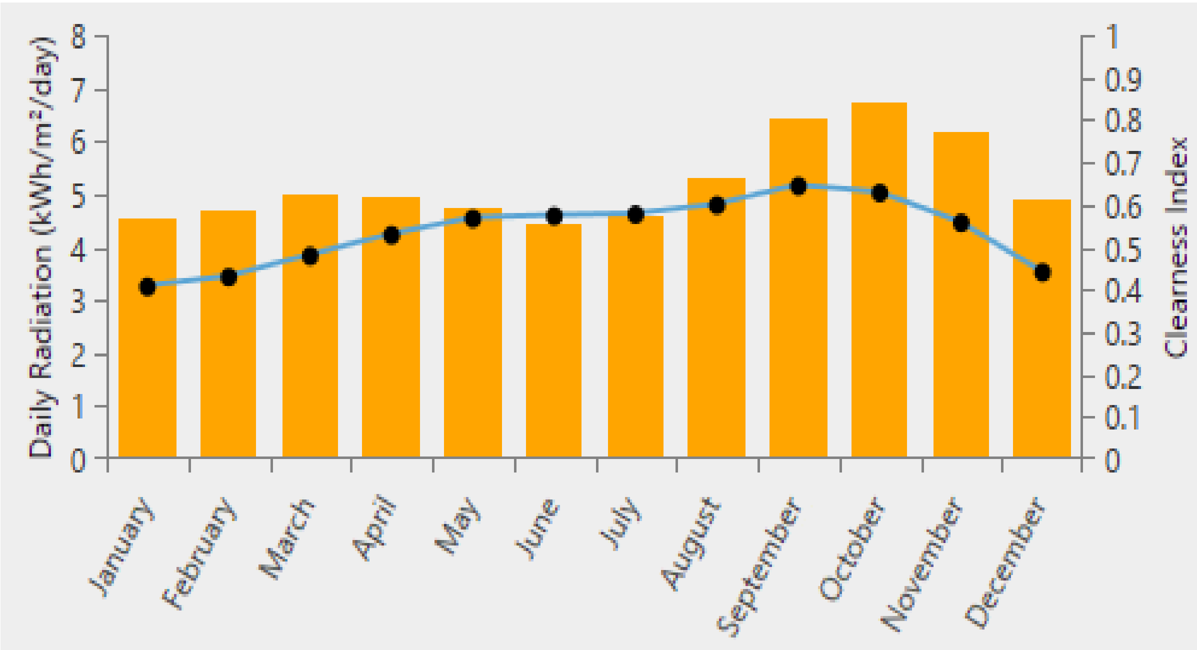


Figure 26: Solar Radiation and Clearness Index for Dwangwa

The figure 26 clearly indicate that the maximum monthly average solar global horizontal irradiation (GHI) is experienced in September, October and November with values of 6.41, 6.73 and 6.16 $kWh/m^2/day$ respectively. However, the average value for the study site is 5.21 $kWh/m^2/day$.

The PV system for the proposed site has no tracking system due to financial burden and complexity of the system. The solar panel considered was a 1kW, which is 2 solar panels of 500W from Bluesun (Jiangsu, China). The selected panel was Monocrystalline Silicon made with model number of BSM500M-96. The price for the product was at $0.31/watt ($155 per 500W panel). The efficiency of the module is 19.51% (Alibaba.com, 2019a).

In this research paper, the initial cost of 1kW solar panel was considered as $2,822 while the replacement cost is the same as capital cost (Wiemann, Rolland, & Glania, 2014). The operation and maintenance of the solar PV is estimated as 1% of the capital cost which is about $ 28.22 per year per kW (Lipu, Golam, Ullah, Hossain, & Munia, 2017). The PV module rated power is 1 kW with lifetime of 25 years. The derating factor for the solar module was considered as 95% and the ground reflection of 20%. The solar module slope for the study site is 12.518° and Azimuth angle is 180°. However, Zalengera (2015) proposed initial cost of 1, 175 per kW for Likoma Island in Malawi hence 0.5 multiplier on cost initial cost was considered for sensitivity analysis.

1.5. Input data for wind power system in Dwangwa

Malawi in general has poor wind speed and few areas have been identified to have some potential for wind energy generation. However, areas close to the lake and on the island such as Likoma have relatively good wind speeds. Dwangwa also is close to lake Malawi and have good wind speeds for small wind turbine technology. The wind speed data for Dwangwa were obtained from NASA Surface meteorology and solar energy database. The wind speeds were measured at anemometer height of 50 metres for a period of 10 years from July, 1983 to June, 1993 which is also similar to airport data. The figure 27 shows the average wind speeds in m/s for Dwangwa.

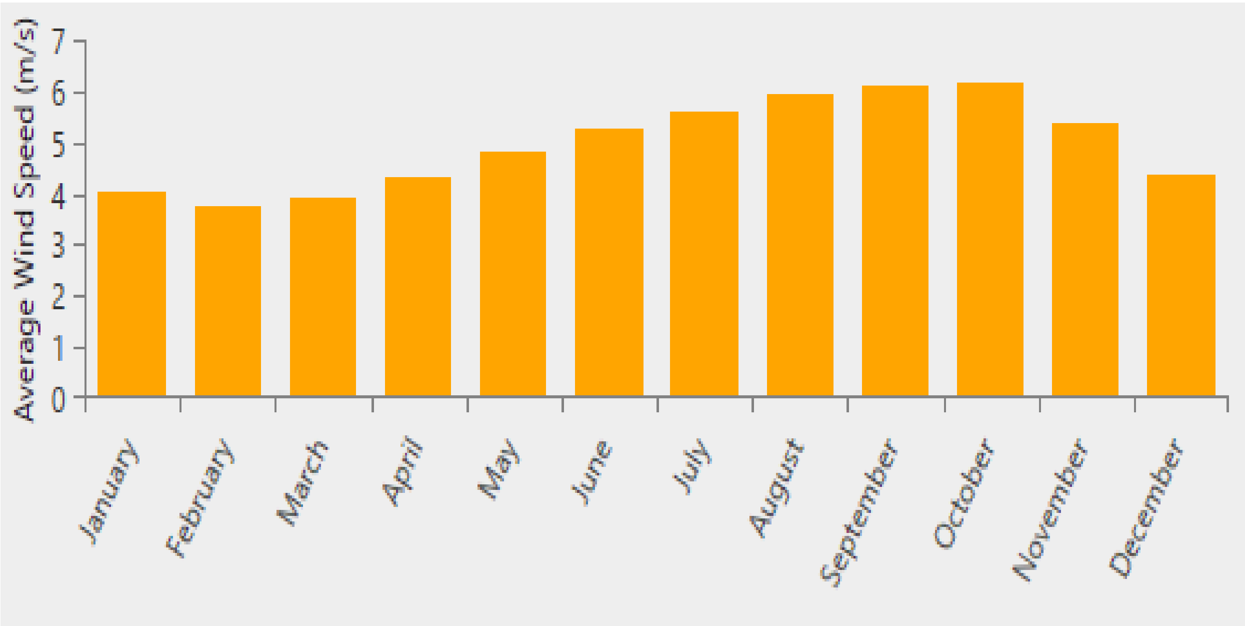


Figure 27: Monthly average wind speed in Dwangwa

Figure 27 also shows that wind speeds start increasing from April reaching maximum wind speed in September and October with a value as high as 6.15 m/s. The annual average wind speed for Dwangwa is 4.98 m/s. The wind power curve for Generic 10 kW wind turbine is shown in figure 28 below.

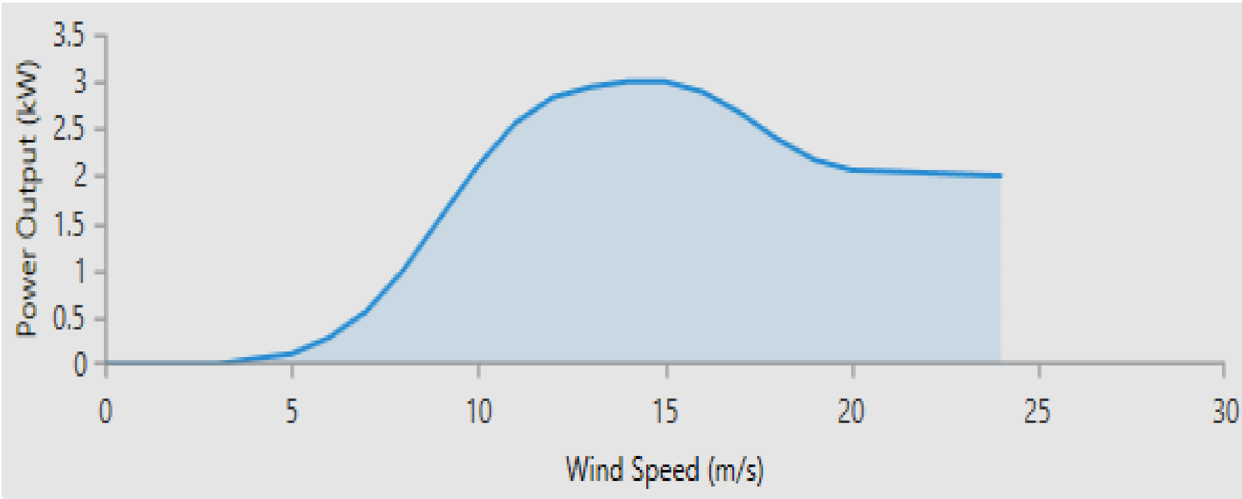


Figure 28:Wind power curve of Generic 10 kW wind turbine

The wind turbine selected for this project work has 10 kW power rating of model number NE-10k and brand name of Naier (Jiangsu, China). This 10kW wind turbine cost ranges from $5,500 to 7,100$ (Alibaba.com, 2019c). In this research paper, the initial capital cost of a wind power was considered as $2,120 per kW. Hence the estimated cost of 10 kW wind turbine is $21,200. The cost reduction for a wind turbine is around 12% between 2015 and 2025, hence, the replacement cost for a 10 kW wind turbine was estimated to be 80% of the capital cost which is $16,960. The operation and maintenance cost is assumed to be 2% of capital cost which is about $42.4 per year per turbine (Ingebrigtsen, 2017; Lipu et al., 2017; Wiemann et al., 2014). The hub height for the wind turbine was considered to be 40m. However, according to Zalengera (2015), the proposed initial cost of $5,765 per kW for Likoma Island in Malawi hence multiplier of 2 on initial cost was considered for sensitivity analysis.

