Feasibility Study and Design of Standalone Solar/Wind/Genset System for Rural Electrification

(Case Study: Shenen Sillasie, Wonji Shoa)

Endalkachew Teshale Wago

A Thesis Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Specialization in Power System Engineering)

Office of Graduate Studies

Adama Science and Technology University

December, 2022

Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled "Feasibility Study and Design of Standalone Solar/Wind/Genset System for Rural Electrification Case Study: Shenen Sillasie, Wonji Shoa" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Endalkachew Teshale	__________________	December, 2022
Name of the student	Signature	Date

Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "Feasibility Study and Design of Standalone Solar/Wind/Genset System for Rural Electrification (Case Study: Shenen Sillasie, Wonji Shoa)" prepared under my guidance by Endalkachew Teshale submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Power System Engineering.

Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

______________________	________________	____________
Advisor	Signature	Date

Approval Sheet

I, the advisors of the thesis entitled "Feasibility Study and Design of Standalone Solar/Wind/Genset System for Rural Electrification (Case Study: Shenen Sillasie, Wonji Shoa)" and developed by Endalkachew Teshale, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

______________________	___________________	_________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Endalkachew Teshale have read and evaluated the thesis entitled "Feasibility Study and Design of Standalone Solar/Wind/Genset System for Rural Electrification (Case Study: Shenen Sillasie, Wonji Shoa)" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Power System Engineering.

_________________________	____________________	December, 2022
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Dr. Yeshitela Shiferaw	____________________	December, 2022
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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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List of Acronyms and Abbreviations

AC	Alternate Current
COE	Cost of energy
DC	Direct Current
EEPCo	Ethiopian Electric Power Corporation
HAWT	Horizontal Axis Wind Turbine
HOMER	Hybrid Optimization and Modeling of Electrical Renewable
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
NMA	National Metrology Agency
NPC	Net present cost
NREL	National Renewable Energy Laboratory
PV	Photo Voltaic
RES	Renewable Energy Sources
SWERA	Solar and Wind Energy Resource Assessment
VAWT	Vertical Axis Wind Turbine

Abstract

*Now a days, Ethiopian government gives attention to rural electrification and Ethiopian Electric Power Utility company uses extension of grid and installation of diesel generator as option for rural villages. However, grid expansion to such areas is not practically possible due to their remoteness, sparse population, and low demand. The introductions of renewable energies for rural areas were the best option to overcome environmental and higher cost of fuel for generators and their operation and maintenance issues. In this study, the feasibility and design of standalone pv/wind/genset system for rural community of Shenen Sillasie has been simulated and optimized using HOMER software. The optimal design of a hybrid power system took into account the community's deferrable energy demand of 9.5Kwh/day with 1.6kw peak load as well as the primary energy demand of 516Kwh/day with 203Kw peak load. And also compares the hybrid system cost versus the grid expansion to electrify the village that is:- at the distance of 9.92km, which is the breakeven distance, the net present cost of expanding the grid is equal to the net present cost of a stand-alone system. The stand-alone system is best when used farther from the grid, and grid extension is best when used closer to the grid. Solar and wind energy are therefore regarded as primary sources for supplying electricity directly to loads and for charging battery banks when solar and wind energy generation is in excess. However, a diesel generator could also be used during periods of high load. By electrifying residential areas and the areas around them, the integration of the hybrid system aims to increase the sustainability of the power supply by lowering the demand for fossil fuels. The final result shows that the community needs a 50kw solar array, 2*250kw wind turbine, 25kw diesel generator, 200 units of S6CS25P batteries and 200kw converter with the best cost of energy 0.289$/kwh and the net present $543,884.*

Key words: *HOMER, hybrid power generation, photovoltaic energy, renewable energy, rural electrification, wind energy.*

CHAPTER ONE

INTRODUCTION

1.1. Background

Ethiopia is one of the least developed countries in the world. Approximately 34% of its over 100 million inhabitants live below poverty line. At the same time the economy is one of the fastest growing in the world, with an average growth of 10, 8% since 2005(International Energy Agency, 2016) & (AFDB, OECD, UNDP, 2016).

Ethiopia is endowed with renewable energy sources. These include first of all hydro, but also wind, geothermal, solar as well as biomass. Only a small portion of the potential is harnessed today. Due to its fast economic growth the energy demand is increasing enormous. Therefore it is expected to rise by a rate of 10 -14% per year till 2037 (Ethiopian Electric Power Corporation, 2013). According to International Energy Agency 2014 report Ethiopia has a final energy consumption of around 40,000 GWh, whereof 92% are consumed by domestic appliances, 4% by transport sector and 3% by industry. The produced electricity of ~ 9000 GWh/yr is mainly generated by hydro energy (96%) followed by wind energy (4%), whereof in total 11% get exported.

Today only 27 % of the rural populations have access to electricity grid. This share is increasing due to an extension of the national grid on the one hand and an increasing number of Stand-alone-systems and Mini-grids on the other hand. But as (2009/10) the early studies taken by Ethiopian Electric Power Corporation (EEPCo) shows, 85% of the population lives in rural areas and the electricity access by the country have increased from 15% to 41%. However, most of the customers live in urban areas and consumes less than 50 kWh per year, while rural area electricity coverage is less than 2% that is almost negligible (Dalelo A., 2003).

Now a day, due to increase in population and industrialization, there is more demand for electrical energy. Heavy consumption of electricity challenges the power generated by using non-renewable energy sources. However, due to capacity constraints and difficult geographical layout of the remote locations, grid connection of remote villages has not been possible. Therefore, special attention should be paid to the development and diversification of the electricity system with cost-effective renewable energy sources to remote and isolated areas. Recently, Solar and wind energy generation application have grown rapidly to meet friendly environmental electricity demand. An isolated Hybrid solar and wind power generation system becomes a favorable option for power supply to Small electrical loads at remote location where no utility grid power supply is available. Due to high demand of energy and limited availability of conventional energy, nonconventional sources become more popular among researchers.

1.2. Statement of the problem

Peoples living in rural areas of Ethiopia uses local solutions such as kerosene (for lighting), diesel (for milling and pumping), traditional biomass (for cooking), dry cells (for radio and tape) and etc. Due to, no electricity supply to these areas have been brought negative impact on economy and day to day activities of people living in rural villages of Ethiopia. Therefore, by looking for other resources which can be used as a standalone to supply electric power to the community will reduces the negative impact on the economy.

The rural areas like Shenen Sillasie are among the villages in Ethiopia that are facing similar problems due to the difficulty of providing electricity by extending the grid. This can be reduced by looking another alternative resource that can be used as a standalone to provide electrical access to the community. The thesis proposes hybrid of solar, wind and genset available energies as a first option for electrification.

Shenen Sillasie village is found around Wonji Shoa in the East Shoa zone, Oromia, Ethiopia, located at latitude and longitude of 8.32° N and 39.25° E and an elevation of 1729 meters above sea level. Hence, the geographical location of this area is suitable for the renewable energy sources and rural electrification is possible to establish to this village.

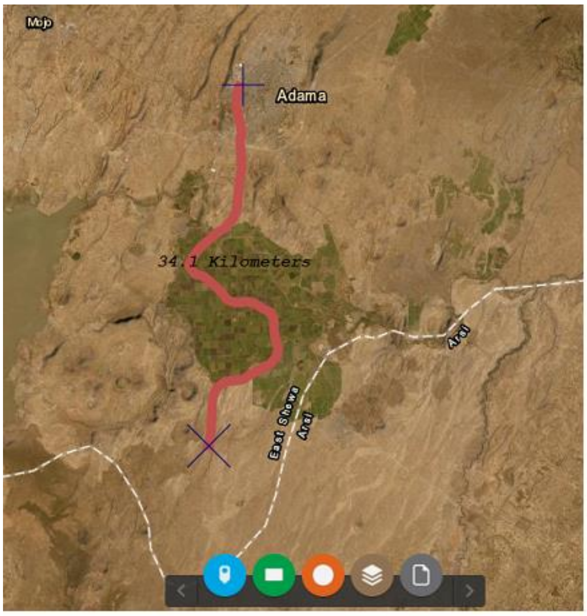

Figure1.1: Google map picture of study area

1.3. Objective of the thesis

1.3.1. General objective

The general objective of the thesis is feasibility study for off-grid electrification of the village of Shenen Sillasie with 400 households. The electrification will be carried out by hybrid system that consists of solar PV, wind and generator set system.

1.3.2. Specific objective

The specific objectives of this thesis work are to:-

- ❖ Estimate and analyze the average solar and wind potential of the area.
- ❖ Estimate the total load and forecast the energy demand of the study area.
- ❖ Design and modeling components of hybrid system (solar module, wind turbines and batteries).
- ❖ Optimal cost estimation and analysis of the PV module, wind turbine, converter and battery.
- ❖ Do optimization and Sensitivity analysis of the PV/Wind/Genset Hybrid system.

1.4. Scope of the thesis

The scope of this thesis work is limited to provide an alternative power supply system to the selected study area with the integration of solar-wind-genset power plant to satisfy their electrical power demand.

1.5. Limitation of the thesis

This thesis will be limited to simulation of the system using HOMER that include its optimization and sensitivity analysis modeled for this specific area and so this need time, resource and financial to implement.

1.6. Significance of the thesis

The study of this thesis contribute the electrical power demand by those people that live in this remote area far from the national grid system and have difficult geographical location to connect to the grid. Also the study is important in the creation of awareness in the peoples and organization in the area with efficient integration and design of hybrid solar-wind-genset power plant which provide electrical power to an isolate area with clean energy source. Hybrid energy systems consist of a combination between renewable energy sources and fossil fuels in conjunction with batteries to circumvent the intermittence, the seasonal and periodical variations, of the renewable energy. Hybrid systems are promising to supply sustainable energy for small grids and standalone systems where one energy source isn't sufficient for the expected load. For a standalone hybrid systems in which their significant load depends on the intermittent energy sources (solar or/and wind); a reliable backup systems are necessary and supplied by storage equipment (battery banks) and diesel generators. These backup systems will also help to optimize the sizing of the hybrid system. There are several kinds of hybrid systems which will be developed by combining solar, hydro, wind and diesel in different scheme according to the available resources in the site (Hybrid Energy System, http://exploringgreentechnology.com/solar-energy/hybrid-energy system).

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Theoretical background

2.1.1. Solar energy system and resource

The sun is the largest energy source of life at the same time it is the ultimate source of all renewable energy (except tidal and geothermal power), even the energy in the fossil fuels ultimately comes from the sun. The sun radiates 100,000,000,000,000 kilowatt hours of energy to the earth per hour. In other words, the earth receives 10^{18} watts of power (Danish Wind Industry Association).

The sun is a typical star with mass 2×10^{30} kg, beam length 700,000 km and it has roughly 5 billion more years of life. Its surface temperature is about 5,800 Kelvin while the internal temperature is approximately 15 million Kelvin. This temperature derives from reactions which were based on the transformation of hydrogen to helium, the process called nuclear fusion, which produces high temperature of the sun and the continuous emission of large amounts of energy. It is calculated that for each gram of hydrogen that is converted to helium sun radiates energy equal to 1.67×10^{5} kWh. The solar energy is emitted to the universe mainly by electromagnetic radiation. Approximately one-third of energy radiated from sun is reflected back. The rest is absorbed and retransmitted to the space while the earth reradiates just as energy as it receives and creates a stable energy balance at a temperature suitable for life (Aldo V., 2005).

2.1.1.1. Solar photovoltaic energy

Photovoltaic(PV) is a method of generating electrical power by converting solar radiation into direct current(DC) electricity using semiconductors that exhibit the photovoltaic effect. PV power generation uses solar panels comprising a number of cells containing a semiconducting material. As long as light is shining on the solar cell, it generates electrical power. Electricity quits when the light goes off. Some PV has been in continuous outdoor operation on Earth or space for over 30 years (Luque A. & Hegedus S., 2003).

The solar cells that are used on calculators and satellites are photovoltaic cells or modules. This PV module consists of many PV cells wired in parallel order to increase current and in series to produce a higher voltage. When we speak of a PV panel it means any number of PV modules and when we speak of array it means any number of PV panels. Individual PV cells are typically only a few inches in diameter, but multiple cells can be connected to one another in modules, modules can be connected in arrays, and arrays can be connected in very large systems.

PV panel convert sunlight to DC electricity. The PV generated electricity is ‘silent’, low in maintenance and does not need in fuel or oil supplies. However, PV energy is available when enough irradiance is accessible. The PV diagram is shown below.

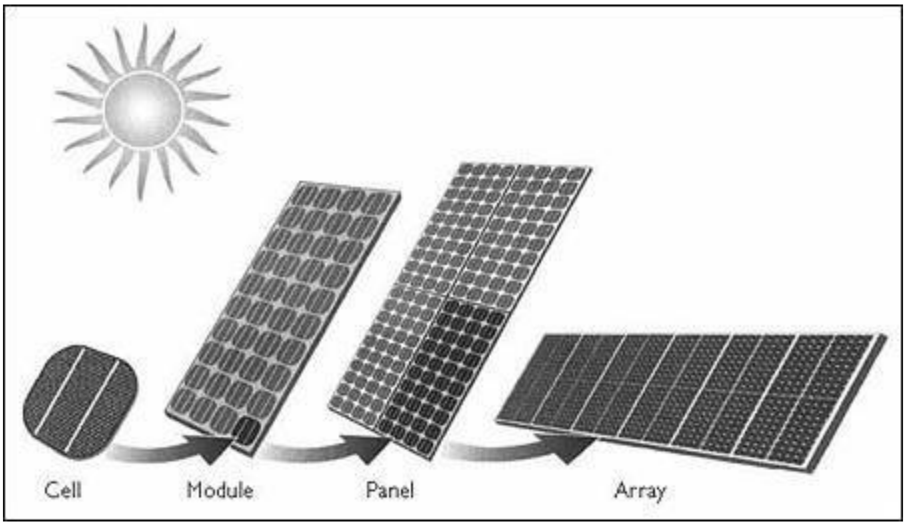

Figure 2.1: PV diagram

2.1.1.2. General working principles of PV cells

PV cells convert sunlight directly into electricity by taking advantage of the photoelectric effect. Cells are constructed from semiconductor materials coated with light-absorbing materials. When photons in sunlight strike the top layer of a PV cell, they provide sufficient energy to knock electrons through the semiconductor to the bottom layer, causing a separation of electric charges on the top and bottom of the solar cell. Connecting the bottom layer to the top with a conductor completes an electrical circuit and allows the electrons to flow back to the top, creating an electric current and enabling the cycle to repeat with more sunlight. Figure 2.2 illustrates how photovoltaic cells work.

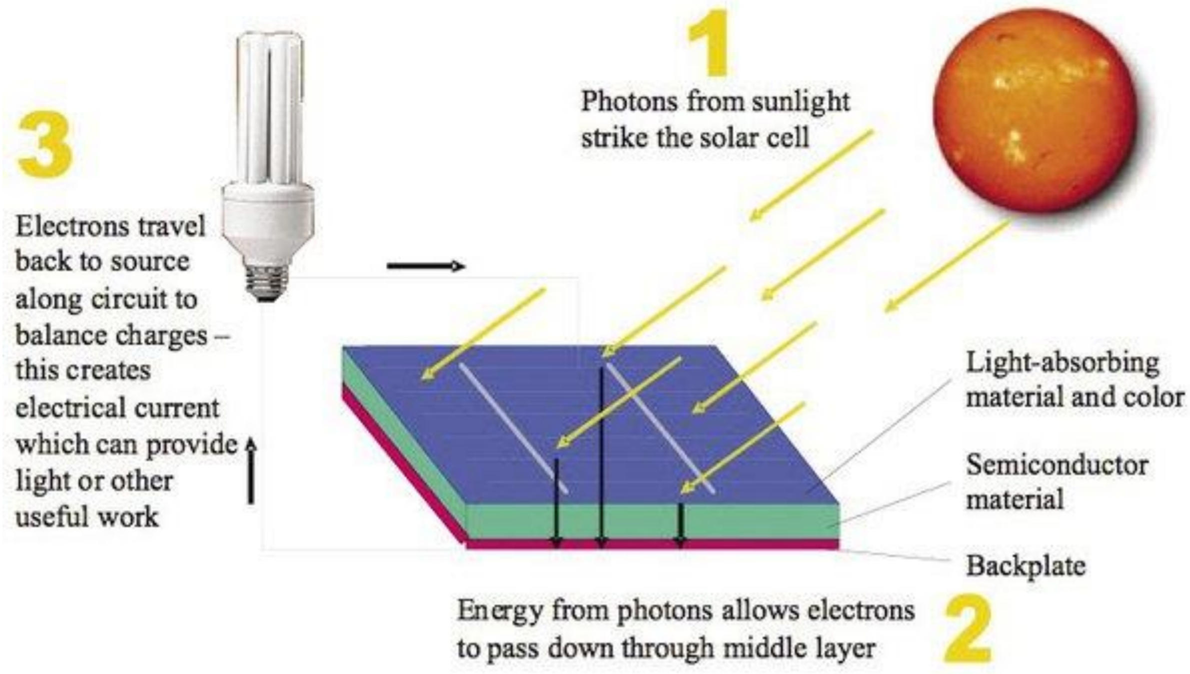

Figure 2.2: How Photovoltaic cells work

2.1.1.3. Common PV cell types

The material that is used widely in the industry for the production of photovoltaic cells is silicon. Based on the structure of the basic material from which they are made and the particular way of their preparation the photovoltaic cells of silicon are categorized into the following four types.

Mono-crystalline silicon: The basic material is mono-crystalline silicon. In order to make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. It is the oldest and more expensive production technique, but it's also the most efficient and widely used sunlight conversion technology available. Cells efficiency oscillates between 14% and 18% (Mukund R., 2006).

Polycrystalline or Multi-crystalline silicon: The particular cell is relatively large in size and it can be easily formed into square shape which virtually eliminates any inactive area between cells. It has a slightly lower conversion efficiency compared to single crystalline and manufacturing costs are also lower. Cells efficiency oscillates between10% and 13% (Luque A. & Hegedus S., 2003).

Thin film solar cells: while the total thickness of a semiconductor is about 1μm. Amorphous or thin film silicon cells are solids in which the silicon atoms are much less ordered than in a crystalline form. By using multiple junctions this kind of photovoltaic cells achieve maximum efficiency which is estimated at about 13% while the installation cost is reduced. The efficiency of this cell oscillates between 6% and 10%. Furthermore the output of an amorphous silicon cell is not decreased as temperature increases and is much cheaper to produce than crystalline silicon (Bizuayehu T., 2011).

Cells efficiency decreases with increases in temperature. Crystalline cells are more sensitive to heat than thin films cells. The output of a crystalline cell decreases approximately 0.5% with every increase of one degree Celsius in cell temperature. For this reason modules should be kept as cool as possible, and in very hot condition amorphous silicon cells may be preferred because their output decreases by approximately 0.2% per degree Celsius increase (Mukund R., 2006).

2.1.1.4. Photovoltaic (PV) module and array

The solar cell is the basic building block of the PV power system. However, it rarely used individually because it is not able to supply an electronic device with enough voltage and power. For this reason, many photovoltaic cells are connected in parallel or in series in order to achieve as higher voltage and power output as possible. Cells connected in series increases the voltage output while cells connected in parallel increases the current. The solar array or panel is a group of several modules electrically connected in series-parallel combination to generate the required current and voltage and hence the power. A typical photovoltaic system is made of 36 individual $100cm^2$ silicon photovoltaic cells and auxiliary devices which are lead-acid batteries with a typical voltage of 12V. This system has the capacity of producing more than 13V during cloudy days and can charge a 12V battery.

