Design and Modeling of Off-Grid Solar PV/Wind Hybrid System with Storage Battery for Rural Electrification in Ethiopia

Case Study of Tikishign/South Welo Zone in Amhara Region, Ethiopia

By: Getie Tesfaye Zelie

A Thesis Submitted to
The department of Electrical and Computer Engineering

School of Electrical Engineering and Computing

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

Office of Graduate Studies
Adama Science and Technology University

Adama
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Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by **Getie Tesfaye** have read and evaluated his thesis entitled "Design and Modeling of Off-Grid Solar PV/Wind Hybrid System with Storage Battery for Rural Electrification in Ethiopia" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master's in Electrical and Computer Engineering (Specialization in Power System Engineering).

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DECLARATION

I, Getie Tesfaye, hereby declare that this thesis entitled - Design and Modeling of Off-Grid Solar PV/Wind Hybrid System with Storage Battery for Rural Electrification in Ethiopia is entirely my own work and to my knowledge it has not been done or presented by any other person or University. The result of my own work carried out under the supervision of Dr. Tafese Asrat and I swear that all the material used has been properly referenced.

Name: Getie Tesfaye

Signature: ______________________________

This M.Sc. Thesis has been submitted for examination with my approval as thesis advisor.

Name: Tafese Asrat (Ph.D)

Signature: __________________________

Date of submission: ___________________

Advisor's Approval Sheet

To: Electrical and Computer Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled "Design and Modeling of Off-Grid Solar PV/Wind Hybrid System with Storage Battery for Rural Electrification in Ethiopia" submitted in partial fulfillment of the requirements for the degree of Master's in Electrical and Computer Engineering, the Graduate program of the department of Electrical and Computer Engineering and has been carried out by **Getie Tesfaye Id. No. GSR/1378/08** under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

Tafese Asrat (Ph. D)	______________________	________________
Name of major Advisor	Signature	Date

THIS THESIS WORK IS DEDICATED TO MY FAMILIES

ACKNOWLEDGEMENT

First and foremost, I take this opportunity to give glory to the almighty **God**, without whom the completion of this thesis work would have been impossible.

Next, I would like to express my sincere gratitude to my advisor, **Dr. Tafese Asrat,** for his expert guidance, constructive comments, suggestions and supports for the successful completion of this thesis work. He has been a constant source of inspiration throughout lifespan of my thesis.

It's my pleasure to convey my special gratitude to **Mr. Hinsermu Alemayehu** department head of electrical and computer engineering, **Mr. Merga** staff member of National Meteorology Service Agency (NMSA), Adama Branch, Ethiopia for having a free & open door to me and for providing the required meteorological data for the area of my concern which I was looking for Tikishign Village/South Wello Zone in Amhara Region, Ethiopia.

My sincere thanks goes to my family, friends and everyone whose constant concern and support reinforced my personal efforts, contributing to the completion of this thesis work.

LIST OF ABBREVIATIONS

AC	Alternating Current
Ah	Ampere-hour
BESS	Battery Energy Storage System
CFL	Compact Fluorescent Lamps
COE	Cost Of Energy
DC	Direct Current
DOD	Depth Of Discharge
E33	HOMER Representation Of Wind Turbine
EOL	End of Life
EPBT	Energy Payback Time
EEPCo	Ethiopian Electric Power Corporation
FTC	Farmers Training Center
HAWT	Horizontal Axis Wind Turbine
HOMER	Hybrid Optimization Model For Electric Renewable
HPSs	Hybrid Power Systems
HRES	Hybrid Renewable Energy Systems
IGBT	Insulated-Gate Bipolar Transistors
I_{sc}	Short Circuit Current
Kwh	Kilo Watt Hour
Kw/m^2	Kilo Watt Per Meter Square
LCOE	Levelised Cost Of Electricity
MATLAB	Matrix Laboratory
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MW	Mega Watt
MPH	Miles Per Hour
NASA	National Aeronautics and Space Administration
NMSA	National Metrology Service Agency
NREL	National Renewable Energy Laboratory
NiCd	Nickel–Cadmium Cell

NiMH or Ni–MH	Nickel–Metal Hydride Battery
NPC	Net Present Cost
NOCT	Nominal Operating Cell Temperature
O&M	Operation and Maintenance
PMG	Permanent Magnet Generator
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy System
RPM	Rotations Per Minute
SWERA	Solar and Wind Energy Resource Assessment
SAPS	Stand-Alone Power System
SOC	State Of Charge
STC	Standard Test Condition
TV	Television
UEAP	Universal Electric Access Program
V_{oc}	Open Circuit Voltage
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion System
WTG	Wind Turbine Generator