1.6.Input data hydropower system in Dwangwa

Dwangwa river receives more waters during rainy season and nearly dry during dry season. Thus, in January the average flow rate is 112,025.33 L/s while in September the value is 168.351 L/s. The average river discharge for Dwangwa were obtained from the Ministry of irrigation and water development, Malawi Government. The river discharge was measured at a period of 24 years from January, 1986 to January, 2010. However, due to some missing data the most recent dataset without missing data for the year 2005 was chosen. The figure 29 shows average river discharge for the year 2005.

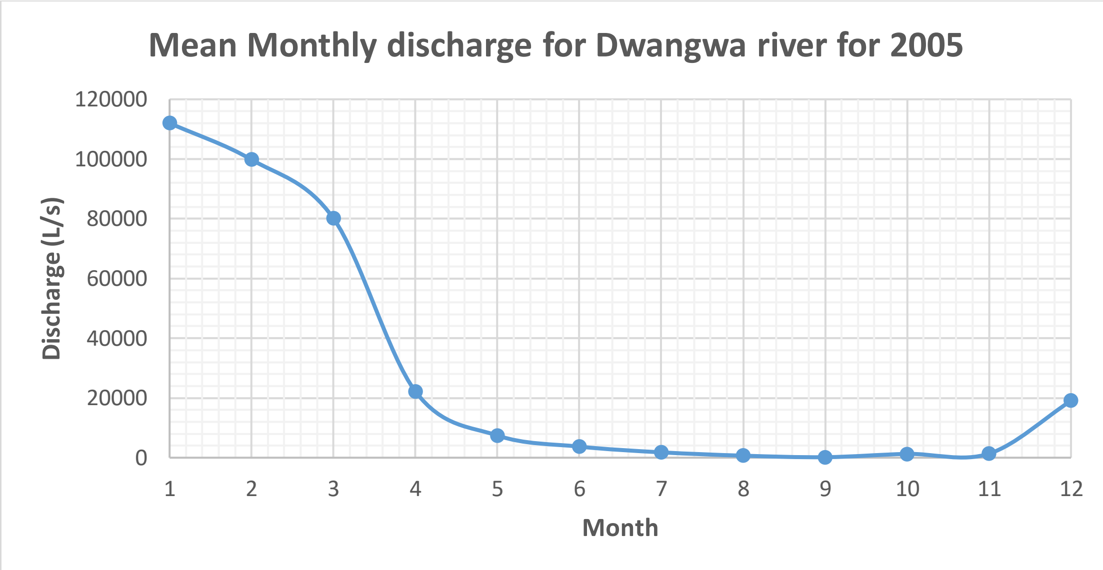


Figure 29: Mean monthly discharge for Dwangwa river for 2005

The scaled annual average flow for Dwangwa river is 29,129.47 L/s which is huge amount of discharge for energy generation. However, this discharge cannot be realized in run-off-river since the water levels decreases during dry season. Thus, for design purpose, three design flow were considered.

Scenario 1: The design flow was considered to be available throughout the year. Thus, the design flow of 159 L/s was chosen to ensure that the hydropower plant is in operation at 100% time of the year.

Scenario 2: The design flow was considered to be available at about 95% of the time of the year. Thus, a 95% design flow for Dwangwa river is 400 L/s.

Scenario 3: The design flow was considered to be available at about 91% of the time of the year. Thus, a 91% design flow for Dwangwa river is 637 L/s.

In each case, the available head for Dwangwa river is 100 m. The pipe head loss was estimated to be 5% while residual flow was assumed to be 2% of the design flow for environmental reasons thereby saving life of aquatic plants and animals. The estimated total lifetime of the system was set at 30 years. The efficiency for the turbine was assumed to be 90%. The figure 30 below shows how the design flow was determined for both 91% and 95% design flow.

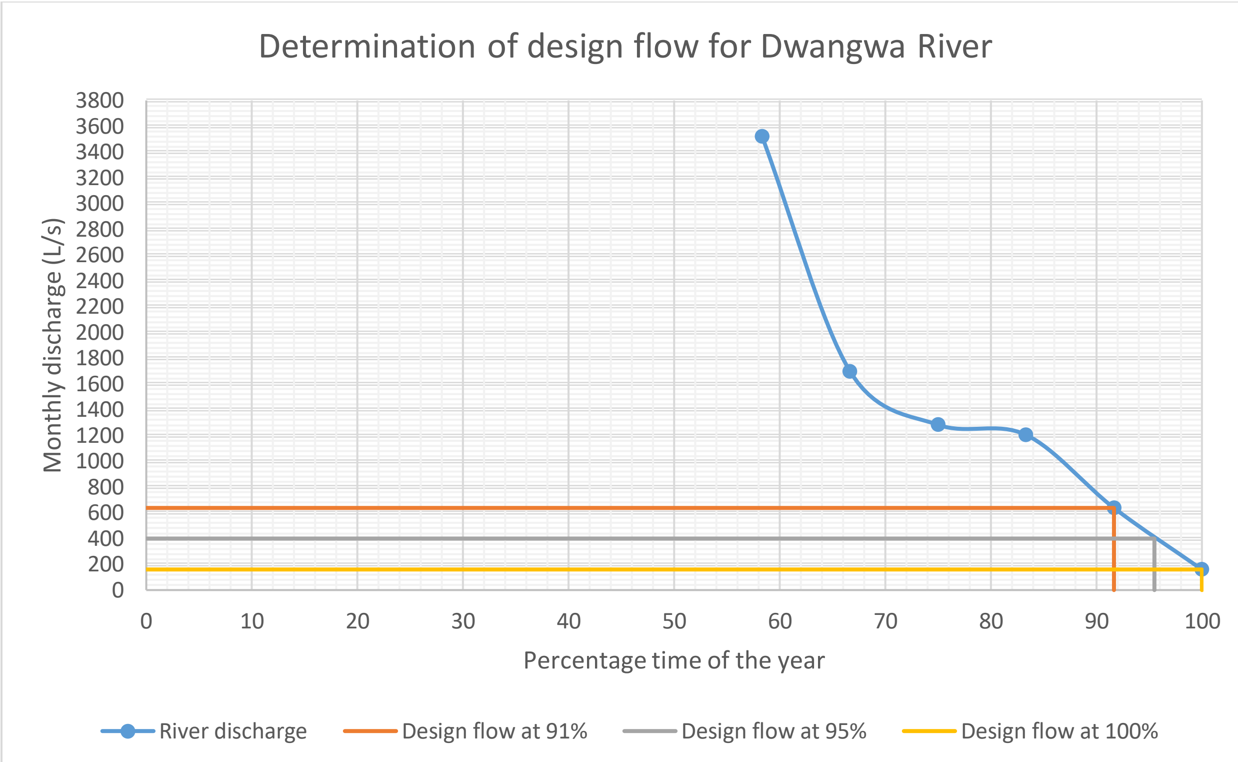


Figure 30: Determination of design flow for Dwangwa river

The hydro system was considered to have capital cost of $ 1,790 per kW and the replacement cost was assumed to be 50% of the capital cost which is $ 895 per kW. The operation and maintenance of the hydropower plant was assumed to be 2% of the capital cost which is $ 35.8 per kW (Wiemann et al., 2014). Acording to Lako (2010), the capital cost of small hydropower plant ranges from $ 2,500 to $ 10,000 per kW which is relatively higher than our proposed capital cost. Thus, a multiplier of 1.5 for capital cost was considered for sensitivity analysis.

1.7.Input data for Battery system

The Lead acid battery was considered for the design because they are relatively cheap, simple and affordable. The selected Generic 1kWh Lead Acid battery has rated capacity of 513 Ah with nominal voltage of 2V. The battery stores total amount of energy equal to 1 kWh. According to Alibaba.com (2019), the cost of 1 kWh battery was $ 217.5 while Wiemann et al. (2014) estimated it as $ 225. Thus, this thesis paper considered $ 225 as capital cost for battery. The replacement cost was assumed to be 70% of the capital cost which is about $ 157.5 per battery. The operation and maintenance cost were estimated to be 1% of the capital cost which is about $2.25 per battery per year.

Zalengera (2015) considered capital cost of $ 806 for 1,150 Ah battery which is relatively higher as compared to the cost of this thesis paper, hence, a multiplier of 2 was considered on capital cost for sensitivity analysis.

1.8. Input data for power converter

A converter needs to maintain flow of whether AC or DC electric energy into power system components. The rated power of the inverter should be equal to or larger than the peak load. In this thesis paper, a 1 kW converter was considered for AC/DC or DC/AC conversion with efficiency of 95%. The converter's initial cost of 1 kW capacity was considered to be $ 1,445 and the replacement cost is estimated to be 80% of the capital cost which is $ 1,156. The operation and maintenance cost is assumed to be 1.2% of the capital cost which is $ 17.34 per year. The lifetime of a converter was 15 years (Lipu et al., 2017; Wiemann et al., 2014).

Zalengera (2015) considered capital cost of $ 26,067 per 100 kW converter which is relatively cheaper as compared to the proposed capital cost in this paper. Thus, a multiplier of 0.5 was considered on capital cost for sensitivity analysis.

1.9. Summary of components costs

The table 9 gives the summary of the input costs of all the components and their lifetime for the optimal system design.

Table 9: Summary of components costs

Component type	**Capital cost ($)**	**Replacement cost ($)**	**O&M cost ($)**	**Lifetime (Years)**
Solar PV (per kW)	2822	2822	28.22	15
Wind turbine (per kW)	2120	1696	42.4	25
Hydro (per kW)	1790	895	35.8	30
Battery (LA ASM) (per 1 battery)	225	157.5	2.25	5
Converter (per kW)	1445	1156	17.34	15

5. Chapter Five: Results and Discussion

5.1. Systems Optimization and Selection of Scenarios

HOMER simulated different configurations of energy system components and displays the feasible hybrid combination. The software's time of simulation depends on the number of parameters and total number of potential values involved in the design.

There are 3 different scenarios being proposed in this paper for further analysis in order to increase the chances of finding most optimized system. The results from all the scenarios has the optimal system combination which encompasses wind-solar-hydro-battery and converter. The best combination will be selected based on less COE, less NPC, smaller excess electricity and less initial capital cost. The suggested scenarios based on the most optimal system design with different hydro input data will be compared in terms of techno-economic aspects.