2.1.1.5. Equivalent electrical circuit of PV cell

The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure 2.3 below. The following parameters call for consideration. The current I_L at the output terminals is equal to the light-generated current I_g, less the diode current I_D and the shunt leakage current I_{SH}. The series resistance Rs represents the internal resistance to the current flow, and depends on the p-n junction depth, impurities, and contact resistance. The shunt resistance Rsh is inversely related to the leakage current to the ground. In an ideal PV cell $R_S = 0$ and $R_{SH} = \infty$. The PV conversion efficiency is sensitive to small variations in R_S, but insensitive to variations in R_{SH}. A small increase in R_S can decrease the PV output significantly.

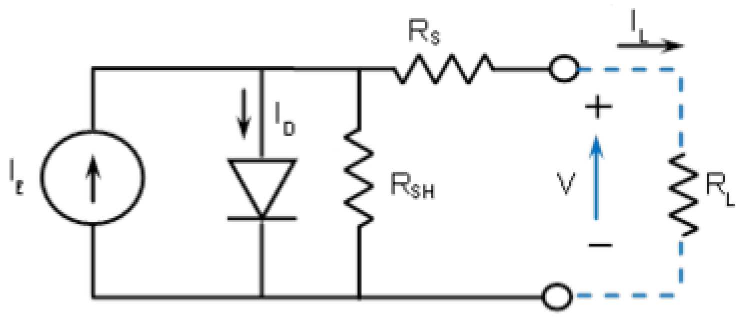

Figure 2.3: A PV cell equivalent electrical circuit

The open-circuit voltage V_{OC} of the cell is obtained when the load current is zero and is given by the following:

$$Voc=(I_g-I_D)Rsh \tag{2.1}$$

The diode current is given by the classical diode current expression:

$$I_D=Io[exp(qVoc/AKT)-1] \tag{2.2}$$

where Io - the saturation current of the diode (A),

Q - Electron charge (1.6×10^{-19} C),

A – Curve fitting constant,

K - Boltzmann constant (1.38×10^{-23} J/°K) and

T - Temperature on absolute scale °K.

Thus, the load current is given by the expression:

$$I_L=I_g-I_D-I_{SH} \tag{2.3}$$

$$I_L=I_g-I_O[exp(qVoc/AKT)-Voc/R_{SH}] \tag{2.4}$$

The last term is the leakage current to the ground. In practical cells, it is negligible compared to I_g and *Io* and is generally ignored. The two most important figure of merits widely used for describing PV cell electrical performance are the open-circuit voltage V_{OC} and the short-circuit current I_{SC} under full illumination. The short-circuit current is measured by shorting the output terminals and measuring the terminal current. Ignoring the small diode and ground leakage currents under zero voltage, the short-circuit current under this condition is the photocurrent I_g.

The maximum photo voltage is produced under the open-circuit voltage. Again by ignoring the ground leakage current, equation 2.5 with I_L give the open-circuit voltage as follows:

$$V_{OC} = (AKT/q)\ln[(lg/lo) + 1] \quad (2.5)$$

2.1.1.6. I-V and P-V Curves

The electrical characteristic of the PV cell is generally represented by the current vs voltage (I-V) curve. The figure below (Figure 2.4) depicts the I-V curve of typical PV cell. This curve shows the variation of current and voltage when cell resistance varies from zero to infinity. In this curve the point at which the voltage is zero is called the short-circuit current. This is the current we would measure with output terminal shorted. On the other hand the point at which current is zero is known as open-circuit voltage. This is the voltage we would measure with output terminal open. Somewhere in the middle of the two regions, the curve has a knee point.

The power output of the panel is the product of the voltage and current outputs. In Figure 2.5, the power is plotted against the voltage which is P-V curve of the PV cell. Note that the cell produces no power at zero voltage or zero current, and produces the maximum power at the voltage corresponding to the knee point of the I-V curve.

This is why the PV power circuit is always designed to operate close to the knee point with a slight slant on the left-hand side. The PV circuit is modeled approximately as a constant current source in the electrical analysis of the system.

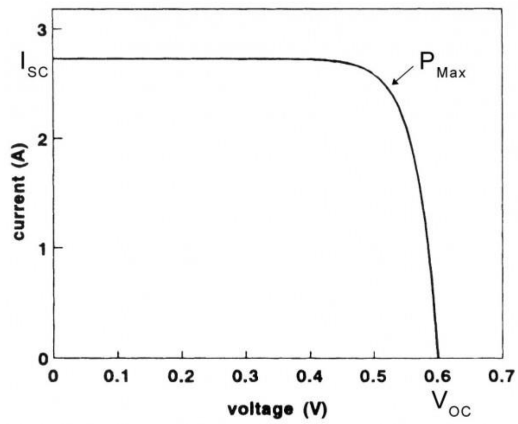

Figure 2.4: I-V characteristics curves of a typical silicon PV cell

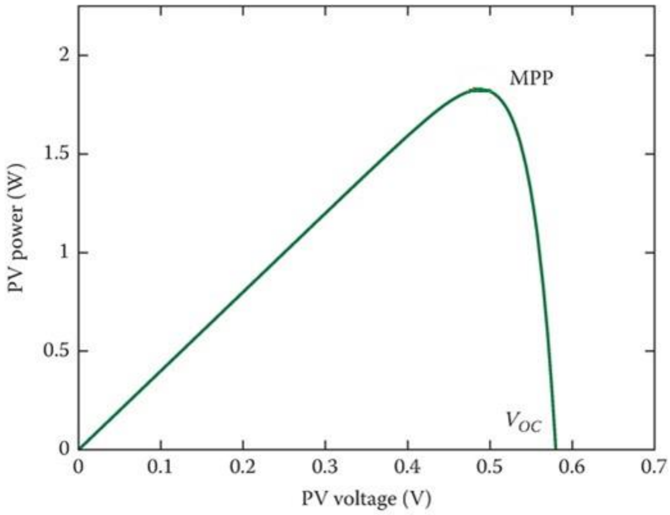

Figure 2.5: P-V characteristics of the PV cell

Finally in order to measure the photovoltaic cells output power the following standard test conditions are established internationally. The irradiance level is 1000 W/m², with the reference air mass 1.5 solar spectral irradiance distributions and cell or module junction temperature of 25°C.

2.1.1.7. Solar radiation estimations

For any solar based system design, the most important factors are the position of the sun in the sky, the slope and orientation of a collecting surface, and obstruction and reflection properties of neighboring structures. Figure 2.6 shows the geometry describing orientation of a collector and position of the sun in the sky.

A point on the earth's surface is expressed by its latitude and longitude. The angle between the collector surface and the horizontal is called slope, β (with $0^0<\beta<90^0$ for a surface facing towards the equator; $90^0< \beta<180^0$ for a surface facing away from the equator). Surface azimuth angle, γ is the angle between the normal to the surface and the local longitude meridian, projected on the horizontal plane. In either hemisphere, γ equals 0^0 for a surface facing due south, 180^0 due north, 0^0 to 180^0 for a surface facing westward and 0^0 to -180^0 eastward. For a horizontal surface, γ is always 0^0.

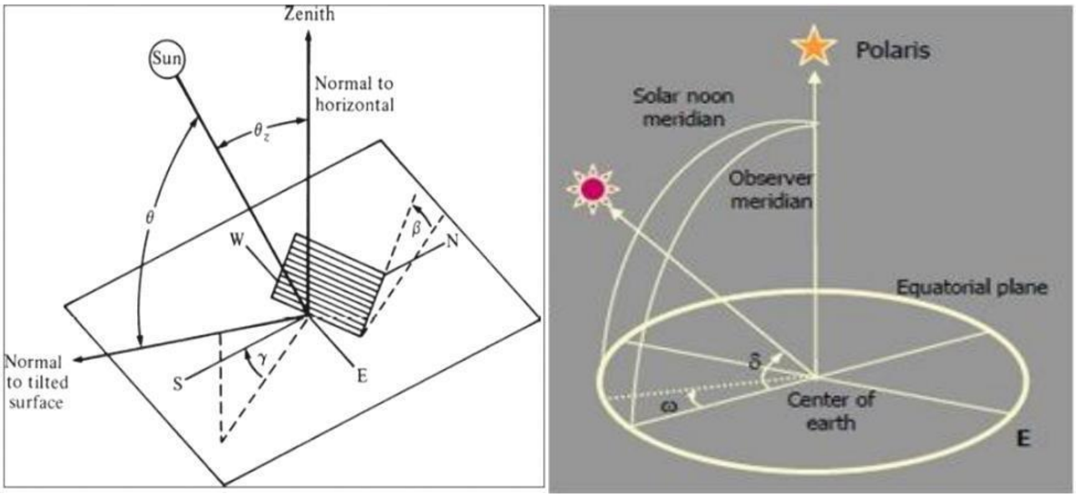

Figure 2.6: Geometry of solar collector and location of sun relative to earth

Location of the sun in the sky, relative to a point on the ground, can be defined in terms of two angles, the solar altitude,α_S (or its complement the solar zenith angle, θ_Z) and the solar azimuth γ_S. Solar altitude,α_S, angle of solar beam to the horizontal. Solar azimuth, γ_S is the angle between the solar beam and the longitude meridian projected on the horizontal plane. Sign convention is the same as for surface azimuth angle (γ). Solar altitude and solar azimuth are functions of location (latitude, ϕ), time of the year (declination angle, δ) and time of the day (hour angle, ω). Solar declination angle (δ) is the angle between the earth's equatorial plane and the earth sun line. Solar hour angle ω is the angle Earth has rotated since solar noon. The relation between these angles is given below (Drake F., & Mulugetta Y., 1996) & (Duffie J.A. & Beckman W.A., 2006).

$$\delta=23.45\mathrm{Sin}(360(284+nd)/365)) \qquad (2.6)$$

where, δ = Solar declination angle(^{0})

nd= day number of the year starting at January 1st as 1

$$\omega = (12-t_L)\,15^0 \qquad (2.7)$$

where, t_L = local solar time in hours

ω = solar hour angle (^{0})

$$\sin(\alpha)= \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\omega) \qquad (2.8)$$

where, α_S = solar altitude (^{0})

ϕ = latitude (^{0})

$\sin(\gamma s) = \cos(\delta)\sin(\omega)/\cos(\alpha s)$ (2.9)

where, γ_S = solar azimuth (^{0})

The sunset/sunrise angle is given by

$\omega_S = \cos^{-1}(-\tan(\phi)\tan(\delta))$ (2.10)

The angle of incident θ_i is the angle between the solar beam and normal to the solar panel which is given by:

$\text{Cos}(\theta i)=\sin(\delta)\sin(\phi)\cos(\beta)-\sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma)+\cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega)$
$+\cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega)+\cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)$ (2.11)

The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (about $1.5x10^{11}$m), measured outside the earth's atmosphere is called the solar constant, G_{sc} (1367 W/m^2) (Duffie J.A. & Beckman W.A., 2006). The intensity of radiation received outside the earth's atmosphere varies as the inverse square of the earth-sun distance and can be expressed in relation to time of the year. The extraterrestrial irradiance on a surface at normal incidence (G_{on}) may be expressed as:

$Gon = Gsc[1+0.003\cos 2\pi nd/365]$ (2.12)

The extraterrestrial irradiance incident on a horizontal plane at an arbitrary angle of incidence is given by,

$Go=Gon \cos(\theta z)$ (2.13)

Where θz =zenith angle (angle between the sun and the vertical line from a point on earth) which equals to the incident angle of a horizontal surface at the point of interest. The whole daily extraterrestrial radiation, Ho from the sunrise to the sunset can be calculated as follows:

$Ho=(24*3600*Gsc/\pi)*(1+0.033*\cos(360N/365))*(\cos\phi\cos\delta\sin\omega s+$
$\pi\omega s(\sin\phi\sin\delta)/180)$ (2.14)

where, N $\rightarrow$Day number starting from January 1st as 1,

Gsc $\rightarrow$1367 W/m^2, the solar constant,

$\phi\rightarrow$Latitude of the location (8.32^0),

$\delta \rightarrow$Declination angle (^{0}) given by equation (2.6).

$\omega s \rightarrow$ Sunset hour angle (^{0})

Ideally, the data required to predict the solar potential of any site are several years of measurements of irradiance on the proposed collector plane. These are rarely available, so the required data have to be estimated from meteorological data available either (i) from the site, or (ii) from some nearby site having similar irradiance, or (iii) from an official solar atlas or database. Here, the sunshine duration data from the nearby station is used to estimate the monthly average solar radiation using the following angstrom type equation (Mulugetta Y. & Drake F., 1996), (Bekele G. & Palm B, 2010), (Aldo V., 2005), (Patil, Mukind R., 1999), & (Japanese Embassy in Ethiopia, 2008).

$$H/Ho= a + b\ n/Ns \qquad (2.15)$$

where, $H \rightarrow$ monthly average daily radiation on horizontal surface (MJ/m^2)

$H_0 \rightarrow$monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2)

$Ns \rightarrow$ the maximum possible daily hours of bright sunshine given by equation

$n \rightarrow$monthly average daily number of hours of bright sunshine a and b are regression coefficients having average value of a =0.30 and b=0.50 (Drake F. et al, 1996).

The day length, Ns, is the maximum possible daily sunshine hour is given by equation 2.16.

$$Ns= (2/15)*\omega s \qquad (2.16)$$

2.1.1.8. Solar energy resource in Ethiopia

Ethiopia receives 4.55 to 6.5 kWh/m^2 /day annual average of solar isolation throughout the country (Drake F. & Mulugetta Y., 1996). This varies significantly during the year, ranging from a minimum of 4.55kWh/m^2 in July to a maximum of 6.55kWh/m^2 in February and March. Other literatures describe the yearly average radiation to be in the range from 4.25 kWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to 6.25 kWh/m^2 around Adigrat in the Tigray regional state (northern Ethiopia) (Patil Mukind R., 1999).

2.1.1.9. Solar energy assessment of Shenen Sillasie

The assessment of the potential for solar radiation of the selected area is done by taking data from different sources. These are National Meteorological Agency of Ethiopia (NMA), National Aeronautics and Space Administration (NASA), Solar and Wind Energy Assessment (SWERA). The monthly average solar radiation and clearness index of Shenen Sillasie for the data taken from NASA is shown on Table 2.1.

Table 2.1.The daily solar radiation and clearness index

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
6.08	6.57	6.52	6.31	6.36	5.77	5.23	5.36	5.84	6.31	6.27	6.08
0.66	0.67	0.63	0.60	0.61	0.56	0.51	0.51	0.56	0.63	0.67	0.68

2.1.2. Wind energy systems and resources

Winds are produced by uneven solar heating of the earth’s land and sea surfaces. Thus, they are a form of ‘solar’ energy. On average, the ratio of total wind power to incident solar power is on the order of two present, reflecting a balance between input and dissipation by turbulence and drag on the surface. Wind is the movement of air caused by the irregular heating of the Earth's surface. It happens at all scales, from local breezes created by heating of land surfaces that lasts some minutes, to global winds caused from solar heating of the Earth. Wind power is the transformation of wind energy into more utile forms, typically electricity using wind turbines (Gipe P., 2004).

2.1.2.1. Historical uses of wind

Wind energy is one of the oldest sources of energy used by humankind, comparable only to the use of animal force and biomass (Wagner H. & Mathur J., 2009). Based on some literatures, the first utilization of wind power was to sail ships in the Nile River around 5000 years ago. Afterwards, wind energy harnessing mechanisms has keep going in utilizing for transportation and other applications such as pump water grind grains and others in the following centuries. The first wind turbine used to generate electricity was installed in U.S in 1890 (Mandefro Y., 2017). However, for much of the twentieth century there was small interest in using wind energy other than for battery charging for distant dwellings. These low-power systems were quickly replaced once the electricity grid became available. The sudden increases in the price of oil in 1973 stimulated a number of research, development and demonstrations of wind turbines and other alternative energy technologies in different countries (Rivera M.R., 2008).

2.1.2.2. Wind speed distribution

Having a cubic relation with power, wind speed is the most critical data needed to appraise the power potential of a candidate site. The wind is never steady at any site. It is influenced by the weather system, the local land terrain, and its height above the ground surface. Wind speed varies by the minute, hour, day, season, and even by the year. Therefore, the annual mean speed needs to be averaged over 10 year or more. Such a long-term average gives a greater confidence in assessing the energy-capture potential of a site. However, long-term measurements are expensive and most projects cannot wait that long. In such situations, the short-term data, for example, over 1 year, is compared with long-term data from a nearby site to predict the long-term annual wind speed at the site under consideration. This is known as the measure, correlate, and predict (mcp) technique.

Because wind is driven by the sun and the seasons, the wind pattern generally repeats over a period of 1 year. The wind site is usually described by the speed data averaged over calendar months. Sometimes, the monthly data is aggregated over the year for brevity in reporting the overall “windiness” of various sites. Wind speed variations over the period can be described by a probability distribution function (PDF) (Mukund R., 2006).

2.1.2.3. Commonly used probability distributions

Two probability distributions are commonly used in wind data analysis: the Rayleigh and the Weibull. The Rayleigh distribution uses one parameter: the mean wind speed. The Weibull distribution is based on two parameters and, thus, can better represent a wider variety of wind regimes. Both the Rayleigh and Weibull distributions are called ‘skew’ distributions in that they are defined only for values greater than 0.

The wind distribution is expressed by Weibull distribution over a certain period of time at a particular site. The Weibull probability density function (PDF) is given by equation (2.17) (Manwell J.F et al., 2002).

$$P(U)= k/c(u/c)^{(k-c)}\exp(-(u/c)^k) \qquad (2.17)$$

$$F(U)= 1- \exp(-(u/c)^k) \qquad (2.18)$$

where, u = the wind speed,

k = a constant known as shape factor, as the value of k increases the curve will have a sharper peak

c = a scale factor in m/s; the larger the scale factor, the more spread out the distribution.

The area under the curve is always unity. The power density can in this case be expressed by equation (2.19).

$$\frac{P}{A} = \frac{1}{2}\sum_{j=1}^{n} \rho \, V_j^3 f_j \qquad (2.19)$$

where V_j is the median velocity in class j and f_j is the frequency of occurrence in the same class. For k = 2 the Weibull PDF is commonly known as the Rayleigh density function in which case equation (2.17) may be rewritten as in equation (2.20).

$$F(u) = \frac{2u}{c^2} exp[-(u/c)^2] \qquad (2.20)$$

2.1.2.4. Wind turbines and components

A wind turbine is a machine which converts the power in the wind into electricity. This is in contrast to a ‘windmill’, which is a machine which converts the wind’s power into mechanical power. As electricity generators, wind turbines are connected to some electrical network. These networks include battery-charging circuits, residential scale power systems, isolated or island networks, and large utility grids. In terms of total numbers, the most frequently found wind turbines are actually quite small: on the order of 10 kW or less. In terms of total generating capacity, the turbines that make up the majority of the capacity are, in general, rather large: in the range of 1.5 to 5 MW (Mukund R., 2006).

There are a number of different wind turbine types available. The horizontal axis turbine, HAWT is by far the most common type of turbine. They come in two different types: the upwind, which face the wind (tower behind rotor) and the downwind arrangement that works away from the wind (tower in front). Another kind of turbine is the vertical axis, VAWT arrangement that uses drag and lift as the driving forces; the horizontal also uses drag and lift, but in other proportions.