Abstract

Hybrid power systems based on new and renewable energy sources, especially solar PV and wind turbine are an effective option to solve the power-supply problem for remote and detached areas from the national grids. Hybrid renewable set-up indicates that various combinations based on the renewable sources could be applied simultaneously to play energy in the form of employed in an off-gird supporting with battery storage as backup systems. In this thesis, solar PV/wind turbine/battery bank/converter have been simulated and optimized for the rural area of ***Tikishign*** *village among the woreda of south Wello Zone in Amhara region of Ethiopia. Based on the design of hybrid system Primary load demand of the village were 260kWh/day, peak load of 49kW, deferrable energy is about 19kWh/day, and deferrable peak load of 2.8kW with COE $0.160/kWh were involved during optimization of the power system. Well known freeware HOMER and MATLAB simulating software tool have been used to design optimal off-grid system and energy management system respectively. Solar PV and wind energy were considered as primary sources to supply electricity directly to the load and to charge battery bank when there were excess energy generation. However, either in peak load times or low generation of primary sources storage battery bank could also be discharged. The load has been suggested for residential loads and deferable load (water pumping). During design of this power system set-up, the simulation and optimization was done based on the load demand, climatic data, economics of integrated system components and other parameters in which the total NPC and levelized COE have to be minimized to select economically feasible and technically capable hybrid power system. Furthermore; a fuzzy logic rule is also modeled to compare the possible potentials available (only solar energy, only wind energy or hybrid energy) and take a decision. The decision of fuzzy logic is based on the instructional rules written on it.*

Keywords: *HOMER, MATLAB, Fuzzy Logic Control, hybrid system, solar PV, wind turbine, Battery bank system, primary load, deferrable load, Rural electrification.*

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CHAPTER ONE

INTRODUCTION

1.1 Background

Energy is the fuel for growth of a country or generally growth of the world. An increased access to electricity enhances opportunities for industrial development and improves health and education. But currently still about 40% of the world's population have no access to electricity. Most of rural people depend almost exclusively on biomass for their daily energy need. According to report of United Nations Food and Agriculture Organization, the number of people suffering from shortage of wood, fuel was expected to highly increase in the coming years [1, 2].

The Ethiopian Government tried to connect this rural location by using national grid extension for the last two decades. However, still the current electricity access is below 50% and the real connection is less than 14% [3]. Today it is widely accepted that Renewable energy system (RES) have a large potential to contribute to the strengthening and development of national sustainable energy infrastructures in many countries in the world by securing better energy independence through the mobilization of domestic renewable energy resources especially in rural areas [4, 5, 6].

A stand-alone power system (SAPS), also known as remote area power supply (RAPS), is an off-grid electricity system for locations that are not fitted with an electricity distribution system. Typical SAPS include one or more methods of electricity generation, energy storage, and regulation [7, 8]. Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. A hybrid energy system, or hybrid power, usually consists of two or more renewable energy sources as well as a backup is used together to provide increased system efficiency as well as greater balance in energy supply [9, 10, 11].

1.1.1 History of Ethiopian Power Sector

The following Figure 1.1 shows that the history of Ethiopian electric power generation starting from the beginning until the current situation.