Scenario 1 simulation results

The HOMER window displays the optimal system design with design flow of 159 L/s which is based on hydropower plant operating at 100% time of the year (precedence). The figure 31 shows the most optimal system combination with the selected parameters.

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

Architecture					Cost				System	
PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Cap Short (%)	Excess Elec (%)
444	17	5,358	140	313	$0.134	$3.60M	$72,292	$2.66M	0.0972	19.5
652		5,754	140	369	$0.145	$3.89M	$87,041	$2.77M	0.0972	24.3
	142	9,228	140	454	$0.278	$7.48M	$132,710	$5.76M	0.0880	32.6

Figure 31: Optimization results at 159 L/s design flow

Scenario 2 simulation results

Scenario 2 has design flow of 400 L/s which is based on 95% of hydropower plant availability throughout the year. The HOMER window in figure 32 displays the most optimal system combination with selected parameters.

Optimization Results

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

PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Cap Short (%)	Excess Elec (%)
1,286	9	9,198	353	403	$0.227	$6.10M	$110,020	$4.68M	0.0983	67.4
1,436		9,312	353	431	$0.231	$6.21M	$112,374	$4.76M	0.0938	68.2
1,548	34	10,422		496	$0.339	$9.10M	$242,697	$5.97M	0.0983	24.6
1,889		11,334		503	$0.357	$9.60M	$282,718	$5.94M	0.0872	28.4
	186	17,718	353	642	$0.430	$11.5M	$206,742	$8.88M	0.0990	64.9
	1,028	38,910		1,375	$1.56	$41.8M	$714,249	$32.5M	0.0958	78.3

Figure 32: Optimization results at 400 L/s design flow

Scenario 3 simulation results

Scenario 3 has design flow of 637 L/s which is based on 91% of hydropower plant availability throughout the year. The HOMER window in figure 33 displays the most optimal system combination with selected parameters.

Optimization Results

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

PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Cap Short (%)	Excess Elec (%)
1,286	9	9,198	562	403	$0.227	$6.10M	$110,020	$4.68M	100	0.0983	75.7
1,436		9,312	562	431	$0.231	$6.21M	$112,374	$4.76M	100	0.0938	76.2
	186	17,718	562	642	$0.430	$11.5M	$206,742	$8.88M	100	0.0990	74.4

Figure 33: Optimization results at 637 L/s design flow

5.2. Comparison of Scenarios for Economic Power Systems

The most optimal system designs are displayed in the figures 31-33 above. The comparison of scenarios was done by keeping all the constraint values constant to all system configurations. The comparison of scenarios was done based on the following:

Based on net present cost (NPC)

The three scenarios presented in this paper indicate that scenario 1 has the lowest NPC while scenario 2 and 3 have the same NPC which are higher. With reference from the figures 31-33, the NPC for scenario 1 is $ 3,600,000 while NPC for scenario 2 and 3 is $ 6,100,000.

Based on cost of energy (COE)

The detailed information about COE for each power system configuration is displayed in figures 31-33. Scenario 1 has COE of $0.134/kWh while scenario 2 and 3 have the same COE of $0.227/kWh. This shows that scenario 1 has the smallest value of COE as compared to scenario 2 and 3. Thus, the scenario 1 is better because the cost of energy is cheaper than the other scenarios.

Based on Excess Electricity Production

Excess of electricity production is another comparison parameter which was adopted. The lowest excess electricity production is the optimal system design. Scenario 1 has the lowest excess electricity production of 19.5% as compared to scenario 2 and 3 which have excess electricity production of 67.4% and 75.7% respectively. Thus, scenario 1 is the best option here. However, excess electricity production can be good for the expansion of the load demand but it attracts extra cost.

Based on initial capital cost

The initial capital cost is one of the determinant in making a decision to start the investment. Thus, the system which has less initial capital cost while serving the same purpose is the optimal system. With reference from the figures 31-33, scenario 1 has lowest initial capital cost of $2,660,000 as compared to scenario 2 and 3 which have the same initial capital cost of $4,680,000. This shows that the optimal system design in terms of initial capital cost is scenario1.

The figures 34 gives the summary of all the scenarios compared based initial capital cost, NPC, excess electricity production and COE per kWh.

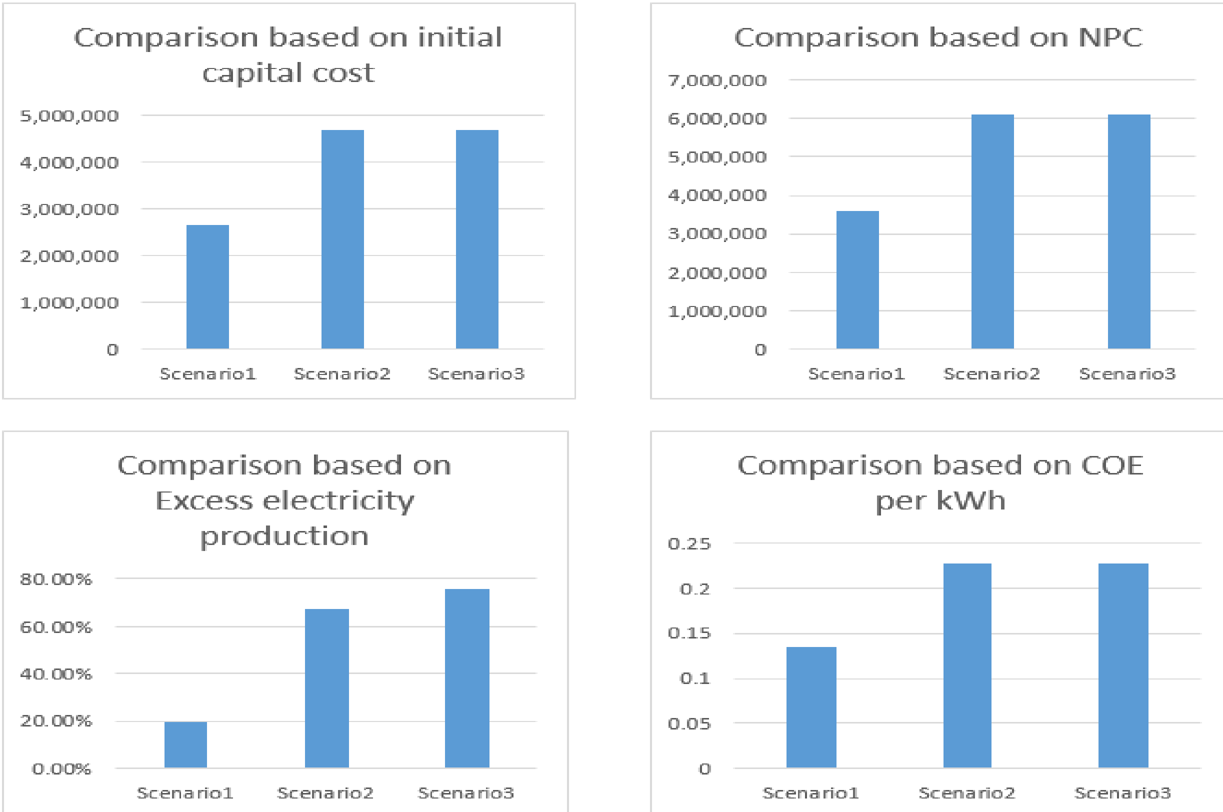


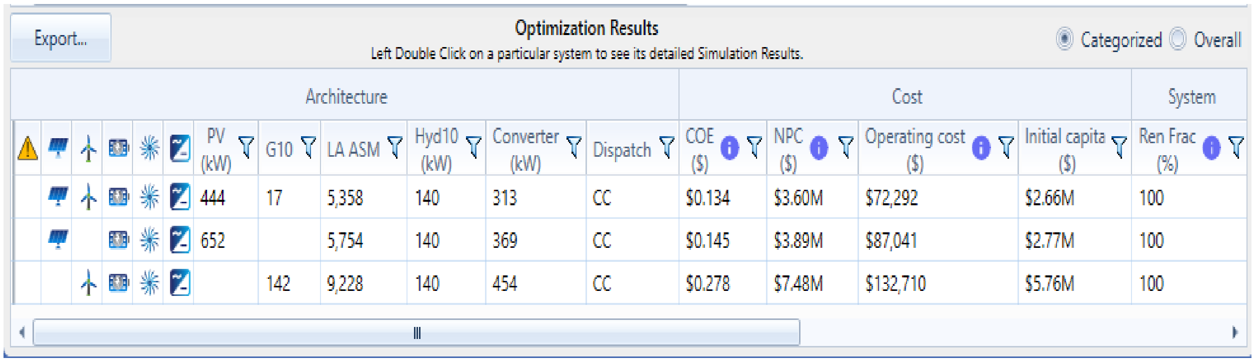
Figure 34: Comparing results of different scenarios

From the comparison, it clearly shows that scenario 1 has the system architecture with less initial capital cost, low cost of energy, less NPC and less excess of electricity production. The optimization analysis of the selected (scenario 1) which comprises of the design flow of 159 L/s which will be available throughout the year.

According to Figure 19: turbine selection chart, with 100m elevation of Dwangwa river then the selected hydro turbine is Kaplan turbine. Thus, the optimal design for the study area comprises of wind-solar-hydro-battery and converter.

5.3. Optimization Analysis of the Selected Scenario

After the simulation of three scenarios, scenario 1 was the winner of the three scenarios. The categorized results of simulation were shown in the HOMER window on figure 36. The most optimal system design is comprised of wind-solar-hydro-battery and converter. The system set up in the first row of figure 35 is the cost efficient system composed of 17 units of wind turbine with rated capacity of 10 kW each, 444 kW of solar photovoltaic capacity, 140 kW of hydro turbine with rated capacity of 10 kW each, 5358 units of batteries while the converter capacity is 313 kW.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Optimization Results

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

Categorized Overall

Architecture						Cost				System
PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capita ($)	Ren Frac (%)
444	17	5,358	140	313	CC	$0.134	$3.60M	$72,292	$2.66M	100
652		5,754	140	369	CC	$0.145	$3.89M	$87,041	$2.77M	100
	142	9,228	140	454	CC	$0.278	$7.48M	$132,710	$5.76M	100

Figure 35: HOMER window of selected scenario

The monthly power generation for all the three technologies were obtained after simulation as shown in figure 36. The wind speed potential is comparatively small throughout the year, however, the wind speed potential is fairly high from month of June to November. The lowest electricity production occurs in September due to declining water levels while production from wind is the increases.