The advantages with upwind turbines are that the tower does not act as an obstacle for the wind hitting the rotor. Despite this, the flow behind the passing blade is affected by the tower and causes a slight drop in power. When the blade passes the tower it also decreases the drag on the construction which can cause an on/off bending process causing fatigue stress. This has of course been taking into account when designing the turbine. The upwind design needs a control system that helps the nacelle turn straight to the wind. In downwind turbines, the tower shades a rotor blade each time it passes by and causes greater power losses compared to the upwind design. An advantage with downwind turbines is that the nacelle is self-adjusting and is not in need of a control system. One drawback with this is the problem with untwisting the cable inside when the nacelle has turned same direction repeatedly. The VAWT´s are not as commercial and economically competitive as the HAWT´s. Some of the VAWT types suffer from low efficiency due to design difficulties as well as the problem with operation close to the ground. Parts of the vertical turbines will therefore receive low quality winds causing power losses. To keep the construction upright it also needs to be supported with guy cables attached to the ground. The vertical turbine is not in need of yaw control, which of course is an advantage and the wind always hits the turbine tangentially (Boyle G., 1996).

The modern wind turbine is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. The size of these turbines ranges from a few Watts (Small Wind Turbines) to several Million Watts (Large Wind Turbines). The modern trend in the wind industry is to go for bigger units of several MW capacities in places where the wind is favorable, as the system scaling up can reduce the unit cost of wind-generated electricity. Most of today's commercial machines are horizontal axis wind turbines (HAWT) with three bladed rotors.

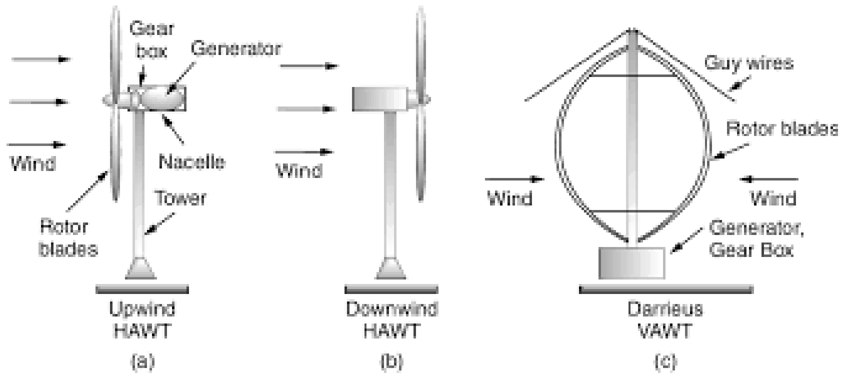

Figure 2.7: Horizontal axis wind turbines (HAWT) are either upwind machine or down wind machines

(a). Upwind machine (b). Down wind machines (c). Vertical axis wind turbines (VAWT) accept wind from any direction (Bekele G., 2009).

The most common turbine type is the horizontal axis wind turbine. A cut-view (Figure 2.8) helps the reader to get familiar with the components of a wind turbine.

Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Hub: Hub is the connection point for the rotor blades and the low speed shaft.

Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1200 to 1500 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring 'direct-drive' generators that operate at lower rotational speeds and don't need gear boxes specially for small scale wind turbines.

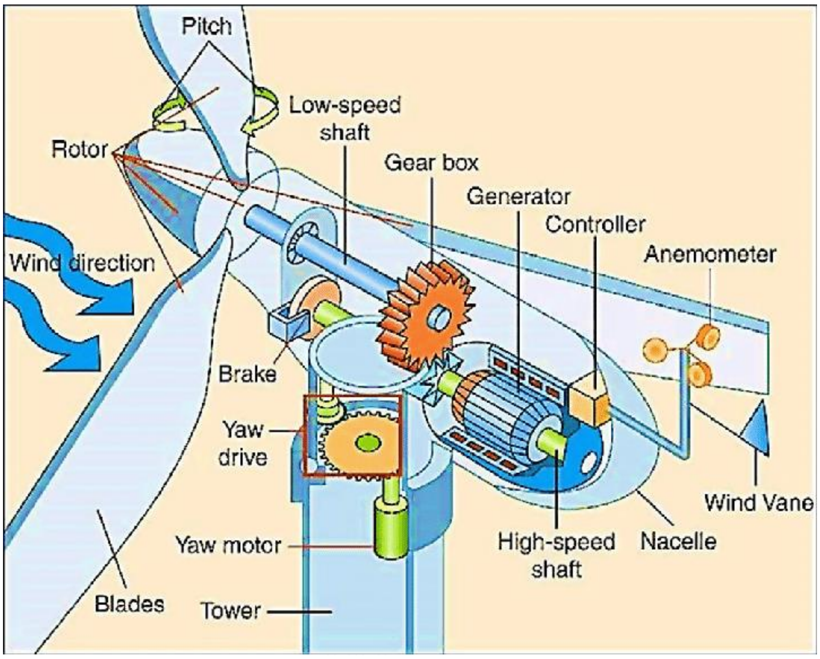

Figure 2.8: Cut-view wind turbine

Generator: The generator is connected to the high-speed shaft and is the component of the system that converts the rotational energy of the shaft into an electrical output.

Tower of wind power generation: The tower is used to support the nacelle and rotor blades and typically made of rolled, tubular steel, and built and shipped in sections because of its size and weight. Common tubular towers incorporate a ladder within the hollow structure to provide maintenance access. Small -scale towers range in height from 24-35m and its weight depends on the material from where it is manufactured.

Nacelle: The rotor attaches to the nacelle, which sits top the tower and includes the gear box, low- and high-speed shafts, generator, controller, and brake. A cover protects the components inside the nacelle. Some nacelles are large enough for a technician to stand inside while working rotor in emergencies.

Controller: The controller starts up the machine at wind speeds of about 3.5 to 7.2 meters per sec (m/s) and shuts off the machine at about 30 m/s.

High-speed shaft: Drives the generator.

Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 RPM.

Pitch: Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor: The blades and the hub together are called the rotor.

Tower: Towers are made from tubular steel or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

Yaw drive: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive; the wind blows the rotor downwind.

Yaw motor: Powers the yaw drive.

Electronic equipment: Such as controls, electrical cables, ground support equipment and interconnection equipment.

2.1.2.5. Working principles of wind turbines

The blade, using aerodynamic lift, capture energy from wind in order to turn the shaft. In small wind turbines the shaft usually drives the generator directly. The generator converts the mechanical energy into electricity. The shaft power causes coils to spin past alternate poles of magnets allowing electric current to flow. If a permanent magnet device is being used the opposite occur: current flow as magnets spin past coil windings. Most small wind turbines use a permanent magnet alternator. Large wind turbines usually use either induction generator or a synchronous generator. In addition, in large wind turbines the shaft connected to the generator via a gearbox those steps up the rotational speed for the generator.

2.1.2.6. Wind energy extraction by HAWT

The energy of wind is extracted by using appropriate wind turbine. The wind energy is tapped by the wind turbine which converts the kinetic energy of the wind into mechanical shaft energy. The rotational energy is converted into electrical energy through the transmission system. The transmission system consists of the rotor shaft with bearings, brake(s), an optional gearbox, as well as a generator and optional clutches. The energy available in the wind can be expressed using equation (2.20).

$$Pw=1/2\rho Av^3 \qquad (2.20)$$

where, ρ=Density of air (kg/m^3)

A = the swept area (m^2)

Pw = power in the wind (W)

v=instantaneous wind velocity (m/s)

Energy conversion from free-flowing fluid streams is limited because full energy extraction implies decrease of fluid velocity (decrease of kinetic energy of the stream), down to zero which is impossible. Some fluid may not pass through the turbine and may simply flow around it (bypass it). This limitation is expressed in terms of Betz limit defined by the power coefficient Cp as given by equation (2.21).

Cp= Rotor power/Power in the wind (2.21)

The power coefficient, Cp, is a function of the axial induction factor. The optimum of this function (which is a maximum value for C_P) is 0.5926 (=16/27) (Gipe P., 2004). Thus the electrical power output from the wind turbine can be expressed by equation (2.22).

$$P_w\, out=\eta_t C_P \frac{1}{2}\rho A v^3 \qquad (2.22)$$

Where, $P_w\, out$ = output power of wind turbine

η_t = Overall efficiency of the transmission system/power train

C_p = the power coefficient

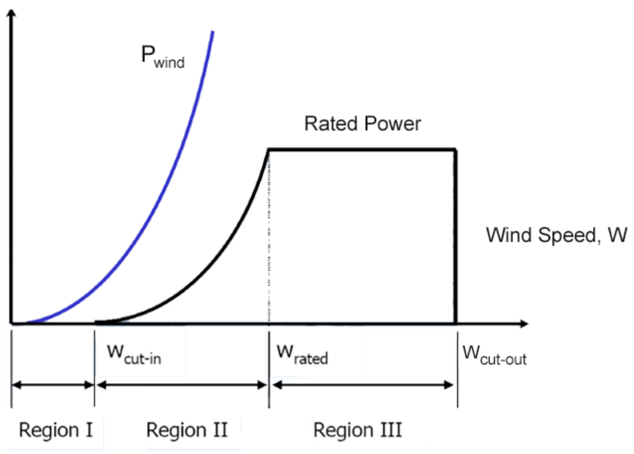

Figure 2.9: General power curve of wind turbine

The power coefficient and efficiency of wind turbines vary greatly from manufactures to manufacturers. As a result, the power output of wind turbines vary from turbine to turbine and is given by power curve which plots the output power of a turbine against wind speed (see Figure 2.9).

2.1.2.7. Wind turbines power control mechanism

All wind turbines are designed with some sort of power control. There are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power in very high wind speeds in order to avoid damage to the turbine. There are three commonly used types of power control in the industry.

- ✓ Stall Control
- ✓ Pitch Control
- ✓ Active stall regulation

The simplest, most robust and cheapest control method is the stall control (also called passive control), where the blades are bolted onto the hub at a fixed angle. The fixed-blade pitch is chosen so that the turbine reaches its maximum or rated power at the desired wind speed. The design of the rotor aerodynamics causes the rotor to stall (lose power) when the wind speed exceeds a certain level which limits the aerodynamic power on the blades.

Another type of control is pitch control, where the blades can be turned out or into the wind as the power output becomes too high or too low, respectively. Generally, the advantages of this type of control are good power control, increased energy capture, assisted startup and emergency stop. The pitch change system has to act rapidly. From an electrical point of view, good power control means that at high wind speeds the mean value of the power output is kept close to the rated power of the generator. The extra complexity arising from the pitch mechanism and the higher power fluctuations at high wind speeds can be mentioned as the demerits of this control scheme.

The third possible control strategy is the active stall control, in which the stall of the blade is actively controlled by pitching the blades. At low wind speeds, the blades are pitched similar to a pitch-controlled wind turbine, in order to achieve maximum efficiency. At high wind speeds, the blades go into a deeper stall by being pitched slightly into the direction opposite to that of a pitch controlled turbine. The active stall wind turbine achieves a smoother limited power, without high power fluctuations as in the case of pitch-controlled wind turbines. This control type has the advantage of being able to compensate variation in air density and inherits the advantages of both pitch and stall control mechanisms.

2.1.2.8. Wind energy resources

Wind resource is the most important element in determining turbine performance at a given place. The energy that can be extracted from a wind stream is proportional to the cube of its velocity. In addition, the wind resource itself is intermittent. It varies with year, season, and time of day, elevation above ground, and form of terrain. Proper choice of site which is free from large obstructions, improves wind turbines performance.

2.1.2.9. Wind speed measurement

The wind speed is measured with an instrument called an anemometer. These instruments come in several types. The most common type is a cup anemometer which has three or four cups attached to a rotating shaft. When the wind hits the anemometer, the cups and the shaft rotate. The angular speed of the spinning shaft is calibrated in terms of the linear speed of the wind. Normally, the anemometer is fitted with a wind vane to detect the wind direction. A data logger collects wind speed and wind direction data from the anemometer and wind vane respectively.

It is very important that the measuring equipment is set high enough to avoid turbulence created by trees, buildings or other obstructions. Readings would be most useful if they have been taken at hub height where the wind turbine is going to be installed (Japanese Embassy in Ethiopia, (2008).

If the measurement of wind speed was not made at the wind turbine hub height, it is important to adjust the measured wind speed to the hub height (in this case the hub height is 10m). This can be done using either the logarithmic law, which assumes that the wind speed is proportional to the logarithm of the height above ground, or the power law, which assumes that the wind speed varies exponentially with height. Using the logarithmic law the wind speed at a certain height above ground level can be given as follows:

$$V(Z).\ln(Zr/Zo)=V(Zr).\ln(Z/Zo) \quad (2.23)$$

where, Zr Reference height (m)

Z - Height where wind speed is to be determined (m)

Z0 - Measure of surface roughness (0.1 to 0.25 for crop land)

V(Z) - Wind speed at height of Z_m (m/s)

V(Zr) - Wind speed at the reference height (m/s)

Using power law the wind speed at a certain height above ground level can be given as follows (Mukund R., 2006):

$$V_2=V_1\left(\frac{h2}{h1}\right)^{\alpha} \quad (2.24)$$

Where: V_1 is wind speed measured at the reference height h1 (m/s), V_2 is wind speed estimated at height h2 (m/s), and is ground surface friction coefficient.

Table 2.2: Friction Coefficient α of Various Terrains

Terrain type	Friction coefficient α
Lake, ocean, smooth and hard ground	0.10
Foot-high grass on level ground	0.15
Tall crops, hedges and shrubs	0.20
Wooded country with many trees	0.25
Small town with trees and shrubs	0.30
City area with tall buildings	0.40

2.1.2.10. Wind resource in Ethiopia

Ethiopia has an accessible wind energy reserve of 100 GW with a flow rate of 6 hours per day and an average speed of 3.5-5.5 m/s. The rift valley divides two fundamental zones with uniform periodicity. There are two distinct wind speed maximum in the first of them, which covers the majority of the highland plateaus, and they happen between March and May and September and November, respectively. The second zone, which includes the majority of the Ogaden and the eastern lowlands, experiences its highest average wind speeds between May and August. Currently two projects are constructed, one Ashegoda Wind Farm (near Mekele) of 120MW and the other Adama Wind Farm of nearly 51MW. And Adama ll Wind Farm is a 153MW onshore wind power project.

2.1.2.11. Wind potential assessment in the study area

The resource assessment for the wind potential is done by taking the data's only from NASA. This is because of the absence of full data regarding wind speed in the National Metrological Agency of Ethiopia and in SWERA. Therefore, the annual average wind speed for Shenen Sillasie, which is located at latitude and longitude of 8.32°N and 39.25°E and an elevation of 1729 meters above sea level, is found to be 4.2 m/s at a height of 10m. This value is used as an input to the wind resource in modeling the hybrid system.

Table 2.3: Monthly averaged wind speed of the village

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
4.73	4.36	4.03	3.84	4.04	4.51	4.30	4.07	3.79	3.75	4.30	4.67

2.1.3. Battery

The battery is made of numerous electro-chemical cells connected in series-parallel combination to provide the desired battery voltage and current levels. The battery stores energy in an electrochemical form. It is the most widely used and important device to avoid components over-sizing in hybrid systems by storing in the time of excess generation and supplying power in shortage times. The rechargeable battery which is commonly called secondary battery converts electric energy to chemical energy in charge mod and converts chemical energy to electrical energy in discharge mode. The most common battery is the rechargeable lead-acid battery due to its fair cost, maturity and easier operation. The battery rating is usually stated in terms of the nominal voltage during discharge time and the nominal ampere-hour (Ah) capacity it can deliver before the voltage drops below the specified limit (minimum state of charge). The main comparison parameters between different batteries are maximum throughput capacity (Ah) and minimum state of charge (in %). The maximum throughput capacity (Ah) is a life time delivery of ampere-hour (Ah) of a battery and minimum state of charge is the lowest percentage level of a battery will be discharged without losing its performance, it shows how depth it will be discharged (Mukund R., 2006), (Getnet T., 2011), (Volker Q., 2005).

2.1.4. Converter

A converter is an electronic power device that is required in a hybrid system to maintain the energy flow between AC and DC electrical components. AC/DC converter is usually referred as rectifier, changes AC to DC voltages which is a reverse process of inverter. DC/DC converter adapts a certain voltage level from power source to the required level either by step-up or step-down. AC/AC converter changes AC voltage of a specific voltage amplitude and frequency to AC voltage of a required voltage and frequency values. But when it converts frequency only it is referred as cyclo-converter.

The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power. The rectifier capacity, which is the maximum amount of dc power that the device can produce by rectifying ac power, as a percentage of the inverter capacity has been specified. The final physical properties of the converter are its inversion and rectification efficiencies, which are assumed to be constant.

The economic properties of the converter are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years.

2.1.5. Diesel generator

A diesel generator is only an electric generator that is powered by a diesel engine (prime mover). An electromechanical system that transforms mechanical energy into electrical energy via the interplay of electromagnetic and electrostatic forces inside the system is known as an electrical generator. Figure 2.10 shows the per-phase equivalent circuit of a synchronous generator driven by a prime mover, which in this case is the diesel engine. T is the mechanical torque of the prime mover, Ea is the internal voltage generated, Ia is the armature current, Ra + jXs is the synchronous impedance, and Va is the load voltage (Bekele G., 2009).

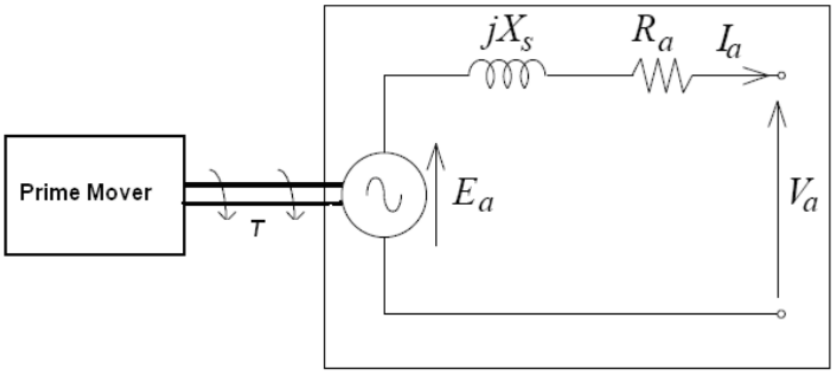

Figure 2.10: The per-phase equivalent circuit of a synchronous generator driven by a diesel generator (prime mover)

With the generator under load the voltage Va is given by equation (2.25)

$$Va = Ea - (Ra + jXs)Ia \qquad (2.25)$$

The winding resistance, Ra, is generally much smaller than the synchronous reactance, jXs. Hence, equation (2.25) can be rewritten as in equation (2.26) that is the per-phase terminal voltage of the generator.

$$Va = Ea - jXsIa \qquad (2.26)$$

The electrical power output is given by equation (2.27)

$$P_{out} = mVa\ Ia \cos\varphi \qquad (2.27)$$

where, m= the number of phases; m=3 for a 3-phase generator

cosφ= the cosine of the angle between the voltage Va and the current Ia.

2.1.6. HOMER software tool

HOMER is a user-friendly micro-power design tool that was developed by NREL in the U.S.A. The software helps in evaluating designs of both off-grid and grid-connected power systems with different varieties of hybrid system models. HOMER is used to model a power system physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life time. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. HOMER's optimization and sensitivity analysis algorithms help to evaluate technical and economic feasibility of these technology options combinations for the hybrid system (Getnet T., 2011).