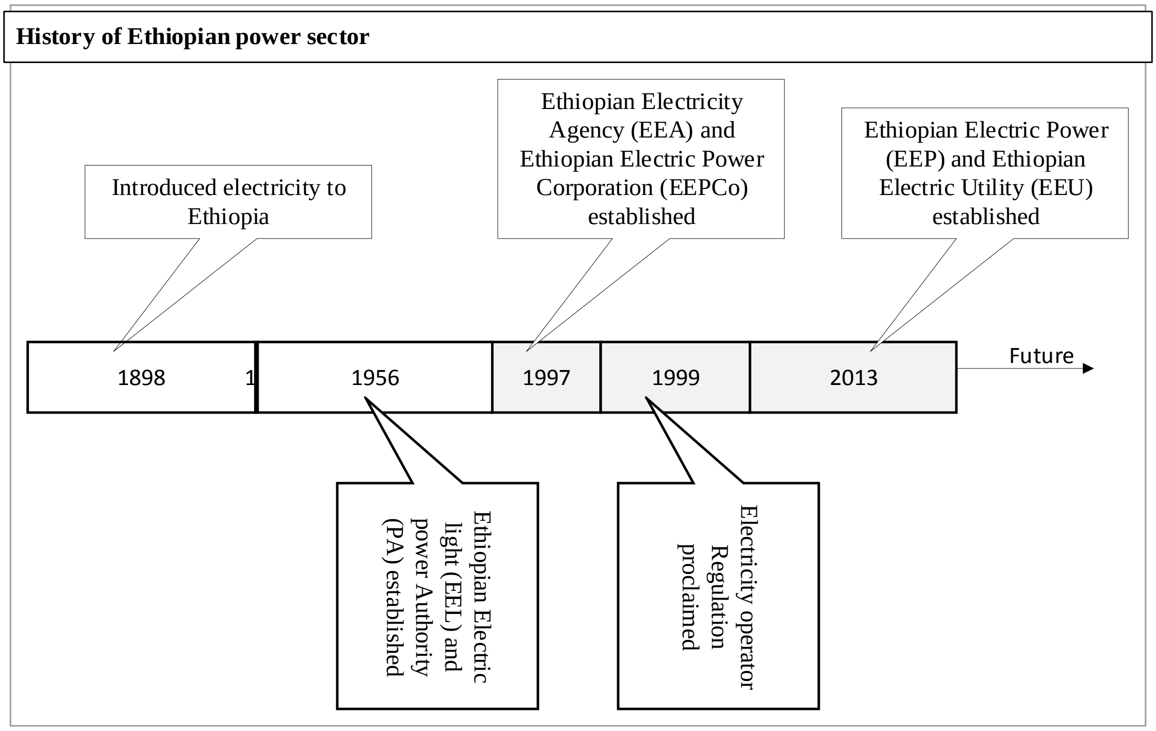


Figure 1. 1 History of Ethiopian electric power sector (source: EEPCo)

1.2 Statement of the Problem

Despite of the abundant renewable energy resources, many communities still live without access to electricity either from the utility grid or independent renewable energy generated electricity. There is a challenge to supply electricity to the population because of two reasons. First, there is no enough power generation to fulfill the current power demand. Second, even if there is enough power generation, installation of grid system to each village is challenging due to their geographical locations and economic constraints. Electrifying these remote areas by extending transmission lines from the utility grid to these rural communities is very labor and time intensive accordingly capital intensive. Certain fundamental services that should be provided to particular community are electricity, water supply, communication, transportation; health care and education are some mandatory needs for any community to escalate out of poverty. Thus, supply of reliable electricity is prerequisite to cater this all services. The demand as well as the energy exploitation is rising in Ethiopia however from single source mainly hydro. To fulfill the ever-increasing demand of the country, the power generation system has to expand to exploit the renewable sources. Hybrid renewable energy systems are the possible means of electricity generating for rural remote areas. This thesis focuses on solar PV/wind turbine/battery bank with energy manegnent for rural electrification due to abundant solar radiation and significant wind distribution availability for the Tikishign village which could not join the main grid.

1.3 Objective

General Objective

Design and Modelling of off-grid solar PV/Wind turbine/Battery bank hybrid power system with energy management. As a case study of Tikishign/south welo zone in Amhara region, Ethiopia

Specific Objectives

The specific objectives of this thesis are:

- To select the best optimized hybrid model for providing electricity to the community by considering its overall installation cost, contribution of renewable energy sources and energy cost per kWh.
- To analyze the power and energy demand of the society of the selected areas by considering the basic needs of the people.
- To select appropriate solar modules, wind turbines and batteries depending on the energy demand for the selected sites.
- To determine the demand of the community at the life span of the project through load forecasting.
- To control the system using fuzzy logic controller, draw conclusions and give recommendations for future works.

1.4 Methodology

Different methodologies have been applied to address each specific objective of this thesis work. First the site should be identified, problems of the community is clearly stated, data required for the thesis work is collected through various data collection mechanisms and different literatures are surveyed to identify the way to do the thesis work, to get data and to enhance academic knowledge and research skills. And following that the data collected from various sources are analyzed using software tool and integrated to give solution for the problems and challenges raised at the start of the thesis work.

1.4.1 Site Location

The case study area is identified by directly visiting the site. site map in Woreda level obtained from Google earth and Google Map were used.

Figure 1. 2 Location of the site under Woreda level (source: google earth map)

1.4.2 Problem Identifications

The problem identification involved a literature survey and direct observation in collecting general information about Delanta Woreda, Tikishign village community, such as geography, climate, population, current energy supply sources, current energy utilization mechanism, effects of the current energy supply mechanism, and effects of traditional energy access mechanism. The main focus of the survey was on the renewable energy sources availability, the effect of the current biomass-based energy supply on women health and the effect of fully dependent biomass-based energy supply on the environment.

1.4.3 Data Collection and Literature Survey

There are two sources of data collection methods which are primary data gathering and secondary data collections. The primary data gathering conducted through use of questionnaires, site visits and interviews about the selected site. And also, the secondary data gathered from books, journals, newspapers, magazines, conference papers, reports, etc.