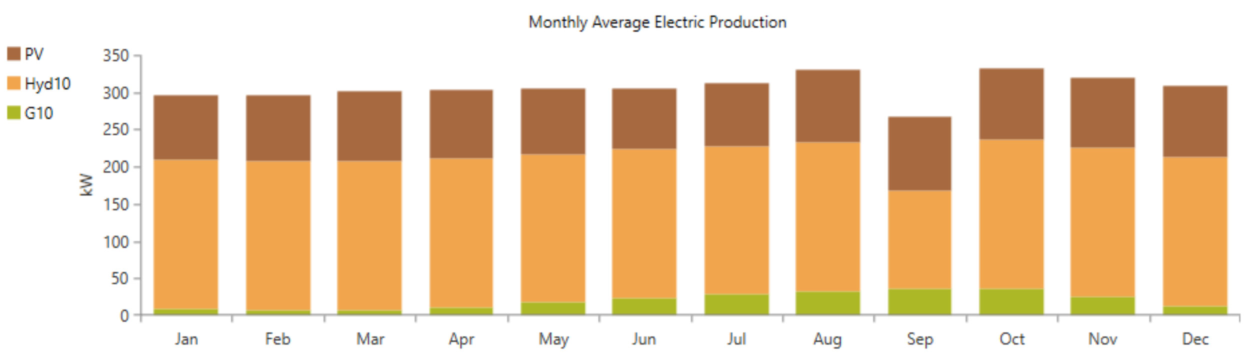


Figure 36: Monthly average electricity production

The results show that the annual AC primary load consumption 2,077,528 kWh which is supplied by all the three power units of the hybrid system. The electricity generation by each power unit of the hybrid system is given in figure 37. Hydro is the highest power producer which contribute 63.4% (1,703,110 kWh/year) seconded by PV which contributes 29.9% (802,761 kWh/year). The smallest electricity producer is wind which contributes 6.67% (179,113 kWh/year). Thus, the total electricity production for the system is 2,684,984 kWh/year.

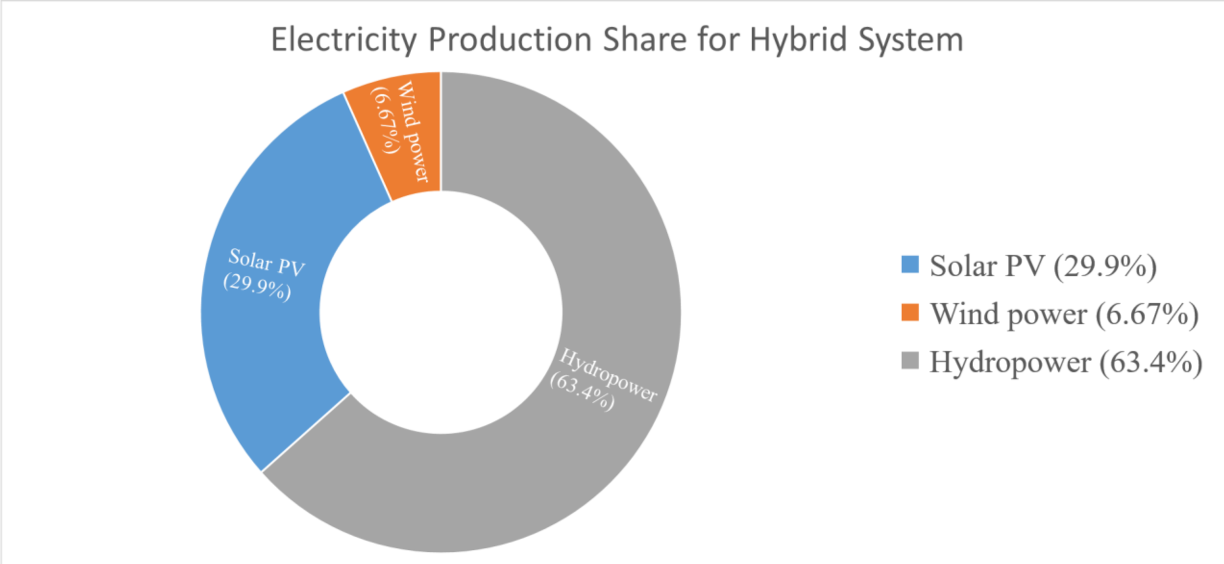


Figure 37: Electricity Production Share for Hybrid System

Looking at the power production of this hybrid system and total electric power consumption of the load, the surplus of 19.5% (522,715 kWh/year) was realized from the simulation results. Although 19.5% excess of electricity was produced but there was a capacity shortage of 2,020 kWh/year (0.0972%) in the course of the year. However, this power system design has shown that it would be able to accommodate for the growing demand of the community in future. The figure 38 shows the comparison of electricity production, electricity consumption and excess electricity.

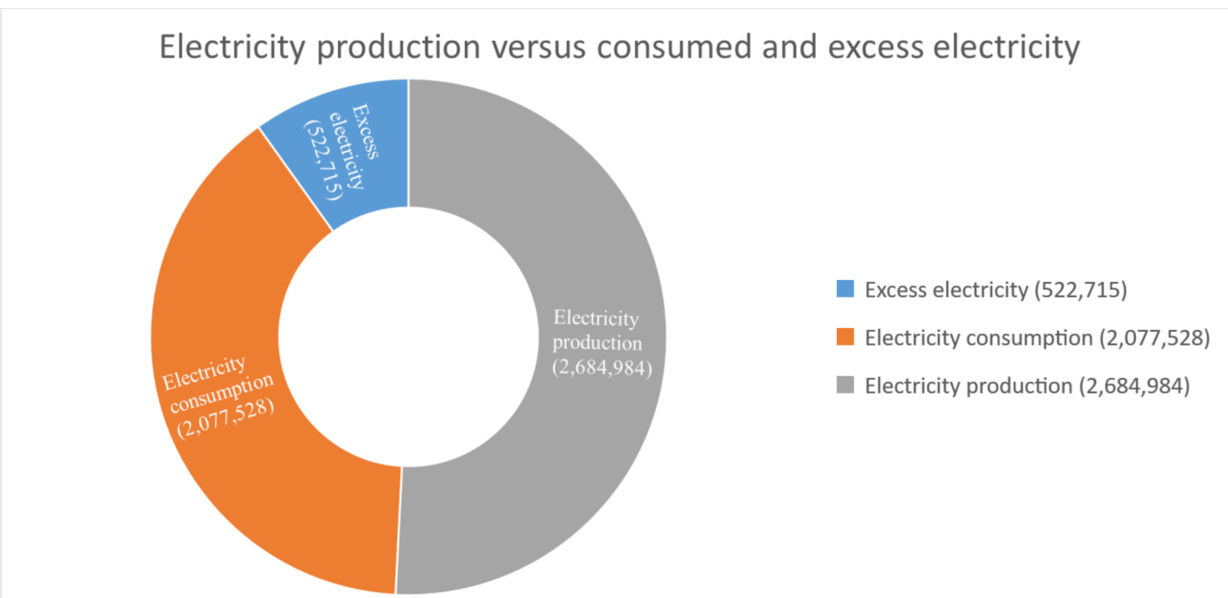


Figure 38: Electricity production versus consumed and excess electricity

5.3.1. Electricity production by wind turbines

The electricity production by wind turbines is shown in the table 10 and figure 39.

Table 10: Wind turbine simulation results

Quantity	Value	Units
Total Rated Capacity	170	kW
Mean Output	20.4	kW
Maximum Output	170	kW
Wind Penetration	8.62	%
Hours of Operation	6,456	hrs/yr
Levelized Cost	0.196	$/kWh

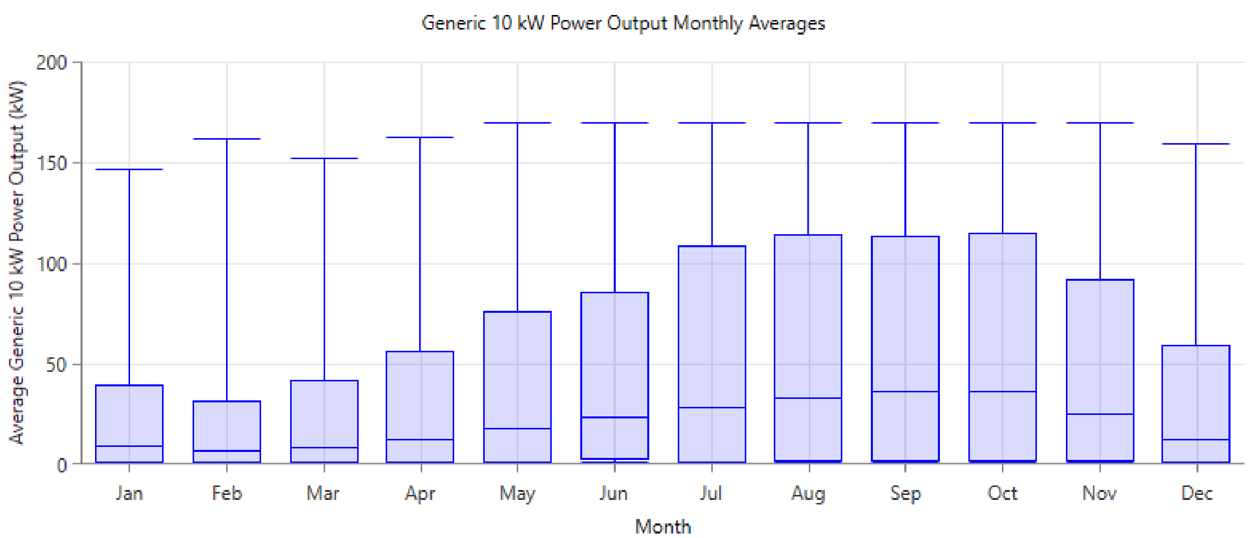


Figure 39: Wind turbine (Generic 10kW) monthly avearge power output

The results clearly show that energy production by wind turbine is comparatively higher in July, August, September and October. The total rated capacity of wind turbines is 170 kW and the maximum output power is also 170 kW. The mean power output for wind system is 20.4 kW. The levelized cost of energy for wind is $0.196/kWh.