To use HOMER, the user has to provide resource availability data of the site and component costs for the selected technology options of the specific hybrid model. HOMER uses these inputs to simulate different system configurations, or combinations of components, and generates results and displays a list of feasible configurations sorted by net present cost in increasing order (HOMER).

2.1.7. Hybrid energy system

The term 'hybrid' is used to refer to something made by combining different features, and similarly the hybrid energy systems consist of a combination between renewable energy sources and fossil fuels in conjunction with batteries to circumvent the intermittence, the seasonal and periodical variations, of the renewable energy. Hybrid systems are promising to supply sustainable energy for small grids and standalone systems where one energy source isn't sufficient for the expected load. For a standalone hybrid systems in which their significant load depends on the intermittent energy sources (solar or/and wind); a reliable backup systems are necessary and supplied by storage equipment (battery banks) and diesel generators. These backup systems will also help to optimize the sizing of the hybrid system. There are several kinds of hybrid systems which will be developed by combining solar, hydro, wind and diesel in different scheme according to the available resources in the site (Mandefro Y., 2017).

2.2. Related works

Large number of researches was carried on hybrid standalone system for electric power generation all over the world. Different papers used different Technology options and ways to evaluate the different configurations of renewable energy resources, such as solar energy, wind energy and their hybrid configurations. As many studies' result shows, they have been published for different form of applications: some of the papers are reviewed as follows.

According to Terefe J. (2013) Simulation and Optimization of Wind Turbine, Solar PV, Storage Battery and Diesel Generator Hybrid Power System for a Cluster of Micro and Small Enterprises Working on Wood and Metal Products at Welenchity Site. The work was started by investigating wind and solar energy potentials of the desired site, compiling data from different sources and analyzing them using HOMER software. The solar-wind hybrid energy system would be cost effective if there is reduction in component cost by installation of many of this hybrid system in a farm and also lowering the investment cost per kilowatts.

(Drake F. & Mulugeta Y., 1996) studied the solar and wind potential distribution of Ethiopia. Regression coefficients of the angstrom equation (a and b) relating sunshine duration to daily solar radiation and Weibull parameters (shape factor K and the scale factor c) are estimated throughout the country. Uses HOMER software for analysis.

(Bekele G., 2009) determined solar and wind potentials of selected locations in Ethiopia and studied feasibility of Wind/PV hybrid system to electrify 200 model families using HOMER for optimization and sensitivity analysis.

(Tamrat B., 2007, July) has made a feasibility comparison of independent electrification at Dillamo and Gode sites in Ethiopia by either of the wind, solar PV or micro hydropower system.

Technical and Economic Assessment of solar PV/diesel Hybrid Power System for Rural School Electrification in Ethiopia was studied by Zelalem G. (2013) In his paper, he has compared only diesel supply system to that of solar PV/diesel hybrid system with battery bank and he showed that the hybrid system is cost effective and environmentally friendly. The hybrid system model is simulated using HOMER software with two sensitivity variables that are solar radiation and diesel fuel price. The system generally designed to produces energy for two hundred households with an average of five members per household.

The main focus of this thesis work is to assess the feasibility of the PV, wind power potentials with batteries and generators set as backup for rural electrification of Shenen Sillasie village area with 400 households and propose the optimal hybrid system using HOMER as Simulation tool for optimization and uses many sensitivity inputs to get better optimization results.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1. Site description

As stated in the first chapter introduction, the rural area in which this thesis was conducted is Shenen Sillasie, near Wonji Shoa which located in Ethiopia, Oromia, East-Shewa, at latitude of 8.32°N and longitude of 39.25°E there are challenging issues with providing electric access via extending the grid due to the challenging geographical configuration of the remote places.

3.2. Electric load estimation

One of the basic inputs to HOMER is the load profile of the system. The term loads refers to a demand for electric energy. Two types of loads can be modeled using HOMER: primary load which is electric demand that must be served according to a particular schedule, deferrable load which is electric demand that can be served at certain period of time, the exact timing is not important.

According to (Bekele G. & Palm B., 2010) electric load in the rural Ethiopian villages can be assumed to be composed of lighting, television and radio, water pumps, health post and primary schools load. Tamrat B., (2007, July) considered only lighting, television and radio as a community load. In this study, electricity for flour mills is added to the load together with radio receiver and health post is upgraded to health clinic with additional medical equipment. Water pumps are considered as deferrable loads while the others as primary loads. As indicated previously, the community understudy, which equipped with primary school and a health center, has 400 households with an average 6 members per family.

3.3. Electric load estimation of study area

The total power generated by the hybrid solar-wind-genset system is given as the addition of the power generated by the solar panel, power generated by the wind turbine and diesel generator. To decide the power generated by the system, the number of households and the appliances they use in their home and the electricity need for public services must be known.

3.4. Primary loads

The total watt-hour energy required for primary loads by the village is the sum of energy hours used by all households (domestic loads), health center, churches and school. The loads estimated below were taken from different sources and early related studies.

3.4.1. Domestic (Household) loads

Table 3.1: The home appliances used by households

Home appliance	No. Of loads	Power consumption per load(W)	Total power consumption per household(W)	Total power consumption per 400 households (KW)	Operating Hours/day (Period)	Kwh/day
Internal lighting	3	11	33	13.2	18:00-23:00 (5 hours)	66
Television	1	70	70	28	8:00-9:00 18:00-21:00 (4 hours)	112
Tape/radio	1	5	5	2	8:00-10:00 12:00-14:00 18:00-20:00 (6 hours)	12
Mobile charger	1	4	4	1.6	6:00-8:00 (2 hours)	3.2
Electric stove	-	1000	*	200	7:00-7:20 12:00-12:20 19:00-19:20 (1 hour)	200
External lighting	1	11	11	4.4	19:00-6:00 (11 hours)	48
Total				249.2		441.6

***Note: Electric stove is assumed to be used by half of the households.

As shown in households table the watt-hour energy required on average is 441.6 KWh/day.

For the community flour machines of 7.5kw capacity each working from 9:00 to 12:00 and 15:00 to 18:00 are assumed and their daily used kWh/day energy for three machines is 45kWh/day.

3.4.2. Health center Loads

Table 3.2: The electric energy needed by the health center of the village

Appliances	Quantity	Power consumption per load(W)	Total power consumption (W)	Total load(kW)	Operating hours/day (period)	kWh/day
Internal lighting	16	11	176	0.176	17:00-1:00 (8 hours)	1.408
Television	2	70	140	0.14	8:00-12:00 14:00-16:00 18:00-20:00 (8 hours)	1.2
Vaccine Refrigerator	3	100	300	0.3	0:00-24:00 (24 hours)	7.2
Computer	2	60	120	0.12	9:00-12:00 20:00-22:00 (5 hours)	0.6
Printer	2	50	100	0.1	11:00-11:30 21:30-22:00 (1 hour)	0.1
Microscope	2	15	30	0.03	10:00-12:00 14:00-16:00 (4 hours)	0.12
Ceiling Fan	12	75	900	0.9	11:00-12:00 13:00-18:00 (6 hours)	5.4
External lighting	10	11	110	0.11	19:00-6:00 (11 hours)	1.21
Total				1.876		17.158

Total watt-hour energy required by health center of the village on average is 17.158 KWh/day.

3.4.3. Churches loads

The energy used by the churches at the villages is shown under.

Table 3.3: The energy used by the churches at the village

Appliances	Quantity	Power consumption per load(W)	Total power consumption (W)	Total load(kW)	Operating hours/day (Period)	kWh/day
Internal lighting	15	11	165	0.165	18:00-20:00 4:00-6:00 (4 hours)	0.66
External lighting	10	11	110	0.11	19:00-6:00 (11 hours)	1.21
Ceiling fan	15	75	1125	1.125	11:00-12:00 13:00-18:00 (6 hours)	6.75
Megaphone	6	15	90	0.09	6:00-9:00 (3 hours)	0.27
Total				1.49		8.89

As shown in the above table the watt-hour energy required by churches at the village on average is 8.89kWh/day.

3.4.4. School loads

The energy used by the school at the villages is given in table 3.4.

Table 3.4: The energy used by the school at the village

Appliances	Quantity	Power consumption per load(W)	Total power consumption (W)	Total load (kW)	Operating hours/day (Period)	kWh/day
Internal lighting	20	11	220	0.22	18:00-21:00 (3 hours)	0.66
External lighting	12	11	132	0.132	19:00-6:00 (11 hours)	1.452
Ceiling fan	10	75	750	0.75	11:00-12:00 13:00-17:00 (5 hours)	3.75
Refrigerator	2	100	200	0.2	8:00-19:00	2.2

					(11 hours)	
Microscope	2	15	30	0.03	10:00-11:00 14:00-15:00 (2 hours)	0.06
Computer	8	60	480	0.48	9:00-12:00 14:00-15:00 19:00-21:00 (7 hours)	2.88
Printer	2	50	100	0.1	11:00-11:30 20:30-21:00 (1 hour)	0.1
Megaphone	2	15	30	0.03	7:00-7:30 12:30-13:00 (1 hour)	0.03
Tape/Radio	4	5	20	0.02	7:00-8:00 12:30-13:00 17:30-18:00 19:00-20:00 (3 hours)	0.06
Total				1.962		11.592

The school watt-hour energy required by school on average is 11.592kWh/day.

The total watt-hour energy required for primary loads by the village is the sum of energy hours used by all households, flour mill, health center, school and church which is 524.24kWh/day which are primary loads.

3.5. Deferrable loads in target area

The deferrable load is the load that should be met after the primary load requirement is delivered, except in special cases where the water tank remains empty below the required level regardless of time. The goal is to provide the community with water to meet the water supply needs.

Water pumping system is required for the households, the school and health center. A minimum of 100 l of water per day per family and 3600 l/day for health center and primary school is suggested. To complete this, 5 water pumps 270W power rating, with pumping capacity of 1200 l/hr. and operating for 7 hours/day are to be installed to supply 40,000 l/day for the 400 families. And another 1 pump of 270 W with the same capacity supply

3600 l/day for the school and health center operating for 3 hours/day are assumed. The total consumption of electricity by the pumps is calculated to be 9.45kWh/day for the households and 0.81kWh/day for the school and health center, totally 10.26kWh/day. The proposed 3 days water storage capacity requirement is 28.35 kWh for households and 2.43kWh for school and health center. The peak deferrable load is 1.35kW for households and 0.27kW for school and health center, totally 1.62kW.

Exceptions: In the weekends it is assumed that flour mills are not working because of religious concern and evening classes are conducted at day time. In the rainy season from 15% to 30% deferrable load can be expected to decrease because water consumption from the pumps is expected to be shared by river and rain water ponds (Bekele G. & Palm B, 2010). 15% deferrable load decrease for June and September while 30% for July and August are assumed. There are no classes in July and August (annual break) and in January (semester break).

Table 3.5: Energy consumed by deferrable loads

Jan-May	June	July & Aug	Sept	Oct-Dec
10.26	8.721	7.182	8.721	10.26

The total watt-hour energy required by the village is the sum of watt-hour energy required for primary loads and deferrable loads,

That is 524.24kWh/day + 10.26kWh/day = 534.5 kWh/day and for the future load demand is 10.69 kWh/day as reserve, it is 2% of the total demand. So the total watt-hour energy demand including the reserve is 545.19kWh/day.

Table 3.6: Hourly demands of primary loads

Hour	Demands(in kw)
00:00-01:00	5.228
01:00-02:00	5.052
02:00-03:00	5.052
03:00-04:00	5.052
04:00-05:00	5.217
05:00-06:00	5.217
06:00-07:00	1.99
07:00-08:00	68.695
08:00-09:00	30.73

09:00-10:00	10.74
10:00-11:00	8.8
11:00-12:00	11.645
12:00-13:00	69.195
13:00-14:00	5.275
14:00-15:00	3.475
15:00-16:00	10.945
16:00-17:00	10.775
17:00-18:00	10.211
18:00-19:00	44.401
19:00-20:00	115.643
20:00-21:00	46.818
21:00-22:00	18.598
22:00-23:00	18.428
23:00-00:00	5.228

3.6. Electric load forecasting of the study area

The energy approach technique is used to forecast the village's power consumption. Annual energy consumption for residential customers is anticipated using appropriate growth rates such as population growth rates, customer growth (market penetration), and consumption per connection growth rates, as indicated in the sections below (EEPCo, UEAP., Electric Power Distribution Network Design and Construction Training Manual).

Population growth rate: First year population figure is projected by an annual growth rate of 3%, until the end of the forecast period. This population figure is converted to total number of households using an assumed average number of occupants per household (Bizuayehu T., 2011), (EEPCo, UEAP., Electric Power Distribution Network Design and Construction Training Manual). The demand for electrical energy is increasing due to the increase in the world population. The increase in energy demand is also related to the increased use of electrical appliances in households, social activities and lifestyle.

Residential consumption: The number of potential residential customers is changed to annual residential consumption by assuming an average per household consumption, which starts with 545.19kWh on the first year. This average consumption per household is made to grow at a rate of 2.57% per year for the whole forecast period (Bizuayehu T., 2011), (EEPCo, UEAP. Electric Power Distribution Network Design and Construction Training Manual).

Market penetration (customer growth): At the first year of electrification, all households are assumed to be connected. Therefore, market penetration rate is necessary. After the first year of interconnection, 5% market penetration rate (MP) is taken to change the total number of households to potential residential customers until the end of forecast.

Table 3.7: Energy forecast for the study area

Year	Average consumption rate increase	Number of Household	Yearly energy consumption (KWh)	Daily energy consumption (KWh)
2021	545.19	400	218,076	597.468
2022	559.201	420	234864.42	643.464
2023	573.572	441	252945.252	693
2024	588.313	464	272977.232	747.882
2025	603.433	488	294475.304	806.782
2026	618.941	513	317516.733	869.91
2027	634.8477	539	342182.91	937.487
2028	651.163	566	368558.258	1009.748
2029	667.898	595	397399.31	1088.765
2030	685.063	625	428164.375	1173.053

The preceding table displays the community's projected yearly and daily energy use over the next 10 years using the energy approach technique. This approach is utilized by the HOMER program. However, it did not take into consideration the community's future fluctuation in energy usage. This is taken as a fundamental draw back of the software.

3.7. Resource assessment

Anything that comes from outside the system and is used by the system to produce electricity is referred to as a resource. That includes any fuel consumed by the system's components as well as the four renewable energy sources (solar, wind, hydro, and biogas). Location has a huge impact on renewable resources. The solar resource depends strongly on latitude and climate, the wind resource on large-scale atmospheric circulation patterns and geographic influences, the hydro resource on local rainfall patterns and topography, and the biomass resource on local biological productivity. Furthermore, a renewable resource may display significant seasonal and hour-to-hour variations at any one location.

Since the resource dictates the quantity and time of renewable power generation, the type of the available renewable resources has an impact on the economics and behavior of renewable energy systems. Therefore, careful modeling of the renewable resources is an essential element of system modeling. In this section how to HOMER model the renewable resources used in this thesis is described (Lambert T. et al., 2006).

3.7.1. Solar energy resource

The HOMER user must supply solar resource information for the area of interest in order to simulate a system that includes a PV array. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes Earth's surface in a typical year. The data can be in one of three forms:

i. Hourly average global solar radiation on the horizontal surface (kW/m2)
ii. Monthly average global solar radiation on the horizontal surface (kWh/m2.day) or
iii. Monthly average clearness index.

The clearness index is the ratio of the solar radiation striking Earth's surface to the solar radiation striking the top of the atmosphere. A number between zero and 1, the clearness index is a measure of the clearness of the atmosphere (Lambert T. et al., 2006).

In this work by providing site monthly solar resource data, HOMER generates synthetic global solar radiation data with monthly average clearness index. The monthly average clearness index typically ranges from 0.517 (a cloudy month) to 0.678 (a very sunny month). The monthly average solar radiation and monthly average clearness index is shown as in the figure below.

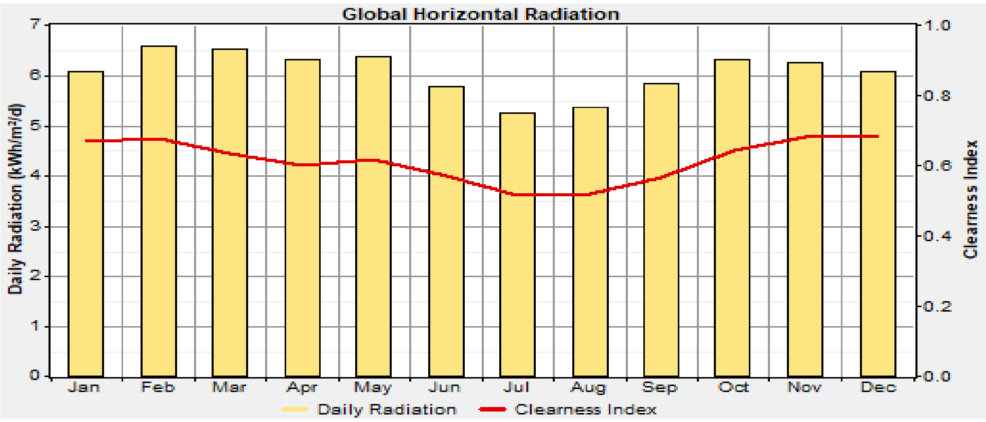

Figure 3.1: Annual solar radiation and clearness index of the site

3.7.2. Wind resource

To model a system comprising one or more wind turbines, the wind resource data indicating the wind speeds the turbines would experience in a typical year has been provided. The user can provide measured hourly wind speed data if available. Otherwise, HOMER can generate synthetic hourly data from 12 monthly average wind speeds and four additional statistical parameters: the Weibull shape factor, the autocorrelation factor, the diurnal pattern strength, and the hour of peak wind speed. By providing all these data for this site: a typical autocorrelation factor ranges from 0.8 – 0.95 then by taking 8.5 for this work, Typical values for diurnal pattern strength range from 0 to 0.4. A value of 0.25 has been selected for calculations, The typical range for the time of peak wind speed is 14:00-16:00 a time 15 has been selected, The monthly average wind speed is 4.2m/s source from NASA monthly averaged wind speed at 25 m above the Surface of the Earth and the elevation of the site above sea level is 1729m has been entered to the software. The monthly average wind speed for the site, together with other related data, such as values of Weibull parameter k, diurnal pattern, autocorrelation, etc. was fed into HOMER. Figure below shows the wind speed resource data measured at 25 m height (Lambert T. et al., 2006).

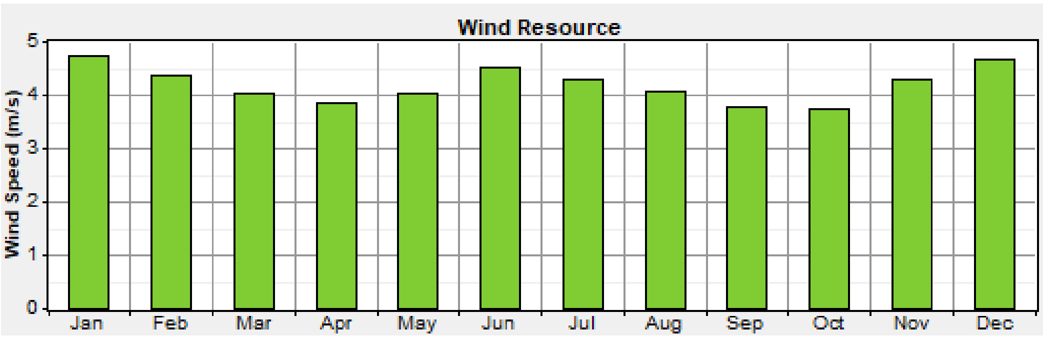

Figure 3.2: Annual wind resource distribution for the site

3.7.3. Fuel

HOMER provides a library of several predefined fuels, and users can add to the library if necessary. The physical properties of a fuel include its density, lower heating value, carbon content, and sulfur content. The user can also choose the most appropriate measurement units, either L, m^3, or kg. The two remaining properties of the fuel are the price and the annual consumption limit, if any.