5.3.2. Electricity production by solar PV

The electricity production by solar PV is shown in the table 11 and figure 40.

Table 11:Solar PV simulation results

Quantity	Value	Units
Rated Capacity	444	kW
Mean Output	91.6	kW
Mean Output	2,199	kWh/d
Total Production	802,761	kWh/yr
Maximum Output	519	kW
PV Penetration	38.6	%
Hours of Operation	4,332	hrs/yr
Levelized Cost	0.076	$/kWh

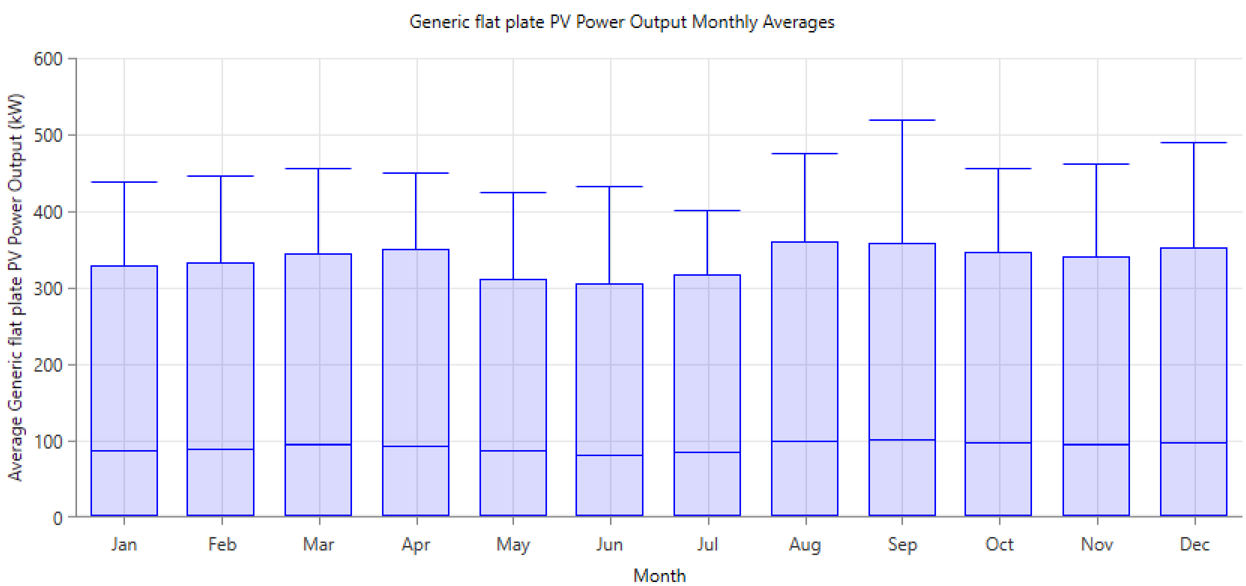


Figure 40: Solar PV monthly average power output

From the results, the rated power capacity is 444 kW and the average power output is 91.6 kW with 0 kW during no sun. Solar PV only operate when the sun is available hence no production at night hence total hours of operation is 4,332 hours per annum. The levelized cost of energy for solar PV is $0.076/kWh.

5.3.3. Electricity production by hydropower

The electricity production by hydropower system is shown in the table 12 and figure 41.

Table 12: Hydropower simulation results

Quantity	Value	Units
Nominal Capacity	140	kW
Mean output	194	kW
Capacity factor	138	%
Total Production	1,703,110	kWh/yr
Minimum output	132	kW
Maximum output	200	kW
Hydro penetration	81.9	%
Hours of operation	8,760	hrs/yr
Levelized Cost	0.00101	$/kWh

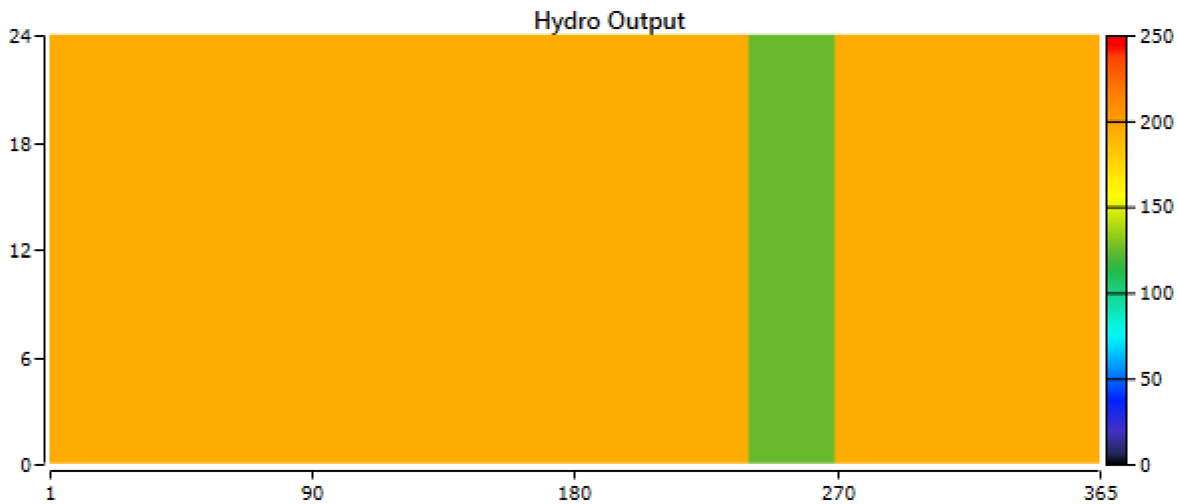


Figure 41: Hydropower hourly production in a year

The results show that the electricity production by hydro turbine is nearly constant throughout the day. Maximum production of 200 kW is experienced throughout the year except the month of September which has the minimum production of 132 kW. Hydropower system has operation hours of 8,760 hours per year (whole year). The levelized cost of energy for hydropower is $0.00101/kWh.

5.3.4. Battery simulation results

The simulation results show that the whole hybrid system needs 5358 batteries of 5,496 kWh capacity with autonomy of 18.5 hours. Since the battery storage has minimum state of charge of 40% then usable nominal capacity is 3,298 kWh. The expected lifetime of the battery system is 14.2 years. Table 13 summarises the battery simulation results for the optimal hybrid system.

Table 13: Battery simulation results summary

Quantity	Value	Units
Batteries	5,358	qty.
String Size	6.00	batteries
Strings in Parallel	893	strings
Bus Voltage	12.0	V

Quantity	Value	Units
Autonomy	18.5	hr
Storage Wear Cost	0.171	$/kWh
Nominal Capacity	5,496	kWh
Usable Nominal Capacity	3,298	kWh
Lifetime Throughput	4,922,396	kWh
Expected Life	14.2	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	375,884	kWh/yr
Energy Out	317,487	kWh/yr
Storage Depletion	966	kWh/yr
Losses	59,363	kWh/yr
Annual Throughput	345,666	kWh/yr

The battery state of charge in figure 42 indicate that the month of September, storage was heavily used by the load which is evidenced by low hydropower capacity due to low water levels.

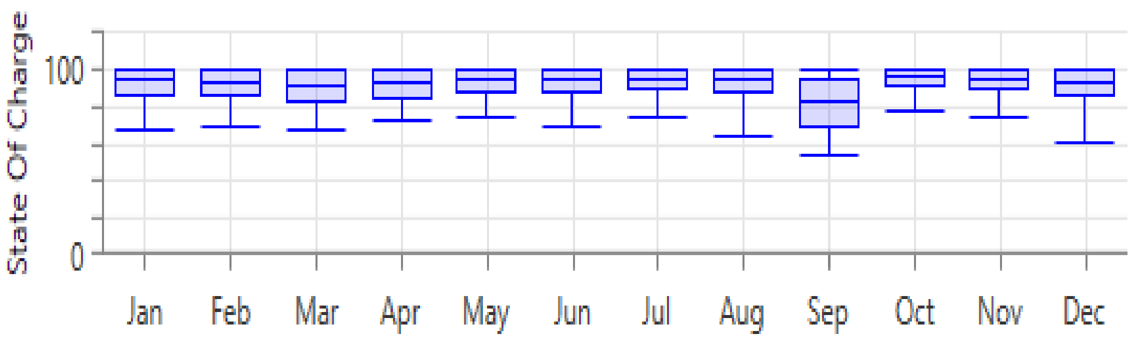


Figure 42: Monthly Battery state of charge

5.3.5. System converter simulation results

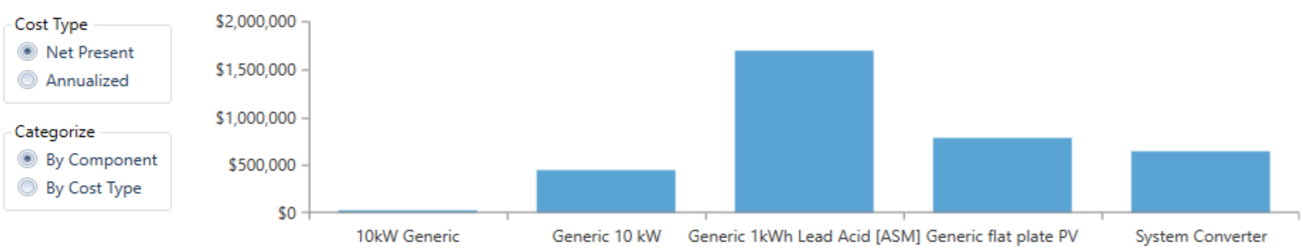
The converter capacity for the optimal system is 313 kW and inverter is expected to operate at about 5,139 hours in a year while rectifier is 1,937 hours. The table 14 summarises the converter simulation results.

Table 14: Converter's summary of simulation results

Quantity	Inverter	Rectifier	Units
Capacity	313	313	kW
Mean Output	42.5	6.94	kW
Minimum Output	0	0	kW
Maximum Output	311	178	kW
Capacity Factor	13.6	2.22	%
Hours of Operation	5,139	1,937	hrs/yr
Energy Out	372,258	60,760	kWh/yr
Energy In	391,850	67,512	kWh/yr
Losses	19,593	6,751	kWh/yr

5.3.6. Cost summary of the system

Figure 43 clearly indicate that battery (Generic 1kWh Lead Acid) is the largest contributor of NPC with NPC of $1,685,912. The solar panels (Generic flat plate PV) had the second highest total NPC which is about $788,644. The third position of NPC is system converter followed by wind turbines (Generic 10 kW) with NPC of $646,889 and $453,582 respectively. However, hydro turbine (10 kW Generic) is smallest contributor of NPC which is $21,171.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
10kW Generic	$17,900.00	$0.00	$4,628.05	$0.00	($357.34)	$22,170.71
Generic 10 kW	$360,400.00	$0.00	$93,181.54	$0.00	$0.00	$453,581.54
Generic 1kWh Lead Acid [ASM]	$1,205,550.00	$373,927.20	$155,847.68	$0.00	($49,412.50)	$1,685,912.37
Generic flat plate PV	$626,628.54	$0.00	$162,015.02	$0.00	$0.00	$788,643.56
System Converter	$452,158.97	$153,471.37	$70,143.51	$0.00	($28,884.86)	$646,888.99
System	$2,662,637.51	$527,398.57	$485,815.79	$0.00	($78,654.70)	$3,597,197.17

Figure 43: Cost summary of the system from simulation results

The whole hybrid system capital cost $2,662,638 while Net present cost (NPC) and levelized cost of energy (COE) are $3,597,197 and $0.134/kWh respectively. The highest capital cost for the hybrid system is contributed by battery while the smallest capital cost is contributed by hydropower (10 kW Generic). The figure 44 gives the percentage share of capital cost for the individual component.

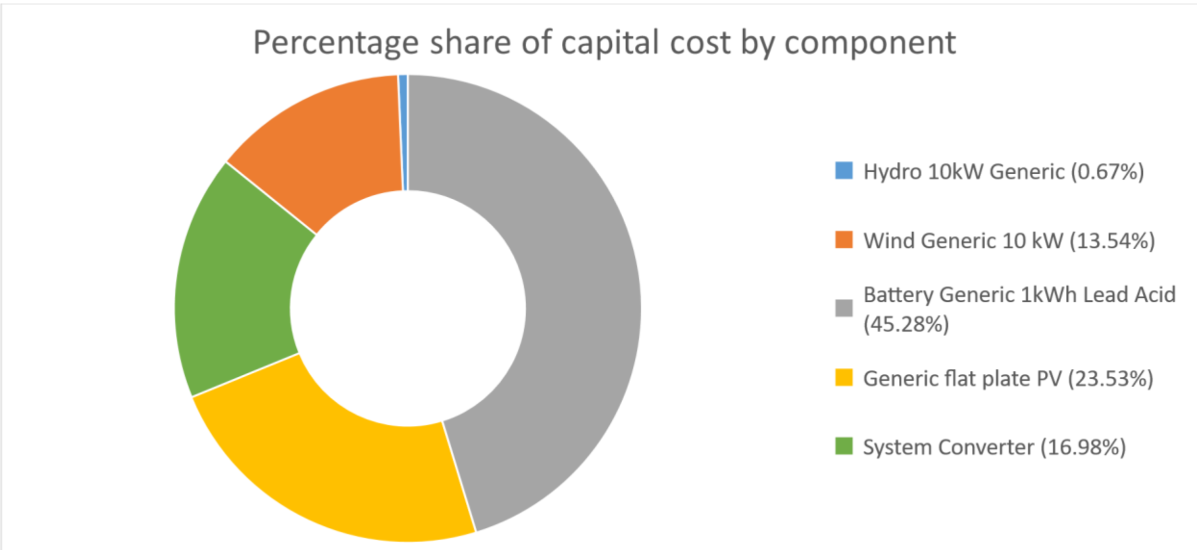


Figure 44: Percentage share of capital cost by component

5.4. Sensitivity analysis

Sensitivity analysis is done in order to determine the effects of varying some parameters in the proposed system design. This is performed considering the uncertain variables proposed in the system design which may occur in future or present hence the appropriate hybrid system is designed.

The first sensitivity analysis was done to determine the best design flow for the hydropower plant. This was done to determine the effect of changing the design flow for the river where the system was simulated at 159 L/s, 400 L/s and 637 L/s. The results which are already presented in previous chapter showed that increase in flow rate result in increase in capital cost, levelised cost of energy and also increase excess production of electricity. Therefore, this sensitivity analysis was used to choose the best scenario which showed that the best design flow was 159 L/s which will be available throughout the year.

Other sensitivity variable which were considered were already discussed in the previous chapter which include; the wind capital cost multiplier of 2, solar capital cost multiplier of 0.5, hydro capital cost multiplier of 1.5 which yielded $26,850, converter capital cost multiplier of 0.5 and finally battery capital cost multiplier of 2.

The results in figure 45 which is a plot of capital cost of hydro and capital cost of lead acid battery superimposed with cost of energy. The results show that increase in capital cost for hydro alone has negligible change in cost of energy whereas increase in capital cost of lead acid battery has also significant increase in cost of energy.

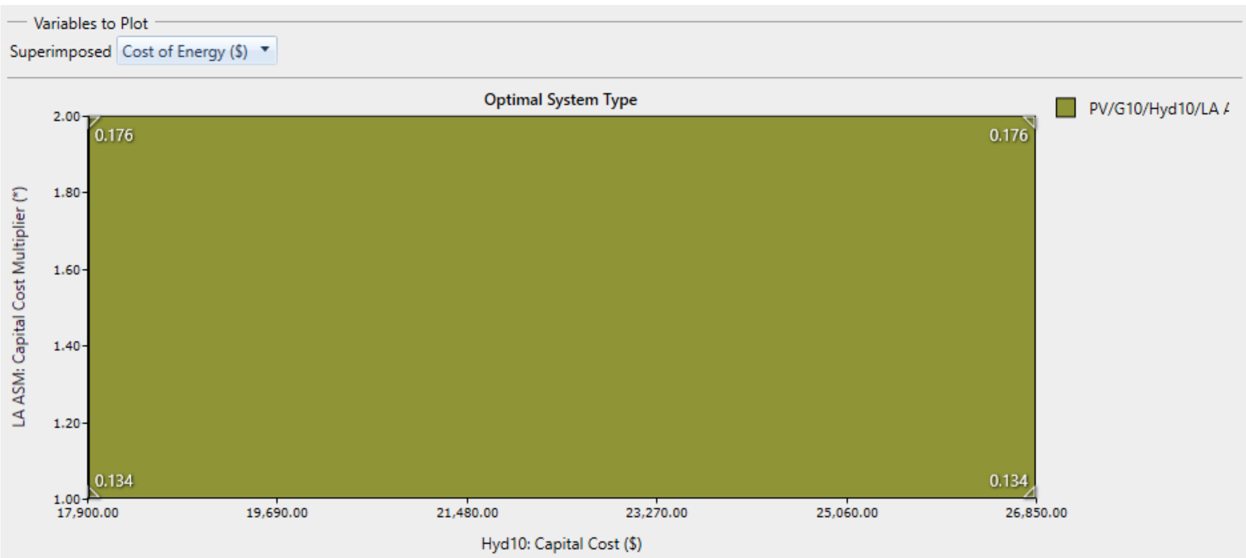


Figure 45: plot of capital cost of hydro and lead acid battery superimposed with cost of energy

Sensitivity plot in figure 46 of capital cost of solar PV against capital cost of wind (G10) to determine the effect their change with respect to cost of energy. The results show that reducing the capital cost of solar PV by half reduces the cost of energy for the whole optimal system from $0.154/kWh to $0.134/kWh. On the other hand, if capital cost of Wind (G10) increases 2 times then the cost of energy for the whole optimal system increases from $0.134/kWh to $0.143/kWh.

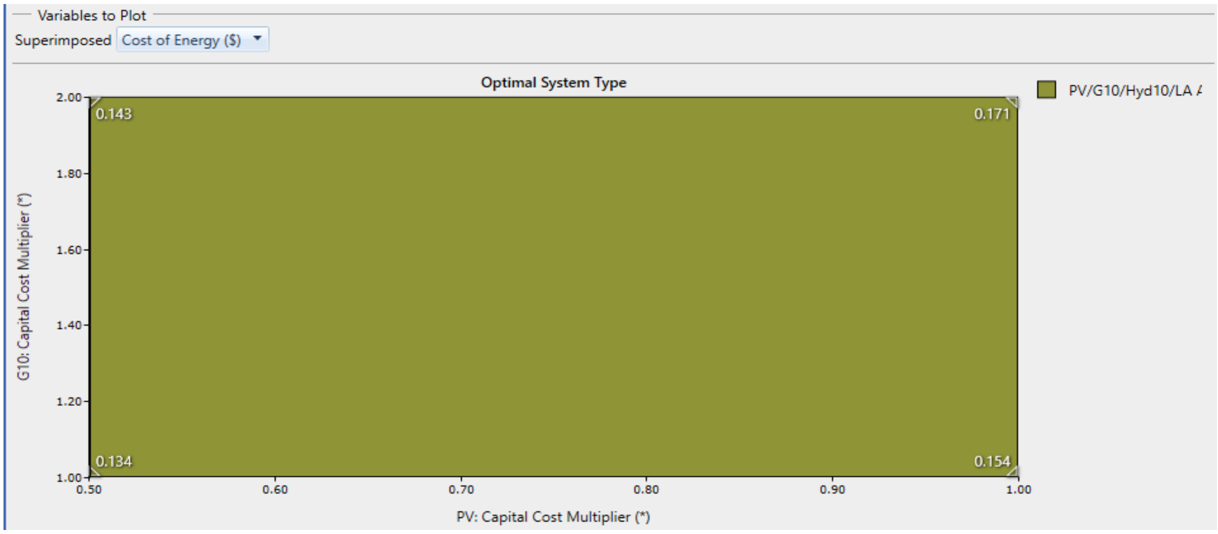


Figure 46:plot of capital cost of solar PV and wind (G10) superimposed with cost of energy

The spider plot of capital cost of hydro, wind, solar PV and lead acid battery show the effect of changing the capital cost with respect to cost energy as shown in figure 47. This plot shows how each of the components respond to change in terms of cost energy for the whole system. The results show that if capital cost increases for lead acid battery (LA ASM), it has greater impact on the cost of energy followed by solar PV and wind turbine (G10). However, hydropower (Hyd10) has relatively little impact on the cost of energy.