3.8. Components assessment

Any element of a micro power system that produces, delivers, transforms, or stores energy is referred to as a component in HOMER. HOMER simulates ten different component kinds. Photovoltaic panels, wind turbines, and hydroelectric turbines are the three renewable energy sources that provide intermittent power. Generators, the grid, and boilers are three other sorts of components that may be dispatched by the system, which means that they can be controlled as necessary. The other two types of components are converters and electrolyzes, that converts electrical energy into another form. Batteries and hydrogen storage tanks are the final two categories of components that may store energy. The performance and cost of each of the system's components is a major factor for the cost results and design. Thus, the development of these data took a lot of time and effort. A different set of performance and cost parameters is used by HOMER to characterize each of these different components.

3.9. Selection and cost estimation of component sources

It is known that as input into HOMER, values are given as primarily load, deferrable loads and component resources. These are the principal guidelines for selecting the size of the power components. Cost minimization is another criterion considered when selecting the components.

3.9.1. Solar array

The PV array is a device that produces dc electricity in direct proportion to the global solar radiation incident upon it. Due to the remote location's complexity and financial load, the PV system planned for the site does not include tracking system. The PV power system will have the following characteristics:

- Derating factor of 90% and 20 years of life time,
- Slope of 8^0, Azimuth angle of 0 degree and ground reflectance of 20%
- Sizes to consider (kW):- 0, 25, 50, 100, 150, 200 and 250.

To describe the cost of the PV array, its initial capital cost in dollars, replacement cost in dollars, and operating and maintenance (O&M) cost in dollars per year has to be specified. Here are the PV prices taken from different sources (Volker Q., 2005), (Munuswamy S. et al., 2011). The replacement cost is the cost of replacing the PV array at the end of its useful lifetime, which is specified in years. By default, the replacement cost is equal to the capital cost.

Generally, the cost of a solar panel bases runs between $0.7 to $1.5 per watt which will be in average $1.2/W. The cost of solar panel 1 kW rating is given by equation. Assume the labor cost is $100/kW. Capital cost (1kW) = solar panel cost/kW + installation cost/kW Capital cost (1 kW) = $1200 + $100 = $1300. The replacement cost is equal to initial cost which is $1100. Operating and maintenance costs are $30/ year (solar panel price, 2021).

PV cost: - size (kW) 1, capital ($) 1300, operating & maintenance ($/yr.) 30.

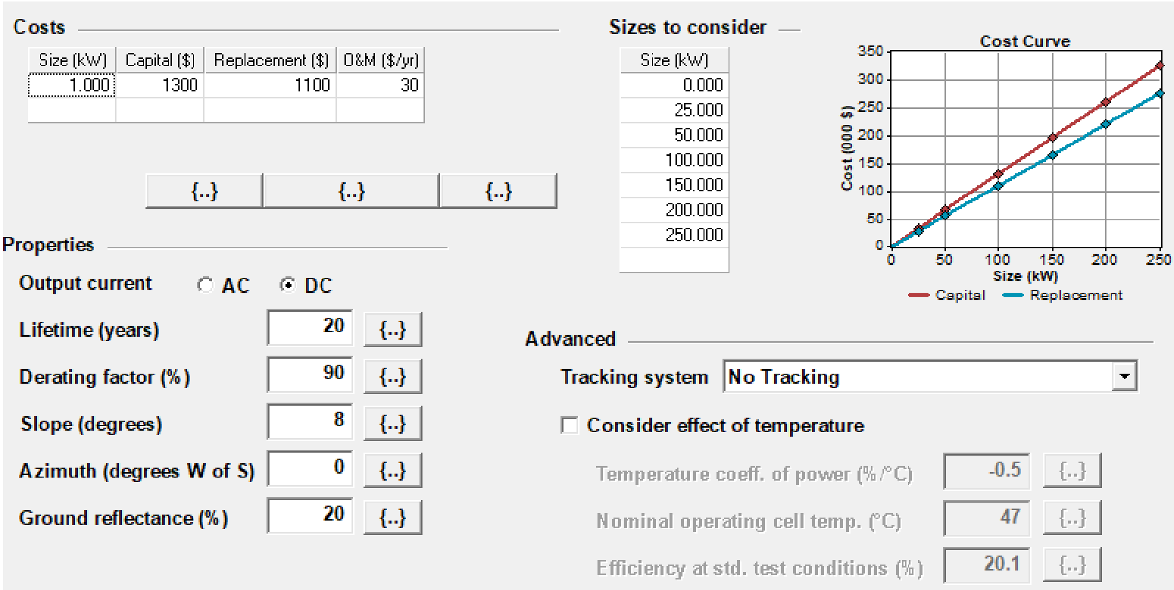

Figure 3.3: The solar PV inputs in HOMER

3.9.2. Sizing of standalone PV system and selecting the PV module

- ✓ Total AC watt hour per day multiply by 1.2 to correct inverter, wiring and other losses.

  534.45kwh/day X 1.2 = 641,340wh/day or 641.34kwh/day

- ✓ Choosing inverter DC input voltage 48V
- ✓ To get total amp hours per day used by AC loads can be found by total amp hours per day divide by inverter DC input voltage

  641,340/48= 13,361.25Ah/day
- ✓ Multiplying total average amp hours per day by 1.2 to compensate for loss from battery charge and discharge.

13,361.25 X 1.2= 16,033.5Ah/day

- ✓ To get the total solar array amps required divide the total average amp hours per day by average sun hours per day of study area 6.05

  16,033.5/6.05= 2,650.1653
- ✓ Selecting (Astropower, P300,300W,36V,8.33Amp)
- ✓ Then determining the total solar modules in parallel required,

  2,650.1653/8.33=318.147 round up to the next whole number =319
- ✓ To get number of modules in series; dividing nominal voltage by individual array voltage

  48/36=1.333 round up to the next whole number=2
- ✓ Finally, by multiplying number parallel and series modules we get the total number of solar module required

  319 x 2=638 solar modules needed.

  Solar panels cost ranges between $0.7-$1.50 per watt which will be in average $1.1/W. Assume the labor (installation) cost is $30 for 300W.

  Capital cost (W) = solar panel cost/W + installation cost/W

  Capital cost (W) = $330 + $50 = $380.

  The replacement cost is equal to initial cost which is 330$. Operating and maintenance costs are $10/year.

Cost of arrays= Number of PV modules X cost/module

Cost of arrays=638 X $380

Cost of array=$242,440

*Assume that the system is hybrid so the solar array size and cost will be decreased much depending on the renewable energy that used.

3.9.3. Battery

A device store a certain amount of DC electricity at fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs replacement.

The key physical properties of the battery are its nominal voltage, capacity curve, lifetime curve, minimum state of charge, and round-trip efficiency. The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes. Capacity typically decreases with increasing discharge current. The lifetime curve shows the number of discharge–charge cycles the battery can withstand versus the cycle depth. The number of cycles to failure typically decreases with increasing cycle depth. The minimum state of charge is the state of charge below which the battery must not be discharged to avoid permanent damage. The round trip efficiency indicates the percentage of the energy going into the battery that can be drawn back out.

The battery bank's capital and replacement costs in dollars, and the O&M cost in dollars per year have been specified (Solar and Converter Price, 2021).

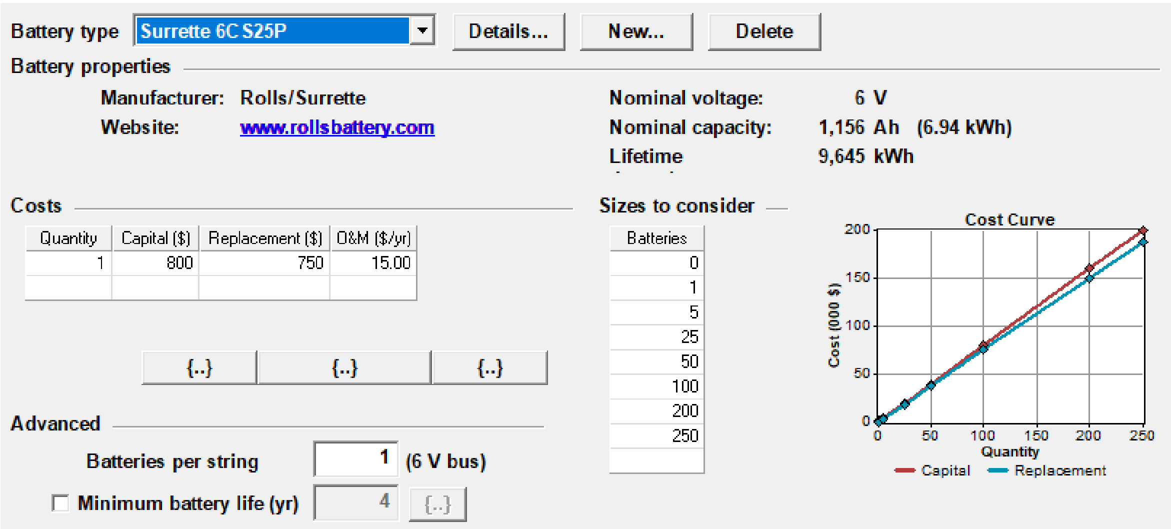

Figure 3.4: Battery inputs in HOMER

3.9.4. Sizing and selecting battery

- The total daily amp-hour required is 13,361.25
- The maximum number of consecutive cloudy weather days expected in this area will be 2.
- The amount of amp-hours our system will need to store can be found by multiplying the above two results 13,361.25 X 2= 26,722.5
- The depth of discharge for the battery we have chosen. If discharge limit is 80% so we use 0.8. This number should not exceed 0.8.
- By dividing the amp-hour of storage need by the depth of discharge limit

  26,722.5/0.8=33,403.125Ah

- The multiplier that corresponds to the average winter time ambient temperature our battery bank will experience is 1.02
- Then multiplying the amp-hours by the battery multiplier to get the total battery capacity

  33,403.125 X 1.02=34,071.19Ah

- The amp-hour rating for the battery we have chosen is 200(Trojan L24,24V,200Ah)
- Dividing the total battery capacity by the battery amp-hour rating and round up to the next whole number to get the number of batteries wired in parallel required
  34,071.19/200=170.356=171
- To get the number of batteries wired in series we divide the nominal system voltage 48V by the battery voltage and round off to the next highest number
  48/24=2
- Then total number of batteries can be found by multiplying the number of batteries in parallel by the number of batteries in series
  171X2=342
  24v, 200Ah price bases between $465-$475 average $470 for one battery.
- Cost of batteries=Number of Batteries X Cost/Battery
- Cost of batteries=342 X $470=$160,740

*Assume that the battery size will decrease depending in the hybrid system also not used all the time, it uses for backup so that this will leads to decrease the total cost of batteries.

3.9.5. Sizing and selecting charge controller and converter

A converter is an electronic power device that is required in a hybrid system to maintain the energy flow between AC and DC electrical components. It has an inverter and a rectifier to do the conversions from DC to AC and vice versa. The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power. The rectifier capacity, which is the maximum amount of dc power that the device can produce by rectifying ac power, as a percentage of the inverter capacity has been specified (Battery and Converter price, 2021).

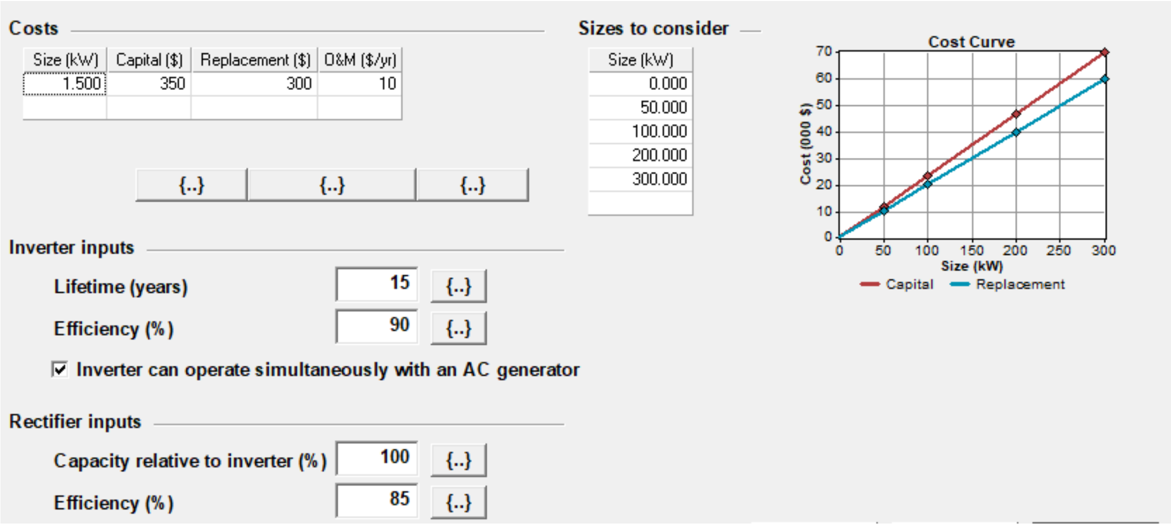

Figure 3.5: Converter inputs in HOMER

- Inverter capacity

  263,378W, 1Phase, 48/230V

- Rating of charge controller in amp(A) and volts(V)

  I=2,650.165A & 48V

- We have choose (Xantrex C60,48V,60A) charge controller
- Total current of controller

  I_{Tot} =1.25 X Number of parallel module X Short circuit current

  I_{Tot} =1.25X319X9.58= 3,820.025A

  Number of charge controller=I_{Tot} /Amperes of individual controller

  =3,820.025/60 =63.667

  Number of charge controller required=64

- Cost of charge controller=Number of charge controller X Cost/charge controller

  =64 X $148= $9,472

3.9.6. Wind turbines

A wind turbine is a device that converts the kinetic energy of the wind into ac or dc electricity according to a particular power curve, which is a graph of power output versus wind speed at hub height.

Each hour, the power output of the wind turbine is calculated in a four-step process.

i. The average wind speed for the hour at the anemometer height is determined by referring to the wind resource data.
ii. The corresponding wind speed at the turbine's hub height is calculated using either the logarithmic law or power law.
iii. The power output of wind turbine is calculated at that wind speed referring to its power curve assuming standard air density.
iv. That power output value is multiplied by the air density ratio, which is the ratio of the actual air density to the standard air density.

In addition to the turbine's power curve and hub height, the expected lifetime of the turbine in years, its initial capital cost in dollars, its replacement cost in dollars, and its annual O&M cost in dollars per year has been specified.

The primary criterion for the selection of the wind turbine is its cost. The wind turbines have been selected from different sources; the various wind turbine websites and those suggested by the HOMER program itself based on their costs. Other selection criteria used are: the type of current they generate (ac or dc), how low the cut-in wind speed is, and for what application the wind turbine be used for. The cut-in wind speed is another is primary criterion, if not import than cost, as the wind resource at the site is not very high. The type of current they generate, whether ac or dc, is also considered as it have impacts on the size of the inverter. As the load assumed for the households is of an ac type a wind turbine that generates ac current has been chosen. As the aim of the research is to supply electric energy to remotely located communities, the wind turbines selected should be those which are applicable for home or off grid applications. Other parameters that will be used are Weibul factor k (2), anemometer height 25 m, an altitude of 1729m and surface roughness length of 0.2m with logarithmic wind shear profile.

Different wind turbines have been tested by running the simulation many times based on the selection criteria listed above. The Fuhrlander 250 type was found to be the best among the wind turbines that were candidates for this application in terms of the cut-in wind speed, which is widely available on the market, as well as the other criteria indicated previously.

This wind turbine was chosen from among several recommended by HOMER. The power curve is shown in the figure below.

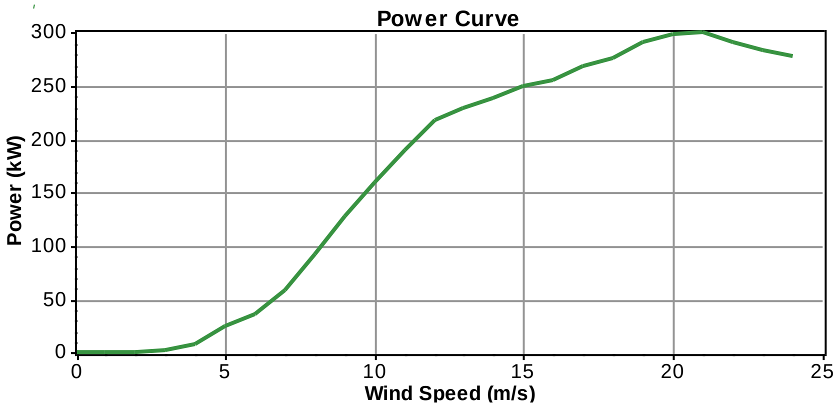

Figure 3.6: Power curve of 250 Kw turbines

The unit cost considered for a Fuhrlander 250 type Wind Turbine consists of a capital cost of $21,000, a replacement cost of $20,000 and an annual O&M cost of $100. The life time for the proposed wind turbine is estimated 15 years (Mandefro Y., 2017). The sizes to consider are 0, 1, 2 and 10.

Other inputs into the software, such as the range of sizes for the PV and the converter and the number of batteries are given so as to give flexibility to the software and optimize the output results.

3.10. Sensitivity inputs

As an iterative optimization model type, HOMER can simulate each system configuration over a range of values for resource availability and component costs. This capability aids in sensitivity analysis, which is the process of determining the factors that have the greatest influence on the design and operation of hybrid systems. However, the main factors that affect the micro power system are often unpredictable. This is a significant issue that must be resolved in the system's design. One of HOMER's key qualities is at play in this situation: With the use of scaling factors, this program may perform a sensitivity analysis on hourly data sets. In this method, it is possible to account for uncertainties in the principal electric load or the renewable energy sources. Because of this, even when there are uncertainties in the important variables, the sensitivity analysis enables the system designer to produce an effective and useful design.

The wind speed and the PV capital cost multiplier, which are interrelated with the PV replacement cost multiplier, are the uncertain variables for which a sensitivity analysis was required. The PV capital cost & replacement cost were not considered for the sensitivity analysis in this thesis work. The solar radiation sensitivities entered are 6.05kwh/h/d, 5.4kwh/h/d and 6.57kwh/d. For wind speed 4.2m/s , 3.6m/s, 3.75m/s. 4.7m/s, and 5.5m/s and diesel price 0.564$/*L* ,0.85$/L, 1.56$/L, and 2$/L are the four values entered. For each of these different values the complete system is simulated with the resulting different technical and cost parameters.