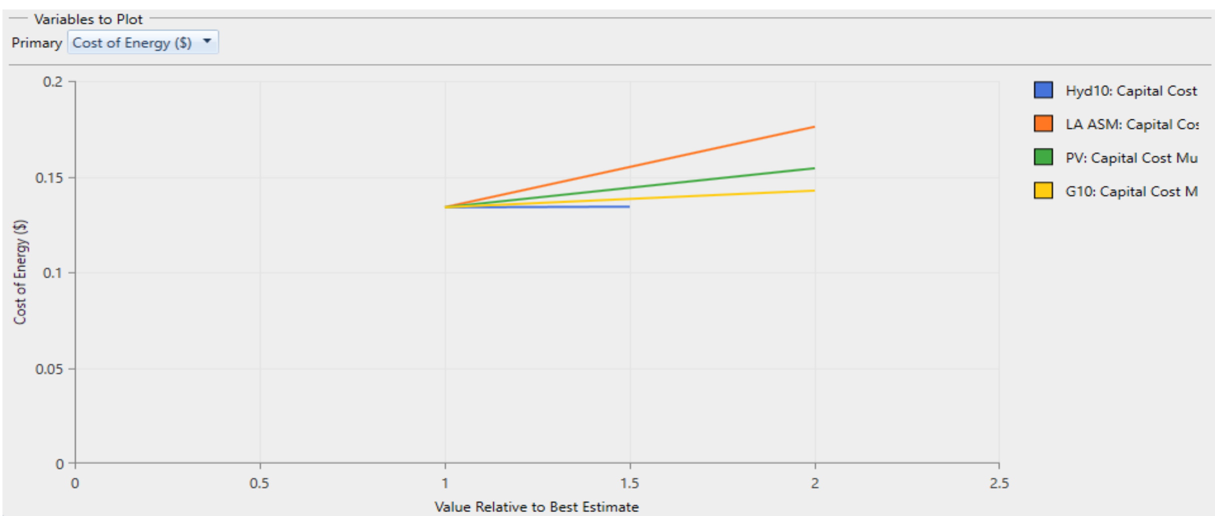


Figure 47: The spider plot of capital cost of hydro, wind, solar PV and lead acid battery on value relative to best estimate against cost of energy

6. Chapter Six: Conclusion and Recommendations

6.1. Conclusion

This thesis work was dedicated to the design of off-grid hybrid renewable energy system for rural villages of Dwangwa with 420 households, commercial load, public activities load, schools, health clinics and pumping load. for the survival of people. The river discharge for Dwangwa river was obtained from the Department of energy for a period of 24 years while solar and wind data were obtained from NASA database. HOMER software was used to analyse these data. The optimal design flow for hydropower was 159 L/s while mean global horizontal solar radiation and mean wind speed at 50m were 5.21 kWh/m^2/day and 4.98m/s respectively.

The proposed hybrid system had proven to be feasible on technical grounds in this particular area with initial capital cost of $2,662,638. According to Malawi Energy Regulatory Authourity (2019), the cost of electricity in Malawi on the grid is K88.02/kWh ($0.11/kWh). This shows that the cost of energy for the proposed hybrid system which is $0.134/kWh is relatively higher. This makes it difficult for people in the rural areas to meet the expense of the electricity. However, Malawi heavily depend on hydropower and looking at the challenges faced by hydropower plants such as low water level and old machines, rural communities might remain without electricity. Therefore, with collective effort from Government and other organisation, this kind of energy system would improve living standards of the rural community.

The optimal system design for the site is comprised of hydro-wind-solar and battery. Thus, environmentally speaking, the proposed system design is completely combination of renewable resources hence clean and reduced pollution to the environment. The sensitivity analysis has also shown that if design flow increases with reduced time of operation for hydropower plant, then there is increased excess electricity production hence another option of increasing the load demand. Again, from sensitivity results, shows that increase in capital cost for battery, solar PV and wind turbine result in increase in cost of energy for the optimal system. However, hydropower has shown that increase in capital cost has very little impact on the cost electricity as compared to other system components.

6.2. Recommendation

Malawi has huge renewable energy resources which are site specific hence the amount of energy that can be generated varies. Theses renewable energy resources can supply huge population without access to electricity through off-grid or grid connection system. However, the main drawback for the implementation this kind of project is economic challenge which is both at supply side and demand side. Thus, investors think of output of the investment hence choose less risk investment and also think of whether people can pay for the service or not.

Hybrid energy systems can be applied where applicable than one source of energy in order to ensure reliability and sustainability. Therefore, Government and other stakeholders should work together in order to increase access to electricity in the country. This can be done through subsidy, taxi holidays and economic incentives.

Suggestions for future work

This thesis work may be improved and expanded by the following:

- ✓ Consider designing a dam to increase hydropower capacity
- ✓ Compare current study with grid extension
- ✓ Consider other renewable energy resources such as solar thermal and biomass
- ✓ Consider exact measured solar radiation and wind speed data

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8. Appendices

Appendix A: Commercial load estimation

Commercial load					
Activity	**Load**	**Quantity**	**Power rating (W)**	**Operating Times**	**Total power (kW)**
10 Groceries	Refrigerator	10	200	00:00-00:00	**2**
	Security lights	10	60	18:00-06:00	**0.6**
	Internal lights	20	20	18:00-21:00	**0.4**
4 Local bars	Refrigerator	8	200	00:00-00:00	**1.6**
	Security lights	8	60	18:00-06:00	**0.48**
	Internal lights	16	20	18:00-05:00	**0.32**
	TV set	4	100	10:00-05:00	**0.4**
	Sound system	4	10	10:00-05:00	**0.04**
6 Female saloon	Internal lights	6	20	18:00-21:00	**0.12**
	Security lights	6	60	18:00-06:00	**0.36**
4 Barber shops	Internal lights	4	20	18:00-21:00	**0.08**
	Security lights	4	60	18:00-06:00	**0.24**
3 Butcheries	Refrigerator	9	200	00:00-00:00	**1.8**
	Security lights	3	60	18:00-06:00	**0.18**
	Internal lights	6	20	18:00-20:00	**0.12**

8 Restaurants	Refrigerator	16	200	00:00-00:00	**3.2**
	Security lights	8	60	18:00-06:00	**0.48**
	Internal lights	32	20	18:00-20:00	**0.64**
	TV set	8	100	10:00-20:00	**0.8**
1 Welding shops	Welding machines	1	10000	08:00-17:00	**10**
1 Flour Milling	Milling machine	1	10000	08:00-17:00	**10**
1 Bakeries	Bakery machine	1	4000	17:00-06:00	**4**
Small hotel with 20 rooms	room lights	30	20	18:00-23:00	**0.6**
	Security lights	2	60	18:00-06:00	**0.12**
	TV set	20	100	18:00-22:00	**2**
	reception TV set	1	100	07:00-23:00	**0.1**
	Fans	20	75	18:00-06:00	**1.5**

Appendix B: Primary school load estimation

Primary School					
Energy need	**Use**	**Quantity**	**Rated power (W)**	**Time of use**	**Total power (kW)**
Lighting	offices	2	20	08:00-16:00	**0.04**
	Library	4	20	08:00-12:00 13:00-16:00	**0.08**
	staff room	4	20	18:00-20:00	**0.08**
	security lights	2	60	18:00-6:00	**0.12**

	store rooms	2	20	N/A	**0.04**
	16 classrooms	64	20	18:00-20:00	**1.28**
Computer	office	1	200	08:00-17:00	**0.2**
Printer	Office	1	100	N/A	**0.1**

Appendix C: Boarding secondary school load estimation

Boarding Secondary School					
Energy need	**Use**	**Quantity**	**Rated power (W)**	**Operating times**	**total power (kW)**
Lighting	2 offices	2	20	07:00-16:00	**0.04**
	administration	2	20	07:00-16:00	**0.04**
	Library	3	20	08:00-12:00 13:00-16:00	**0.06**
	staff room	4	20	07:00-16:00	**0.08**
	security lights	2	60	18:00-06:00	**0.12**
	2 store rooms	2	20	N/A	**0.04**
	12 classrooms	48	20	17:00-21:00	**0.96**
	20 Hostel	60	20	05:00-07:00 17:00-22:00	**1.2**
	cafeteria	6	20	17:00-19:00	**0.12**
Phone charging	staff room	4	7	07:00-16:00	**0.028**

TV set	staff room	1	200	09:00-16:00 18:00-21:00	**0.2**
Computers	Laboratory	20	200	08:00-12:00 13:00-16:00	**4**
	offices	1	200	08:00-16:00	**0.2**
Printer	administration	1	100	N/A	**0.1**
Refrigeration	staff room	1	200	00:00-00:00	**0.2**
	Kitchen	1	200	00:00-00:00	**0.2**
cooking	Kitchen	1	1500	08:00-09:00 12:00-13:00	**1.5**
electric jug	Kitchen	1	1400	09:00-10:00	**1.4**

Appendix D: Community secondary school load estimation

Community Day Secondary School					
Appliances	**Use**	**Quantity**	**Rated power (W)**	**Operating times**	**total power (kW)**
Lighting	Offices	2	20	07:00-16:00	**0.04**
	Administration	2	20	07:00-16:00	**0.04**
	Library	4	20	08:00-12:00 07:00-16:00	**0.08**
	Staff Room	4	20	07:00-16:00	**0.08**
	Security lights	2	60	18:00-6:00	**0.12**

	Store Rooms	2	20	N/A	**0.04**
	8 Classrooms	32	20	07:00-16:00	**0.64**
Phone charging	Staff Room	4	7	07:00-16:00	**0.028**
TV set	Staff Room	1	100	07:00-16:00	**0.1**
Computer	Offices	1	200	07:00-16:00	**0.2**
	Laboratory	20	200	07:00-16:00	**4**
Printer	Administration	1	100	N/A	**0.1**
Refrigeration	Staff Room	1	200	00:00-00:00	**0.2**
electric jug	10 minute water boiling	1	1400	09:00-10:00	**0.233**

healthy centre					
Appliances	Use	Quantity	Rated power (W)	Time of use	Total power kW
Equipments	Refrigerator	1	200	00:00-00:00	0.2
	Microscopes	2	25	08:00-12:00 13:00-17:00	0.05
	Sterilise machine	1	200	08:00-12:00 13:00-17:00	0.2
	Other lab. Equipments	1	300	08:00-12:00 13:00-17:00	0.3
TV set	Reception	1	100	08:00-17:00	0.1
Computer	Office	1	200	08:00-12:00 13:00-17:00	0.2
Printer	Office	1	100	08:00-12:00 13:00-17:00	0.1
Electric stove	Water heating/ fast food	1	1000	10:00-10:10 15:00-15:10	1

Fan	Office	1	75	08:00-12:00 13:00-17:00	0.075
	2 Wards	4	75	09:00-12:00 13:00-17:00	0.3
Lighting	2 wards	4	20	08:00-17:00	0.08
	Office	1	20	08:00-12:00 13:00-17:00	0.02
	Reception	2	20	08:00-17:00	0.04
	Laboratory	2	20	08:00-17:00	0.04
	Corridors	2	20	08:00-17:00	0.04
	Security lights	4	60	18:00-06:00	0.24

Appendix E: Healthy Centre load estimation

healthy centre					
Appliances	Use	Quantity	Rated power (W)	Time of use	Total power kW
Equipments	Refrigerator	1	200	00:00-00:00	0.2
	Microscopes	2	25	08:00-12:00 13:00-17:00	0.05
	Sterilise machine	1	200	08:00-12:00 13:00-17:00	0.2
	Other lab. Equipments	1	300	08:00-12:00 13:00-17:00	0.3
TV set	Reception	1	100	08:00-17:00	0.1
Computer	Office	1	200	08:00-12:00 13:00-17:00	0.2
Printer	Office	1	100	08:00-12:00 13:00-17:00	0.1
Electric stove	Water heating/ fast food	1	1000	10:00-10:10 15:00-15:10	1
Fan	Office	1	75	08:00-12:00 13:00-17:00	0.075

	2 Wards	4	75	09:00-12:00 13:00-17:00	0.3
Lighting	2 wards	4	20	08:00-17:00	0.08
	Office	1	20	08:00-12:00 13:00-17:00	0.02
	Reception	2	20	08:00-17:00	0.04
	Laboratory	2	20	08:00-17:00	0.04
	Corridors	2	20	08:00-17:00	0.04
	Security lights	4	60	18:00-06:00	0.24

Appendix F: Small healthy centre load estimation

healthy centre					
Appliances	**Use**	**Quantity**	**Rated power (W)**	**Time of use**	**Total power kW**
Equipments	Refrigerator	1	200	00:00-00:00	**0.2**
	Microscopes	2	25	08:00-12:00 13:00-17:00	**0.05**
	Sterilise machine	1	200	08:00-12:00 13:00-17:00	**0.2**
	Other lab. Equipments	1	300	08:00-12:00 13:00-17:00	**0.3**
TV set	Reception	1	100	08:00-17:00	**0.1**
Computer	Office	1	200	08:00-12:00 13:00-17:00	**0.2**
Printer	Office	1	100	08:00-12:00 13:00-17:00	**0.1**

Electric stove	Water heating/ fast food	1	1000	10:00-10:10 15:00-15:10	**1**
Fan	Office	1	75	08:00-12:00 13:00-17:00	**0.075**
	2 Wards	4	75	09:00-12:00 13:00-17:00	**0.3**
Lighting	2 wards	4	20	08:00-17:00	**0.08**
	Office	1	20	08:00-12:00 13:00-17:00	**0.02**
	Reception	2	20	08:00-17:00	**0.04**
	Laboratory	2	20	08:00-17:00	**0.04**
	Corridors	2	20	08:00-17:00	**0.04**
	Security lights	4	60	18:00-06:00	**0.24**

Appendix G: Medium healthy clinic load estimation

Medium healthy centre					
Appliances	**Use**	**Quantity**	**Rated power (W)**	**Time of use**	**total power (kW)**
Equipments	Refrigerator	2	200	00:00-00:00	**0.4**
	Microscopes	3	25	08:00-12:00 13:00-17:00	**0.075**
	Sterilise machine	2	200	08:00-12:00 13:00-17:00	**0.4**
	Other lab. Equipments	1	600	08:00-12:00 13:00-17:00	**0.6**

TV set	Reception	1	100	08:00-22:00	**0.1**
Computer	Office	2	200	08:00-12:00 13:00-17:00	**0.4**
Printer	Office	2	100	08:00-12:00 13:00-17:00	**0.2**
Electric stove	Water heating/ fast food	2	1000	10:00-10:10 15:00-15:10	**2**
Fan	2 Offices	2	75	08:00-12:00 13:00-17:00	**0.15**
	3 Wards	6	75	10:00-00:00	**0.45**
Lighting	3 wards	6	20	17:00-07:00	**0.12**
	2 Offices	2	20	08:00-12:00 13:00-17:00	**0.04**
	Reception	2	20	17:00-07:00	**0.04**
	Laboratory	2	20	08:00-17:00	**0.04**
	Corridors	4	20	17:00-06:00	**0.08**
	Security lights	6	60	18:00-06:00	**0.36**

Appendix H: Higher clinic load estimation

Higher clinic					
Appliances	**Use**	**Quantity**	**Rated power (W)**	**Time of use**	**total power in kW**
Equipments	Refrigerator	3	200	00:00-00:00	**0.6**
	Microscopes	4	25	08:00-12:00 13:00-17:00	**0.1**
	Sterilize machine	4	200	08:00-12:00 13:00-17:00	**0.8**

	Other lab. Equipment	1	1200	08:00-12:00 13:00-17:00	**1.2**
	Other ward equipment	1	600	00:00-00:00	**0.6**
TV set	Reception	1	100	08:00-22:00	**0.1**
Computer	Office	4	200	08:00-12:00 13:00-17:00	**0.8**
Printer	Office	4	100	08:00-12:00 13:00-17:00	**0.4**
Electric stove	Water heating/ fast food	2	1500	10:00-10:10 15:00-15:10	**3**
Fan	4 Offices	4	75	08:00-12:00 13:00-17:00	**0.3**
	6 Wards	12	75	10:00-00:00	**0.9**
Lighting	6 wards	12	20	17:00-07:00	**0.24**
	4 Offices	4	20	08:00-12:00 13:00-17:00	**0.08**
	Reception	2	20	17:00-07:00	**0.04**
	Laboratory	2	20	08:00-17:00	**0.04**
	Corridors	10	20	17:00-07:00	**0.2**
	Security lights	10	60	18:00-06:00	**0.6**

Appendix I: Weekend load estimation

Weekend load estimation								
From	**To**	**Residential consumption (kW)**	**Pumps consumption (kW)**	**Public consumption (kW)**	**Commercial consumption (kW)**	**School consumption (kW)**	**Clinic consumption (kW)**	**Hourly Total consumption (kW)**
0:00	1:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
1:00	2:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
2:00	3:00	140.28	16.2	0.92	17.32	0.96	3.2	178.83
3:00	4:00	140.28	16.2	0.92	17.32	0.96	3.56	179.19
4:00	5:00	165.48	16.2	0.92	17.32	0.96	3.48	204.31
5:00	6:00	159.6	0	0.92	16.56	0.96	3.48	181.52
6:00	7:00	126	48.7	0.65	8.6	1.8	1.8	187.55
7:00	8:00	165.9	48.7	0.65	8.6	0.6	1.8	226.25
8:00	9:00	165.9	48.7	0.4	8.6	0.6	8.87	233.07
9:00	10:00	165.9	33.3	0.4	8.6	0.6	8.87	217.67
10:00	11:00	165.9	33.3	0.4	9.84	0.6	10.68	220.72
11:00	12:00	165.9	33.3	0.4	9.84	0.6	10.62	220.66
12:00	13:00	165.9	33.3	0.4	9.84	0.6	6.73	216.77
13:00	14:00	165.9	33.3	0.4	9.84	0.6	10.52	220.56
14:00	15:00	165.9	33.3	0.4	9.84	0.6	10.52	220.56
15:00	16:00	165.9	48.7	0.4	9.84	0.6	10.52	235.96
16:00	17:00	165.9	48.7	0.4	9.84	0.6	10.52	235.96
17:00	18:00	165.9	48.7	0.2	9.84	0.6	4.07	229.31
18:00	19:00	258.3	15.4	0.92	22.18	3.84	4.04	304.68
19:00	20:00	258.3	15.4	0.92	22.18	4.68	5.27	306.75
20:00	21:00	258.3	0	0.92	20.74	3.2	5.17	288.33
21:00	22:00	258.3	0	0.92	20.02	2.16	5.27	286.67
22:00	23:00	264.18	0	0.92	20.02	0.84	5.07	291.03
23:00	0:00	140.28	0	0.92	20.02	0.96	5.11	167.29

TOTAL	**4274.8**	**604**	**16.1**	**341**	**29.8**	**145.57**	**5411.3**

Appendix J: 10 kW wind turbine Parameter

Parameters	**Quantities**
Model	NE-10k
Rated power	10kw
Maximum power	13kw
Rated voltage	220/240/380v
Start-up wind speed	3m/s
Rated wind speed	10m/s
Survival wind speed	45m/s
Top net weight	400kg
Wheel diameter	8.2m
Number of blades	3
Blades material	Reinforced glass fiber
Generator type	Three phase permanent magnet AC synchronous generator
Magnet material	NdFeB
Generator case	Carbon steel
Control system	Electromagnet/wind wheel yaw
Speed regulation	Tail furling
Working temperature	-40°C - 80°C
Certificates	CE, ISO14001, ISO 9001,TUV
Place of Origin:	Jiangsu, China (Mainland)
Brand Name:	Naier

Appendix K: Solar PV panel information

Parameters	Quantities
Model number	BSM500M-96
Panel technology	Monocrystalline Silicon
Rated Maximum Power at STC	500W
Open Circuit Voltage(Voc/V)	58.95
Maximum Power Voltage(Vmp/V)	48.63
Short Circuit Current(Isc/A)	10.87
Maximum Power Current(Imp/A)	10.28
Module Efficiency	19.51%
Positive tolerance	+3%
Standard Test Condition(STC)	Irradiance 1000 W/m2 Air Mass 1.5 Cell Temperature 25 Centigrade
Place of Origin:	Jiangsu, China (Mainland)
Brand Name:	Bluesun
Certificate:	TUV/IEC61215/IEC61730/CEC/CE/ISO/INMETRO