3.11. Modeling of hybrid system using HOMER tool

HOMER is a software product for micro-power hybrid system optimization model which is developed by National Renewable Energy Laboratory (NREL) in the USA. The software helps in evaluating designs of both off-grid and grid-connected power systems with different varieties of hybrid system models. HOMER comprises built in archive technology options for hybrid system modeling such as; energy sources (Wind, Solar, Hydro, biomass and fuel cell generator), backup storage mechanisms (batteries, hydrogen tank and free wheel) and loads (primary and deferrable). HOMER's optimization and sensitivity analysis algorithms help to evaluate technical and economic feasibility of these technology options combinations for the hybrid system. To use HOMER, the user has to provide resource availability data of the site and component costs for the selected technology options of the specific hybrid model. HOMER uses these inputs to simulate different system configurations, or combinations of components, and generates results and displays a list of feasible configurations sorted by net present cost in increasing order (Getnet T., 2011, Homer).

Based on the theoretical background discussed so far, a standalone PV/wind/genset hybrid energy system was designed for a model community of 400 households, with an average of six members per family. The HOMER software is used as a tool to carry out the research. As previously stated, the primary goal of the research is to design and model hybrid PV/Wind/genset standalone power generation systems to meet the community's load requirements. Figure 3.8 displays a schematic of the standalone hybrid energy system developed by HOMER.

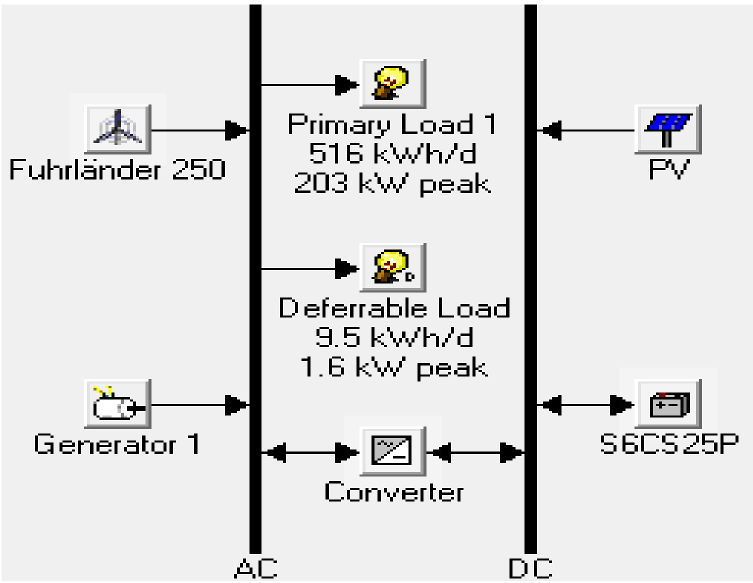

Figure 3.7: HOMER schematic representation for Proposed Hybrid System

HOMER three main functions are Simulation, optimization, and sensitivity analysis. To determine the technical viability and life-cycle cost of a particular power system configuration, the performance for each hour of the year is modeled during the simulation process. The goal of the optimization process is to find the system configuration that meets the technical requirements at the lowest life-cycle cost out of a large number of possible configurations. Multiple optimizations are carried out during the sensitivity analysis process under a variety of input assumptions to assess the effects of uncertainty or changes in the model inputs. Optimization determines the optimal value of the variables over which the system designer has control such as the mix of components that make up the system and the size or quantity of each. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price. The effects of these can be analyzed with the help of the sensitivity analysis. The relationship between simulation, optimization, and sensitivity analysis is depicted in Figure 3.8. The oval figure encircled by another oval figure demonstrates how one optimization is made up of numerous simulations, and the same is true for a sensitivity analysis.

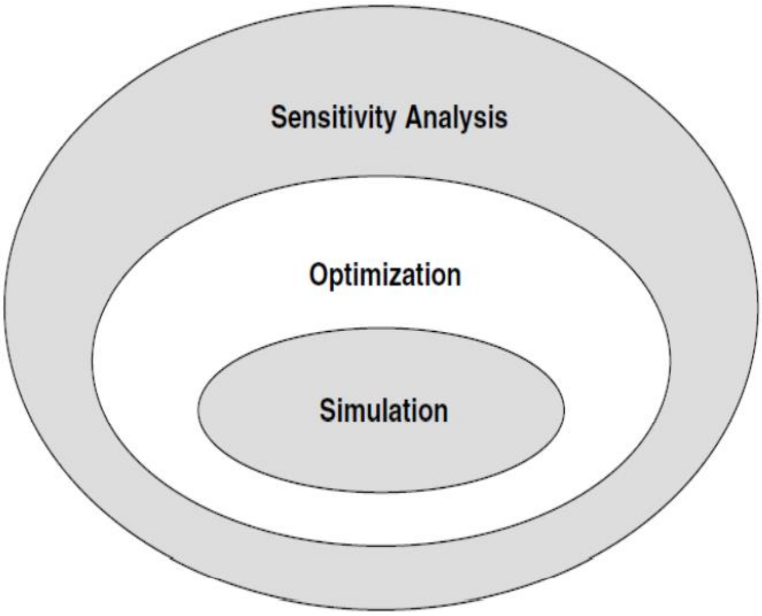

Figure 3.8: Conceptual relationship between simulation, optimization, and sensitivity analysis

3.12. System dispatch

Along with selecting the various components, HOMER also has to make decisions about how these components will work together, such as which generators should run and at what power level, whether power should be sold to or purchased from the grid, whether batteries should be charged or discharged, etc. Additionally, each of these choices needs to be made for every hour of the day. The following sections provide a brief explanation of how operating reserve and load priority affect HOMER's dispatch decisions (Homer).

Operating reserve: The variability of RES power output and the potential for a sudden increase in electric load demand to exceed operating capacity are issues with micro power systems (which will lead to an outage). As a result, every system requires an operating reserve, which is extra generating power, to close the safety gap and be prepared to handle these issues. The operating reserve for a system is always equal to its operating capacity less the electrical load.

Load priority: Following a load priority system, HOMER makes its own decisions regarding how to distribute the electricity generated by the system. HOMER serves the electricity produced from an AC source to an AC load first, the same goes for DC. As all of the loads in this study are AC connections, HOMER serves the primary load first, then the deferred load.

3.13. Economic modeling

The goal of this thesis is to identify the optimal system configuration, and the simulation heavily relies on economics. Total NPC is used as the economic success metric to compare the various configurations' economic performance. This section goes over the benefits of these indicators. To be able to compare the economics of numerous different system configurations with a varying share of renewable and non-renewable energy sources, HOMER has to take into account both the operating and capital costs. Since the NPC comprises of all costs incurred during the system's life span, it considers these factors and therefore is the appropriate parameter to compare the different configurations' economics.

The different items making up the NPC are the costs for construction, maintenance including component replacements and miscellaneous other costs. Furthermore, the NPC also considers salvage costs, which is the residual value of system components after the project's end. An alternative to the NPC to compare the economics of various system configurations is the levelized COE, which is defined as the average cost for every kWh of electricity produced by the system. Yet, HOMER has chosen the NPC as primary economic figure of merit (Munuswamy S. et al., 2011).

Economic inputs: The project's lifetime is considered to be 20 years with an annual interest rate of 8%. The nominal interest rate minus the inflation rate gives the real interest rate. The system fixed capital cost is considered to be $30,000 for the whole project and the system fixed O&M cost is estimated to be $1500/year for the project lifetime. The system fixed capital costs includes various civil constructions, logistics, labor wages, required licenses, administration and government approvals and other miscellaneous costs. The penalty for capacity shortage is not considered in this case.

3.14. The grid system

The micro power system is modeled as a component that either purchases AC electricity from the grid or sells AC electricity by feeding it back into the grid. In order to compare the cost of the hybrid energy system with the grid, HOMER is used in this study. In order to determine whether a grid extension is feasible or whether operating an off-grid system is more cost-effective, the cost of a grid extension is factored into the analysis. The breakeven grid extension distance is calculated in this manner. The breakeven grid extension distance is the distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system. Farther away from the grid, the stand-alone system is optimal. Nearer to the grid, grid extension is optimal. The capital cost of grid extension per kilometer of the Shenen Sillasie village is considered to be $17,689/km.

3.15. System constraints

If a small amount of load is allowed to go unserved, this can significantly affects the economic performance of the hybrid energy system. If the system can be designed to be down for a short period of time in a year or if some load can be shed, this can help in reducing the battery bank and hence significantly reduce the capital cost of the hybrid system (Givler T., & Lilienthal P., 2005). The maximum annual capacity shortage is set at 1% and the minimum renewable fraction is taken as 50%. It also includes the Operating reserve, which was discussed above. An operating reserve of 10% of hourly load, 40% of solar output power and 50 % wind power output respectively is suggested.

3.16. Cost estimation of grid extension

The power is delivered to the end consumers via distribution lines. The national grid is typically extended from a nearby substation or an overhead medium voltage (MV) distribution line. The most prevalent medium voltage levels employed in MV systems by the UEAP under the EEU are 33KV and 15KV. However, given to its advantages over alternative possibilities, the UEAP is currently employing the 33KV voltage level for powering isolated rural regions. The voltage level that is extended for electrifying the outlying rural regions around my research case, however, is 15KV. The transformer, line supports and their base, insulators, line accessories, and conductors are the primary components of an overhead distribution line that might impact the cost of grid extension. The line supports can be built of wood (like local wood poles and South African poles), reinforced concrete poles, or steel, however UEAP is adopting concrete poles for MV distribution lines to provide electric access to certain rural regions because to its strength and availability.

Surveying, excavation, pole erection, pole top arrangement, and conductor stringing are the key operations performed during extension. For the 15KV line, Aluminum Alloy Conductor with a size of $95mm^2$ is utilized in the MV distribution line construction. The number of poles to be installed and the need for guy wire, on the other hand, is determined by the distance between the site and a local substation or MV distribution line, as well as the geographical position of the selected locations. Furthermore, depending on the kind of assembly, different accessories are employed; they are classed as suspension, light angle 1, light angle 2, heavy angle, T-off, tension tower, and dead-end assemblies based on the angle departure from a straight line.

The cost of providing electric connection to Shenen Sillasie village, which is located in Wonji Shoa, is estimated based on the information provided above. It is 31 kilometers from an existing grid, and a preliminary study is being undertaken to determine the type of assembly to be utilized in the installation of MV distribution lines. For the population of this community, 1x250KVA and 2x630KVA rated transformers are required. Extension of 31 km MV, 1.5 km LV distribution line, and building of two transformers with ratings of 1x250KVA and 2x630KVA are required to provide electric access to the 400 households from the surrounding national grid. The overall cost comprises material, transportation, and labor costs, resulting in an investment cost of 28,926,171.5 Ethiopian birr, which is now comparable to 548,363.44 US dollars.

Table 3.8: The total cost needed for extending a grid to Shenen Sillasie site

Summary of cost Estimation	
List of Payment	**Cost**
Trafo. (Net station) erection	9,001,187.5
L.T line extension	6,156,500
H.T line extension	12,100,456
New connection/pillar	633,243
Trafo partial	0.00
Substation partial	0.00
H.T partial	390,185
L.T line partial	0.00
Estimation fee	1,500
Deposit	40,000
Unsold electric	3,100
El. Installation plan approval fee	600,000
Transformer improvement	0.00
Allowance	0.00
Subtotal	28,926,171.5
Trafo deduct	0.00
Total	28,926,171.5

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Results and Discussions

The viability of a PV/Wind/Genset hybrid power system is addressed in this chapter. Previously, the feasibility of a hybrid system that feeds power to 400 model villages was discussed. HOMER software is used to simulate the system. The supplied data for the HOMER simulation program defined the primary load, deferred load and system components that are PV (1kw), wind turbine type Fuhrländer 250, diesel generator, Battery bank Vision type Surrette 6CS25P and converter with their prices based on load estimation. The following two tables show all inputs that are used for the simulation process.

Table 4.1: Homer component inputs

	Size(kW)	Capital cost ($)	Replacement cost ($)	O&M cost ($/yr.)	Size to consider
Solar PV	1	1300	1100	30	0,25,50,100,150,200,250
Wind turbine	250	21,000	20,000	100	0,1,2,10
Genset	1	460	425	0.05	0,25,50,100
Battery	-	800	750	15	0,1,5,25,50,100,200,250
Converter	1.5	350	300	10	0,50,100,200, 300

Table 4.2: Resource sensitivity inputs

Resource inputs	Sensitivity values
Solar radiation (kWh/m^2/day)	6.05, 5.4, 6.57
Wind speed (m/s)	4.2, 3.6, 3.75, 4.73, 5.5
Diesel price ($/L)	0.564, 0.85, 1.56, 2

The simulation of a hybrid system for feasibility analysis consists of system optimization and sensitivity analysis. This simulation result includes multiple combinations of each source, each with its own initial capital and net present cost. The monthly average solar radiation and wind resource data of the village obtained from NASA was input into HOMER.

HOMER is simulated multiple times by modifying choice factors that have an influence on the output after feeding the available data to the program to identify the optimal solutions from diverse system setups. The size of the PV panel, the size of the wind turbine, the number of battery banks, the size of the diesel generator, and the size of the converter are the choice variables that determine the output. The simulation results list the viable combinations of solar panel, wind turbine, diesel generator, converter, and battery of the hybrid system while excluding the infeasible hybrid system combinations.

The optimization result presents the feasible hybrid systems in two selective options: overall and categorized. The Overall option will display all feasible hybrid systems in the order of Cost of Energy (COE) and Net Present Cost (NPC) increasing. The second is the system's categorized optimal outcome, in which only the hybrid system configuration with the lowest cost (least Cost of Energy) is chosen for each system component.

Figure below shows the overall optimization results of a hybrid solar-wind-generator system modeled with HOMER Software.

Double click on a system below for simulation results.

PV (kW)	FL250	Gen (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen (hrs)
50	2	25	200	200	$ 355,167	19,221	$ 543,884	0.289	0.96	0.00	5,831	888
100	2		200	200	$ 408,667	14,709	$ 553,085	0.294	1.00	0.00		
25	2	25	200	200	$ 322,667	23,488	$ 553,279	0.295	0.93	0.01	10,482	1,515
50	2	50	100	100	$ 263,333	30,330	$ 561,119	0.299	0.89	0.01	20,086	1,710
50	2	50	200	200	$ 366,667	19,863	$ 561,680	0.298	0.96	0.00	6,662	525
50	2	50	200	100	$ 343,333	22,412	$ 563,381	0.300	0.94	0.00	10,091	761
100	2	25	200	200	$ 420,167	15,782	$ 575,119	0.305	0.99	0.00	1,230	188
50	2	25	200	300	$ 378,500	20,147	$ 576,303	0.306	0.97	0.00	5,746	877
25	2	50	100	100	$ 230,833	35,290	$ 577,320	0.308	0.86	0.01	24,981	2,142
50	2	25	250	200	$ 395,167	18,679	$ 578,560	0.308	0.98	0.00	3,566	497
25	2	50	200	200	$ 334,167	25,077	$ 580,373	0.308	0.92	0.00	12,301	905
25	2	50	200	100	$ 310,833	27,546	$ 581,285	0.309	0.90	0.00	15,540	1,116
100	1	25	200	200	$ 399,167	18,637	$ 582,145	0.309	0.97	0.00	4,009	617
25	2	25	200	300	$ 346,000	24,379	$ 585,358	0.312	0.93	0.01	10,376	1,495
50	2	50	250	200	$ 406,667	18,241	$ 585,758	0.311	0.98	0.00	3,351	239
100	2		200	300	$ 432,000	15,727	$ 586,408	0.312	1.00	0.00		
50	2	50	100	200	$ 286,667	30,692	$ 588,004	0.313	0.90	0.01	19,391	1,689
100	2	50	200	200	$ 431,667	15,929	$ 588,065	0.312	0.99	0.00	1,597	119
100	2	25	100	200	$ 340,167	25,342	$ 588,983	0.314	0.94	0.01	13,412	2,113
100	1		250	200	$ 427,667	16,603	$ 590,677	0.315	1.00	0.01		
25	2	25	250	200	$ 362,667	23,314	$ 591,571	0.315	0.94	0.01	8,553	1,203
50	2	50	200	300	$ 390,000	20,723	$ 593,458	0.315	0.96	0.00	6,501	517
100	1	50	200	200	$ 410,667	18,737	$ 594,632	0.316	0.97	0.00	4,335	329
100	2	50	100	100	$ 328,333	27,503	$ 598,364	0.318	0.93	0.00	16,345	1,391
50	2	100	200	200	$ 389,667	21,372	$ 599,497	0.318	0.96	0.00	8,102	389

Figure 4.1: The overall optimization results of HOMER simulation

The categorized optimization result of the hybrid solar-wind-genset system is shown blow.

Double click on a system below for simulation results.

PV (kW)	FL250	Gen (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen (hrs)
50	2	25	200	200	$ 355,167	19,221	$ 543,884	0.289	0.96	0.00	5,831	888
100	2		200	200	$ 408,667	14,709	$ 553,085	0.294	1.00	0.00		
	10	50	100	100	$ 366,333	24,935	$ 611,152	0.326	0.98	0.01	15,889	1,393
150		25	250	200	$ 483,167	24,591	$ 724,608	0.385	0.94	0.00	6,387	948
250			250	200	$ 601,667	21,003	$ 807,877	0.430	1.00	0.00		

Figure 4.2: Categorized optimization results of HOMER simulation

The above simulation results in the Figure 4.2 shows the optimal result with least cost of the system that are five alternatives to feed the system loads are possible configurations. Despite the fact that there are numerous alternatives with an equal renewable fraction, the choice of optimal system type is limited by the varying nature of each set-initial up's capital, net present cost, excess electricity and COE. As a result, the one ranked first in blue color with a total NPC of $543,884 and COE of 0.289 is the best optimum solar-wind-genset hybrid system configuration.

The best optimum hybrid System configuration from the result is wind/PV/genset system is presented in table 4.3

Table 4.3: System components

Configured hybrid system components	Amount(Kw)
Solar PV array	50
FL250 wind generator turbine	2
Diesel generator (Gen 1)	25
6FM200D	200 units
Converter	200

The cash flow summary is window displays cash flows as either a present value or annualized cost, categorized by component or cost type. The cost summary categorizes by components shows in the figure 4.3.

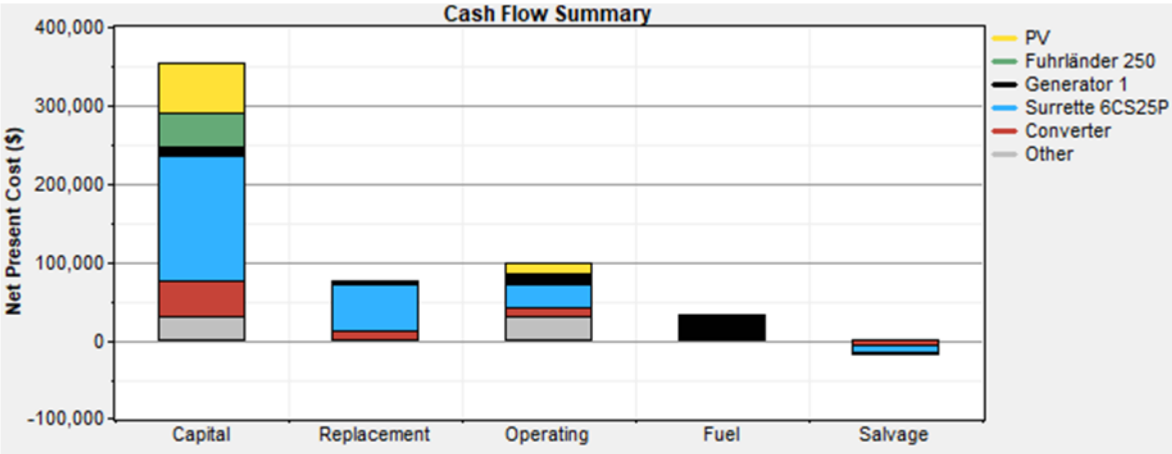

Figure 4.3: The cash flow summary

The cost summary of the optimal hybrid system is presented below.

Table 4.4: Cost summary

Cost type	Cost in $	Cost in ETB
Initial Capital($)	355,167	18,735,059.25
Total NPC($)	543,884	28,689,881
COE($/Kwh)	0.289	15.245

Source: -Commercial Bank of Ethiopia (CBE) on 23/April/2022, (1$=52.75 ETB). Moreover, the renewable fraction is nearly 1(0.96) and capacity shortage is zero.

The wind turbine system produces the majority of the energy produced by the hybrid solar-wind-genset power system, according to the economic dispatch. Even though, the cost of a wind turbine system not exceeds the cost of a solar system.

The total electric production of the hybrid system is 459,697kwh/yr. (100%) that is PV array 100,781kWh/yr. (22%), wind turbine 342,698kWh/yr. (75%) and generator 1 16,220kWh/yr. (4%). The primary and deferrable load consumption is 188,111kWh/yr. (98%) and 3,462kWh/yr. (2%) respectively. And the unmet electric load is 0.1% and capacity shortage is 0.2%. The renewable fraction is 0.965 values so that is the hybrid system have no environmental impact, a clean energy source devoid of pollutants like carbon dioxide and other green gases.

4.1.1. Sensitivity analysis results

This part uses graphs and tables to describe and interpret sensitivity results and determines under what conditions a wind/solar/genset system is more cost-effective and feasible. For each of the sensitivity values, the HOMER software simulates all of the systems in their respective search space. A feasible system is a hybrid system that meets the required loads. The software discards all infeasible systems and displays the results in ascending NPC order.

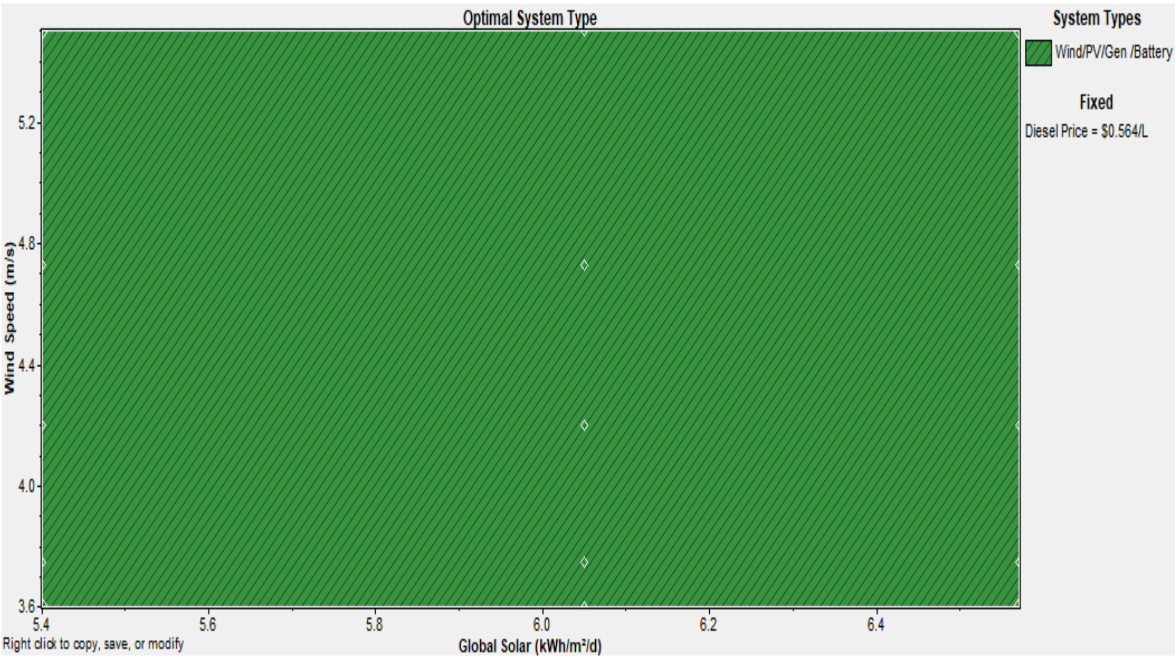

Figure 4.4: Optimal system type graph

The graph above shows that the optimal system design depends on the annual average solar radiation, diesel price and on the wind speed. The Wind/PV/Gen/Battery system configuration of the hybrid system is best optimal system type from the other system configurations that is PV/Wind/Battery or other system type has a lower significant role than Wind/PV/Gen/Battery system type. From so many feasible configurations the software gives the optimal system configuration by comparing and superimposing sensitivity inputs to gain best hybrid system.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this thesis work that has been done are first, wind and solar resource analyses, data collection, community load estimation and feasibility Study of a Standalone Solar/Wind/Genset. For rural electrification of 400 households in Shenen Sillasie. Finally, HOMER is used for optimization, sensitivity analysis of the proposed hybrid system. Then, comparing the cost of hybrid system with the cost required electrifying the village by extending the grid.

The Result of feasibility Study of a Standalone Solar-Wind-Genset shows that there are numerous alternative feasible hybrid set-ups with 100% contribution by the renewable resources and narrow ranges of COE. According, the community electric demands can be satisfied by a hybrid power source containing 50Kw PV, 250Kw (Fuhrländer 250 type) wind turbine, 25Kw diesel generator, 200Kw converters and 200 units of Vision S6CS25P batteries. This hybrid system needs $355,167 initial capital ,$543,884 total NPC with COE selected hybrid system found to be 0.289$/kwh.

The grid extension designed from the closest substation (presented in chapter three) shows that the study area can be electrified by the investment cost 28,926,171.5 Ethiopian birr.

Hence, the attempt of electrifying Shenen Sillasie is determined by comparing by the standalone hybrid system with grid extension. Accordingly, the comparison result shows that the breakeven extension distance was found to be 9.92Km. Therefore, up to 9.92Km extending the grid becomes cost effective and beyond 9.92Kms the standalone system is better.

5.2. Recommendations

Further investigations needed to be carried out to modify this thesis are the following points.

- ✓ The future researcher should broaden this research into other regions and zones.
- ✓ The high initial capital cost of hybrid energy systems is a major impediment to their use. As a result, governments and non-governmental organizations should provide

subsidies to encourage and increase the rural community's interest in using electricity.

- ✓ Considering the possibility of replacing the diesel generator in the hybrid system with locally produced biofuels such as sugar cane byproduct.
- ✓ Connecting the standalone hybrid power system to the national grid it helps to sell the power when it has excess power and pull from the grid when it doesn’t generate enough power.

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Appendix

Appendix i. Detailed optimization results

Detailed Optimization Results

#	PV	FL250	Gen	Surrette 6CS25P	Converter	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost
	kW		kW		kW	$	$	$/yr	$/yr	$/yr
1	100	2	0	200	200	408,667	553,085	41,624	5,676	9,033
2	50	2	25	200	200	355,167	560,257	36,175	5,781	10,151
3	100	2	25	200	200	420,167	578,574	42,795	5,502	9,586
4	50	2	50	200	200	366,667	580,387	37,346	5,537	10,568
5	25	2	25	200	200	322,667	582,712	32,864	6,189	11,387
6	100	2	0	200	300	432,000	586,408	44,000	6,027	9,700
7	50	2	25	250	200	395,167	588,573	40,249	6,841	9,827
8	100	1	0	250	200	427,667	590,677	43,559	6,920	9,683
9	50	2	50	200	100	343,333	591,717	34,969	5,342	11,378
10	50	2	25	200	300	378,500	592,438	38,551	6,124	10,782
11	100	2	50	200	200	431,667	592,548	43,966	5,285	9,744
12	100	1	25	200	200	399,167	593,401	40,656	5,635	10,741
13	50	2	50	250	200	406,667	595,169	41,420	6,603	9,747
14	100	1	50	200	200	410,667	606,806	41,827	5,415	10,877
15	100	2	25	200	300	443,500	607,015	45,171	5,836	10,087
16	150	1	0	200	200	452,667	610,831	46,105	5,676	10,433
17	50	2	50	200	300	390,000	611,714	39,722	5,883	11,173
18	100	2	0	250	200	448,667	612,659	45,698	6,920	9,783
19	100	2	100	200	200	454,667	613,943	46,309	4,849	9,894
20	25	2	25	200	300	346,000	614,494	35,241	6,525	12,002
21	25	2	50	200	200	334,167	614,916	34,036	5,912	12,227
22	25	2	25	250	200	362,667	615,587	36,938	7,242	11,249
23	50	2	50	100	100	263,333	617,520	26,821	4,167	14,835
24	100	2	50	200	100	408,333	617,985	41,590	5,164	11,129
25	50	2	25	250	300	418,500	618,204	42,625	7,179	10,368
26	100	2	50	200	300	455,000	619,595	46,343	5,616	10,205
27	50	2	100	200	200	389,667	622,248	39,688	5,229	11,573
28	100	1	25	200	300	422,500	623,476	43,033	5,974	11,296
29	50	2	100	250	200	429,667	623,518	43,763	6,192	10,133
30	100	1	0	250	300	451,000	624,000	45,935	7,270	10,350
31	100	1	25	250	200	439,167	624,133	44,730	6,772	10,502
32	25	2	50	200	100	310,833	624,921	31,659	5,857	12,925
33	50	2	50	250	100	383,333	625,421	39,043	6,485	11,258
34	50	2	50	250	300	430,000	626,101	43,796	6,946	10,334
35	100	2	25	100	200	340,167	626,643	34,647	4,136	13,642
36	25	10	25	100	200	410,667	628,834	41,827	3,705	10,439
37	100	2	25	250	200	460,167	629,075	46,869	6,713	10,026
38	150	2	0	200	200	473,667	632,813	48,244	5,676	10,533
39	25	2	50	250	200	374,167	633,646	38,110	6,862	11,599
40	0	10	25	200	200	458,167	634,293	46,665	5,641	8,719
41	50	2	100	200	100	366,333	635,451	37,312	5,063	12,540
42	100	1	100	200	200	433,667	635,885	44,170	5,032	11,362
43	50	1	25	200	200	334,167	636,472	34,036	6,468	13,179
44	100	1	50	250	200	450,667	636,485	45,901	6,547	10,596
45	100	1	50	200	300	434,000	636,736	44,204	5,757	11,436
46	150	1	25	200	200	464,167	637,892	47,276	5,509	11,045
47	50	10	25	100	200	443,167	639,957	45,138	3,493	10,226
48	100	2	50	250	200	471,667	640,157	48,040	6,486	10,087
49	50	2	50	100	200	286,667	642,453	29,198	4,486	15,270
50	100	2	100	200	300	478,000	642,483	48,685	5,185	10,404
51	25	10	25	200	200	490,667	642,794	49,975	5,530	8,404
52	25	10	50	100	100	398,833	643,143	40,622	3,314	11,245
53	150	1	0	200	300	476,000	644,154	48,482	6,027	11,100
54	100	2	50	100	100	328,333	644,260	33,441	3,714	14,570
55	100	1	50	200	100	387,333	644,693	39,451	5,330	12,653
56	25	2	50	200	300	357,500	645,658	36,412	6,244	12,811
57	25	2	25	250	300	386,000	645,746	39,315	7,572	11,813
58	100	2	0	250	300	472,000	645,982	48,074	7,270	10,450
59	25	10	25	200	100	467,333	646,163	47,599	5,308	8,978
60	25	2	50	100	100	230,833	647,467	23,511	4,770	16,431
61	150	2	25	200	200	485,167	647,771	49,415	5,465	10,730
62	50	10	0	200	200	511,667	649,213	52,114	5,676	8,333

#	PV kW	FL250	Gen kW	Surrette 6CS25P	Converter kW	Total Capital Cost $	Total NPC $	Tot. Ann. Cap. Cost $/yr	Tot. Ann. Repl. Cost $/yr	Total O&M Cost $/yr
63	25	2	50	250	100	350,833	651,075	35,733	6,843	12,586
64	50	10	50	100	100	431,333	651,376	43,932	3,030	10,926
65	100	2	50	250	100	448,333	651,804	45,664	6,321	11,021
66	150	1	50	200	200	475,667	652,389	48,448	5,294	11,218
67	100	1	25	250	300	462,500	652,626	47,107	7,106	11,006
68	50	2	100	250	300	453,000	653,962	46,139	6,535	10,710
69	100	2	100	200	100	431,333	655,350	43,932	4,837	11,974
70	0	10	50	100	100	366,333	655,767	37,312	3,717	12,257
71	100	2	25	250	300	483,500	657,033	49,246	7,045	10,512
72	100	1	100	250	200	473,667	657,319	48,244	6,106	10,720
73	50	1	25	250	200	374,167	657,692	38,110	7,384	12,663
74	50	2	100	200	300	413,000	657,985	42,065	5,591	12,329
75	150	2	50	200	200	496,667	658,403	50,587	5,236	10,772
76	100	2	100	250	200	494,667	659,384	50,383	6,028	10,124
77	0	10	50	200	200	469,667	659,461	47,837	5,463	9,252
78	100	2	25	100	300	363,500	659,966	37,023	4,487	14,309
79	25	10	50	200	200	502,167	660,545	51,147	5,325	8,686
80	100	2	50	100	200	351,667	660,995	35,818	3,962	14,702
81	50	1	50	200	200	345,667	661,706	35,207	6,148	13,828
82	25	10	25	100	300	434,000	662,157	44,204	4,056	11,106
83	50	10	25	200	100	499,833	664,437	50,909	5,233	9,001
84	50	2	100	250	100	406,333	664,537	41,386	6,169	12,172
85	0	10	25	200	300	481,500	665,202	49,042	5,983	9,304
86	100	1	100	200	300	457,000	665,568	46,546	5,373	11,914
87	25	2	100	200	200	357,167	666,087	36,378	5,558	13,755
88	150	2	0	200	300	497,000	666,136	50,621	6,027	11,200
89	100	1	50	250	100	427,333	666,751	43,525	6,447	12,159
90	100	2	50	250	300	495,000	667,407	50,417	6,817	10,551
91	25	2	50	250	300	397,500	667,669	40,486	7,215	12,288
92	100	1	50	250	300	474,000	667,998	48,278	6,892	11,204
93	150	1	25	200	300	487,500	668,238	49,653	5,849	11,610

#	PV kW	FL250	Gen kW	Surrette 6CS25P	Converter kW	Total Capital Cost $	Total NPC $	Tot. Ann. Cap. Cost $/yr	Tot. Ann. Repl. Cost $/yr	Total O&M Cost $/yr
94	25	10	50	200	100	478,833	668,249	48,770	5,128	9,435
95	25	10	0	250	200	519,167	668,923	52,878	6,920	8,333
96	0	10	25	250	200	498,167	669,124	50,739	6,795	8,624
97	0	10	50	200	100	446,333	669,902	45,460	5,268	10,072
98	50	1	50	200	100	322,333	669,930	32,830	6,036	14,444
99	150	1	0	250	200	492,667	670,404	50,179	6,920	11,183
100	25	10	50	100	200	422,167	670,715	42,999	3,624	11,727
101	50	1	25	200	300	357,500	670,747	36,412	6,825	13,876
102	50	10	25	200	200	523,167	671,518	53,286	5,492	8,782
103	50	10	50	100	200	454,667	671,894	46,309	3,262	11,167
104	25	10	25	200	300	514,000	672,778	52,352	5,869	8,959
105	50	10	25	100	300	466,500	673,280	47,514	3,844	10,893
106	25	2	100	200	100	333,833	674,885	34,002	5,425	14,525
107	150	2	25	200	300	508,500	675,402	51,792	5,799	11,200
108	50	2	50	100	300	310,000	675,775	31,574	4,837	15,936
109	150	1	100	200	200	498,667	676,493	50,790	4,869	11,464
110	150	2	100	200	200	519,667	676,616	52,929	4,773	10,772
111	50	1	50	250	200	385,667	679,226	39,281	6,996	13,148
112	25	2	100	250	200	397,167	680,571	40,452	6,556	12,728
113	0	10	25	250	100	474,833	681,136	48,363	6,647	9,470
114	150	2	50	200	100	473,333	681,562	48,210	5,113	12,100
115	25	2	50	100	200	254,167	681,734	25,887	5,318	17,151
116	150	1	50	200	300	499,000	681,975	50,824	5,632	11,761
117	100	10	25	100	100	484,833	682,123	49,381	3,103	10,910
118	50	10	0	200	300	535,000	682,536	54,491	6,027	9,000
119	0	10	50	100	200	389,667	682,882	39,688	4,023	12,716
120	25	10	100	200	200	525,167	684,442	53,489	4,900	8,927
121	150	2	50	200	300	520,000	684,668	52,963	5,572	11,200
122	50	10	50	200	100	511,333	685,007	52,080	5,053	9,420
123	150	2	25	100	200	405,167	685,154	41,267	3,960	14,434
124	150	1	25	250	200	504,167	685,541	51,350	6,709	11,384

#	PV (kW)	FL250	Gen (kW)	Surrette 6CS25P	Converter (kW)	Total Capital Cost ($)	Total NPC ($)	Tot. Ann. Cap. Cost ($/yr)	Tot. Ann. Repl. Cost ($/yr)	Total O&M Cost ($/yr)
125	50	10	50	200	200	534,667	686,510	54,457	5,279	8,973
126	100	2	100	250	300	518,000	687,281	52,759	6,359	10,605
127	100	1	100	200	100	410,333	687,627	41,793	5,054	13,783
128	0	10	50	250	200	509,667	688,191	51,911	6,596	8,954
129	100	2	100	250	100	471,333	690,449	48,006	5,989	11,880
130	100	1	100	250	300	497,000	690,455	50,621	6,459	11,389
131	200	1	0	200	200	517,667	690,558	52,725	5,676	11,933
132	25	10	50	200	300	525,500	690,622	53,523	5,664	9,242
133	25	2	100	250	100	373,833	690,687	38,076	6,394	13,636
134	0	10	50	200	300	493,000	691,096	50,213	5,806	9,858
135	25	10	25	250	100	507,333	691,764	51,673	6,501	9,252
136	25	10	25	250	200	530,667	692,243	54,050	6,737	8,811
137	150	2	0	250	200	513,667	692,386	52,318	6,920	11,283
138	50	1	25	250	300	397,500	692,700	40,486	7,743	13,382
139	0	10	100	200	200	492,667	693,645	50,179	5,104	9,928
140	0	2	50	200	100	278,333	693,842	28,349	6,571	15,626
141	100	2	50	100	300	375,000	694,318	38,195	4,312	15,369
142	50	1	50	200	300	369,000	694,829	37,583	6,494	14,484
143	150	1	50	200	100	452,333	695,179	46,071	5,238	13,203
144	50	1	50	250	100	362,333	696,150	36,904	7,044	14,110
145	100	10	25	100	200	508,167	696,218	51,758	3,296	10,941
146	150	1	50	250	200	515,667	696,327	52,522	6,480	11,432
147	25	2	100	200	300	380,500	697,062	38,755	5,901	14,341
148	0	2	50	200	200	301,667	697,231	30,725	6,695	15,356
149	0	10	25	250	300	521,500	699,550	53,116	7,136	9,193
150	50	10	100	100	100	454,333	701,222	46,275	2,702	12,417
151	100	10	50	100	100	496,333	701,436	50,553	2,792	11,396
152	50	10	25	200	300	546,500	701,856	55,662	5,832	9,348
153	25	10	0	250	300	542,500	702,245	55,255	7,270	9,000
154	150	2	100	200	300	543,000	703,200	55,306	5,117	11,200
155	150	1	0	250	300	516,000	703,727	52,556	7,270	11,850
156	25	10	50	100	300	445,500	704,038	45,375	3,975	12,394
157	150	2	50	100	100	393,333	704,237	40,062	3,560	15,394
158	0	10	50	250	100	486,333	704,282	49,534	6,420	9,961
159	25	10	50	250	200	542,167	704,555	55,221	6,518	8,921
160	25	10	100	200	100	501,833	705,003	51,113	4,793	10,239
161	50	10	50	100	300	478,000	705,217	48,685	3,613	11,834
162	0	2	50	250	200	341,667	705,386	34,800	7,600	14,429
163	150	1	100	200	300	522,000	706,138	53,167	5,206	12,005
164	150	2	25	250	200	525,167	706,594	53,489	6,704	11,451
165	50	10	0	250	200	551,667	708,786	56,188	6,920	9,083
166	100	1	100	250	100	450,333	709,310	45,867	6,154	13,222
167	200	1	25	200	200	529,167	709,836	53,897	5,482	12,281
168	50	10	100	200	200	557,667	710,342	56,800	4,849	9,200
169	50	1	50	250	300	409,000	710,473	41,658	7,328	13,747
170	200	2	0	200	200	538,667	712,540	54,864	5,676	12,033
171	150	1	25	250	300	527,500	712,993	53,727	7,043	11,850
172	25	10	50	250	100	518,833	713,462	52,844	6,322	9,700
173	100	2	100	100	100	351,333	713,910	35,784	3,687	16,994
174	100	1	50	100	100	307,333	714,287	31,303	4,518	17,496
175	0	10	100	250	200	532,667	714,290	54,253	6,173	9,253
176	150	1	100	250	200	538,667	714,667	54,864	6,017	11,433
177	50	10	25	250	100	539,833	714,692	54,983	6,443	9,435
178	25	10	100	200	300	548,500	714,733	55,866	5,239	9,490
179	0	10	100	200	100	469,333	714,847	47,803	4,987	11,226
180	25	2	50	100	300	277,500	715,057	28,264	5,669	17,817
181	50	2	100	100	100	286,333	715,159	29,164	4,486	18,420
182	150	2	50	250	200	536,667	715,312	54,661	6,471	11,434
183	50	1	100	250	200	408,667	716,197	41,624	6,630	14,012
184	0	10	50	100	300	413,000	716,206	42,065	4,374	13,383
185	25	10	100	100	100	421,833	716,376	42,965	3,170	13,700
186	50	10	50	200	300	558,000	716,703	56,834	5,618	9,533
187	25	2	100	250	300	420,500	716,807	42,829	6,918	13,496
188	100	10	50	100	200	519,667	717,663	52,929	3,077	11,466
189	150	2	25	100	300	428,500	718,477	43,644	4,311	15,101
190	150	1	50	250	100	492,333	718,505	50,145	6,365	12,759
191	150	2	100	200	100	496,333	718,893	50,553	4,779	12,922
192	0	10	50	250	300	533,000	719,171	54,287	6,939	9,540
193	150	2	50	250	100	513,333	719,187	52,284	6,284	12,121
194	50	10	100	200	100	534,333	719,442	54,423	4,692	10,098
195	150	2	50	100	200	416,667	720,063	42,438	3,798	15,500
196	50	10	25	250	200	563,167	720,507	57,360	6,697	9,169
197	50	1	100	200	100	345,333	720,701	35,173	5,685	16,104
198	0	2	50	250	100	318,333	721,590	32,423	7,539	15,333
199	150	1	50	250	300	539,000	722,259	54,898	6,815	11,850
200	25	10	100	100	50	410,167	723,256	41,776	3,234	14,181

Appendix ii. System report of the best cost effective found in first row in figure 4.2

System architecture

PV Array	50 kW
Wind turbine	2 Fuhrländer 250
Generator	25 kW
Battery	200 Surrette 6CS25P
Inverter	200 kW
Rectifier	200 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$543,884
Levelized cost of energy	$0.289 /kWh
Operating cost	$ 19,221/yr

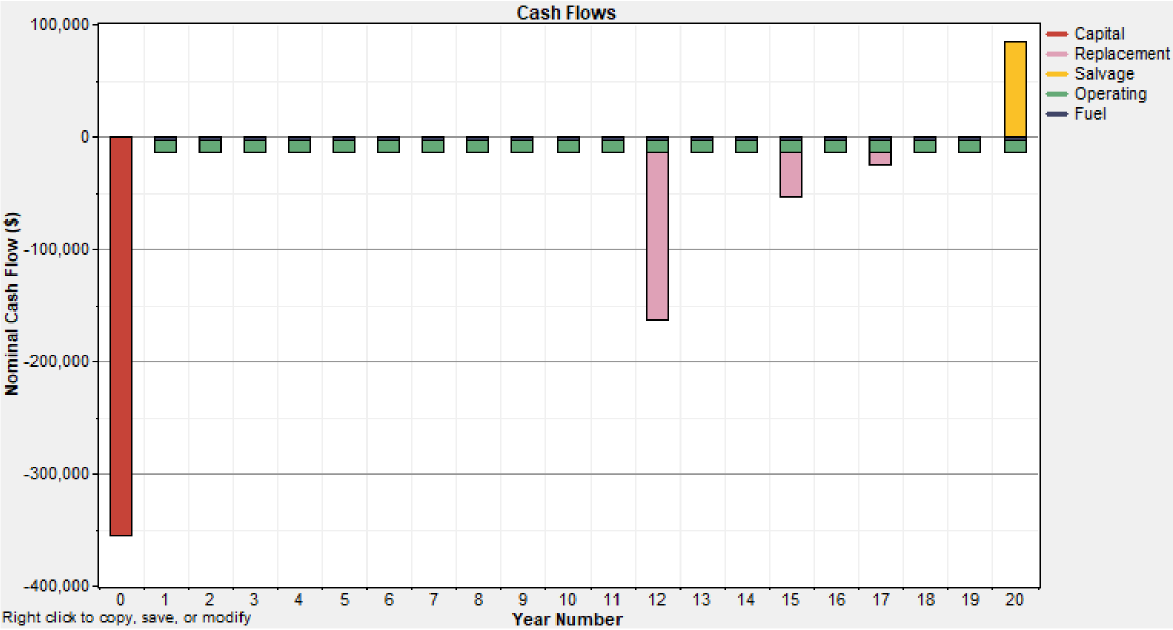
Net Present Cost

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	65,000	0	14,727	0	0	79,727
Fuhrländer 250	42,000	0	1,964	0	0	43,964
Generator 1	11,500	2,896	10,898	32,289	-1,860	55,722
Surrette 6CS25P	160,000	59,567	29,454	0	-10,727	238,294
Converter	46,667	12,610	13,091	0	-5,721	66,646
Other	30,000	0	29,530	0	0	59,530
System	355,167	75,072	99,664	32,289	-18,309	543,883

Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	6,620	0	1,500	0	0	8,120
Fuhrländer 250	4,278	0	200	0	0	4,478
Generator 1	1,171	295	1,110	3,289	-189	5,675
Surrette 6CS25P	16,296	6,067	3,000	0	-1,093	24,271
Converter	4,753	1,284	1,333	0	-583	6,788
Other	3,056	0	3,008	0	0	6,063
System	36,175	7,646	10,151	3,289	-1,865	55,396

Cash Flows



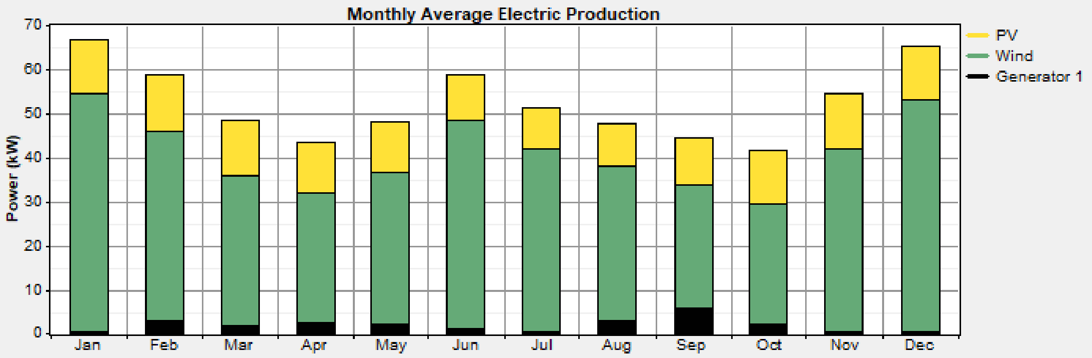
Electric Production Consumption and Quantity

Production	kWh/yr	%
PV array	100,781	22
Wind turbines	342,696	75
Generator 1	16,220	4
Total	459,697	100

Consumption	kWh/yr	%
AC primary load	188,111	98
Deferrable load	3,462	2
Total	191,572	100

Quantity	kWh/yr	%
Excess electricity	227,494	49.5
Unmet electric load	229	0.1
Capacity shortage	378	0.2

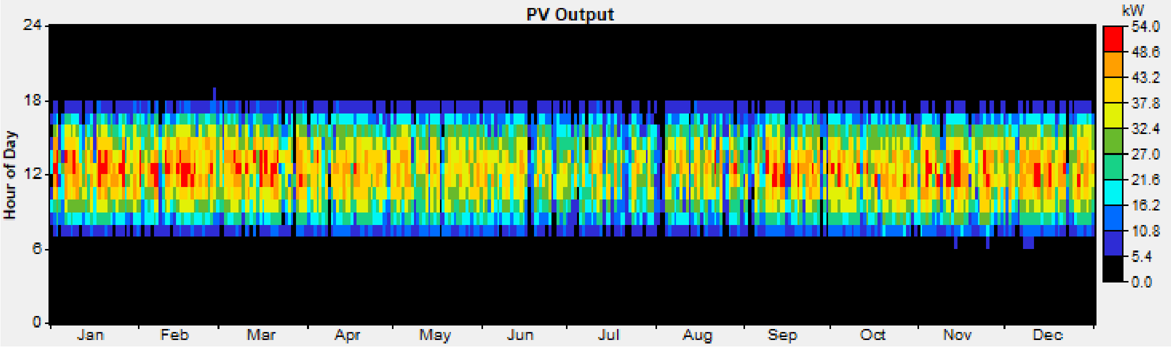
Quantity	Value
Renewable fraction	0.965



PV

Quantity	Value	Units
Rated capacity	50.0	kW
Mean output	11.5	kW
Mean output	276	kWh/d
Capacity factor	23.0	%
Total production	100,781	kWh/yr

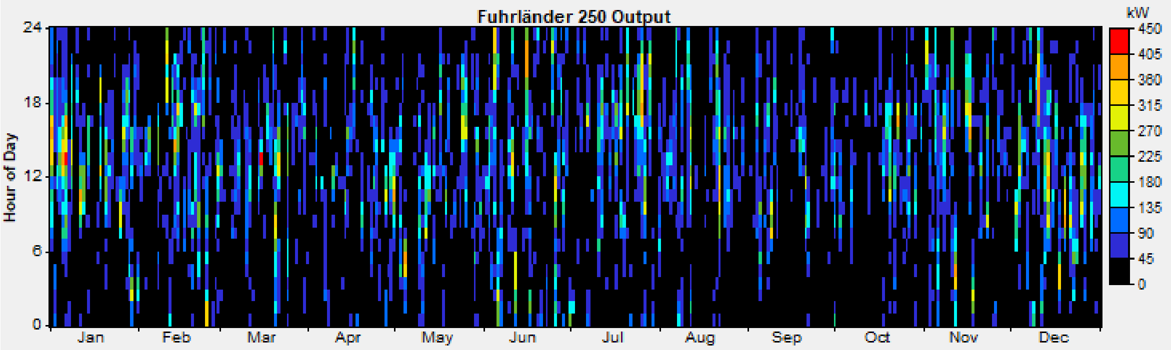
Quantity	Value	Units
Minimum output	0.0	kW
Maximum output	53.8	kW
PV penetration	53.5	%
Hours of operation	4,407	hr/yr
Levelized cost	0.0806	$/kWh



Wind turbine

Quantity	Value	Units
Total rated capacity	500	kW
Mean output	39	kW
Capacity factor	7.82	%
Total production	342,696	kWh/yr

Quantity	Value	Units
Minimum output	0	kW
Maximum output	415	kW
Wind penetration	182	%
Hours of operation	7,318	hr/yr
Levelized cost	0.0131	$/kWh

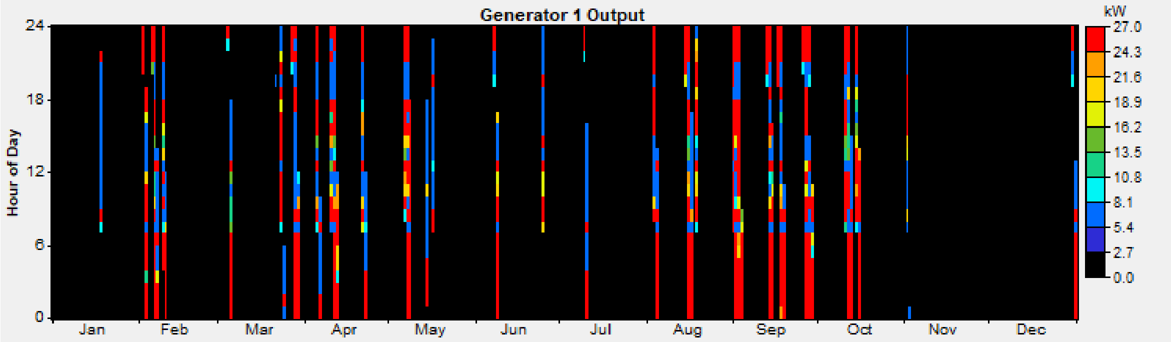


Genset (generator G)

Quantity	Value	Units
Hours of operation	888	hr/yr
Number of starts	29	starts/yr
Operational life	16.9	yr
Capacity factor	7.41	%
Fixed generation cost	3.60	$/hr
Marginal generation cost	0.206	$/kWh

Quantity	Value	Units
Electrical production	16,220	kWh/yr
Mean electrical output	18.3	kW
Min. electrical output	7.50	kW
Max. electrical output	25.0	kW

Quantity	Value	Units
Fuel consumption	5,831	L/yr
Specific fuel consumption	0.359	L/kWh
Fuel energy input	57,377	kWh/yr
Mean electrical efficiency	28.3	%

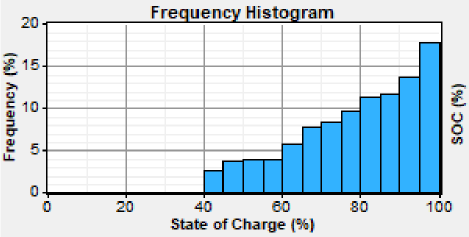


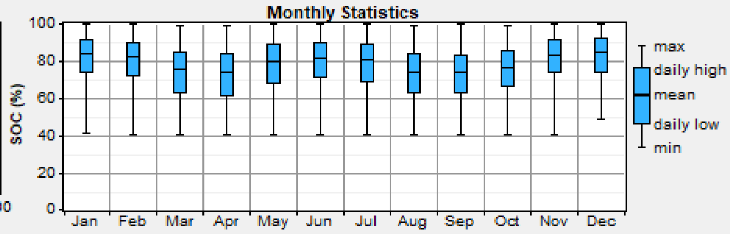
Battery

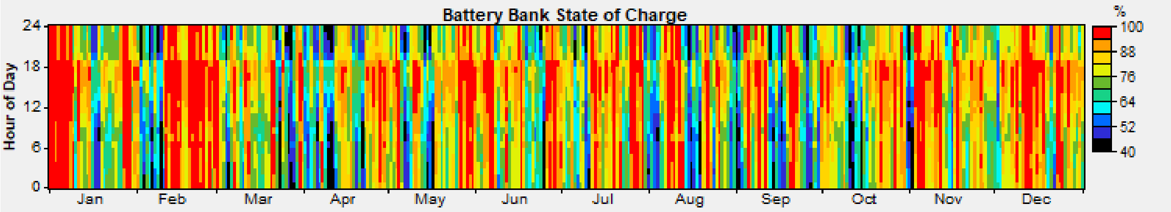
Quantity	Value
String size	1
Strings in parallel	200
Batteries	200
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	1,387	kWh
Usable nominal capacity	832	kWh
Autonomy	38.0	hr
Lifetime throughput	1,929,040	kWh
Battery wear cost	0.087	$/kWh
Average energy cost	0.018	$/kWh

Quantity	Value	Units
Energy in	106,825	kWh/yr
Energy out	85,694	kWh/yr
Storage depletion	259	kWh/yr
Losses	20,872	kWh/yr
Annual throughput	95,809	kWh/yr
Expected life	12.0	yr



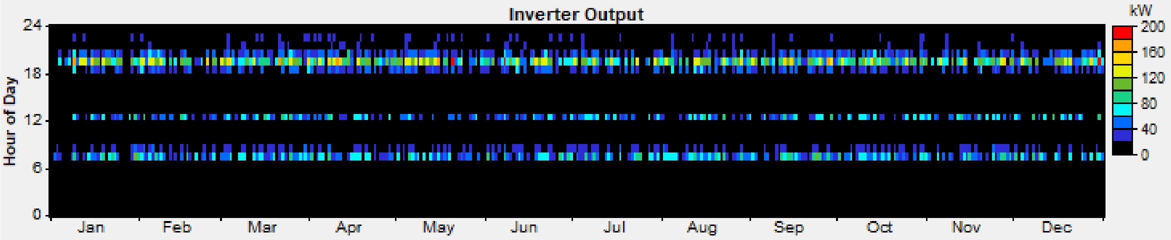


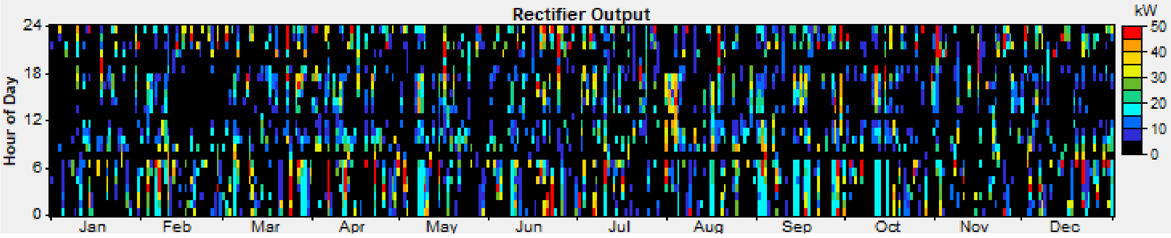


Converter

Quantity	Inverter	Rectifier	Units
Capacity	200	200	kW
Mean output	11	6	kW
Minimum output	0	0	kW
Maximum output	195	49	kW
Capacity factor	5.4	2.9	%

Quantity	Inverter	Rectifier	Units
Hours of operation	4,217	3,356	hrs/yr
Energy in	106,075	59,285	kWh/yr
Energy out	95,467	50,392	kWh/yr
Losses	10,607	8,893	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	15,355
Carbon monoxide	37.9
Unburned hydrocarbons	4.2
Particulate matter	2.86
Sulfur dioxide	30.8
Nitrogen oxides	338