1.4.4 Analysis and Evaluation of Data

Analysis and evaluation of the collected data in the way to input into the Hybrid optimization model for electric renewable (HOMER) software. The software simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications, using the appropriate and cost-effective power generating technologies. The major applications of HOMER are the design of micro power systems optimization for the efficient evaluation of various renewable energy power generation technologies. It compares a wide range of equipment with different constraints and sensitivities to optimize the system design. And also, MATLAB is used to energy management system. Finally based on the findings make Conclusion and recommendation.

1.5 Scope of the Thesis

The scope of the thesis to model and design of off-grid hybrid renewable energy system for 720 households. In addition to this the thesis were limited to solar PV/wind turbine/battery bank system. And also, HOMER and MATLAB used as simulation and modeling tools.

1.6 Significant of the Thesis

The main contribution of the thesis is to explore and put forward the appropriate off-grid PV/wind/battery bank hybrid system model and design with energy management. Even though the power consumption of rural community is not so much high, the battery bank system has the possibility to save the electrical power during high generation and discharge to supply the load when low generation of renewable energy. The thesis can also be used as a reference for future studies that can be done on off-grid solar PV/wind/battery bank hybrid system. In addition, anyone who is going to implement off-grid hybrid system in different urban areas in Ethiopia can use as a procedure.

1.7 Organization of the Thesis

The thesis consists of five chapters. The first chapter covers the introduction part which deals with the background, statement of the problem, objectives, scope and significance of the thesis. Chapter two gives the theoretical overviews of solar PV energy, components of wind energy and battery bank and also introduction about fuzzy logic controller which used for energy management system. Chapter three presents materials and methods which studied about the Potential assessments of renewable energies in Tikishign village areas. The assessment was based on the data obtained from primary data and secondary data (Local Source, NMSA and International source, NASA). Estimation of load and also load forecasting requirement per season were presented. Modeling and design of Hybrid power system, overview of HOMER software including energy management system, etc. chapter four were all about the results and discussion of optimization and sensitivity analysis of the system findings of the thesis work and also energy management system. Chapter five presents conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW AND BASIC THEORY OF SYSTEM COMPONENTS

2.1 Literature Review

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [14, 15]. Worldwide investments in renewable technologies amounted to more than US$286 billion in 2015, with countries like China and the United States heavily investing in wind, hydro, solar and biofuels [16, 17]. Globally, there are an estimated 7.7 million jobs associated with the renewable energy industries, with solar PVs being the largest renewable employer. As of 2015 worldwide, more than half of all new electricity capacity installed was renewable [18, 19, 20].

The thesis investigated by **Berihun G/Yohannes** (2013), A standalone wind/micro hydro/battery hybrid system and only micro hydro system options are considered separately in order to electrify the selected village. HOMER simulation software has been used as the modeling and designing tool. For the first option many feasible hybrid system combinations are listed and sorted according to their net present cost (NPC). Accordingly, levelized cost of energy (COE) and breakeven grid extension distance depend on the selected sensitivity variables. The COE the most favorable wind/micro hydro hybrid system is $0.112/KWh. Likewise, the breakeven grid extension distance of the hybrid system 23.2km. On the other hand, the levelized COE of the micro hydro system is $0.035/KWh which is smaller than that of hybrid system. And it is believed that the standalone micro hydro system is economically feasible and pollution frees to implement for his particular work [21].

The thesis investigated by **Solomon T/Michael** has been design off-grid hybrid system provide electricity to rural community of Haressaw among the sub-districts of Atsbi district in the regional state of Tigray, Ethiopia. This paper conducts Primary load demand of 1505KWh/day, peak load of 284KW, deferrable energy is about 17KWh/day, and deferrable peak load of 3.6KW was involved during optimization of the power system. Well known freeware HOMER modeling tool have been used to design the off-grid system. Wind and solar energy are considered as primary sources to supply electricity directly to the load and to charge battery bank when excess generation is happened however in peak demand times diesel generator could also be engaged. The community's load has been suggested for lighting, water pumping, school and health clinic equipment load, television, radio, flour milling machines and local food (enjera) baking [22].

The thesis investigated by **Sisay Fitwi**, feasibility of solar PV-Wind-Biogas hybrid system with battery storage as a backup is studied to electrify the village in Adigrat district. It also compares the cost of the hybrid system against the cost required to electrify the village by extending the grid. The feasibility of his paper is analyzed using HOMER software. The data for biogas energy potential estimation is obtained from the Ministry of Mines and Energy (MME) of Ethiopia. The paper utilized meteorological data obtained from NMSA of Ethiopia, NASA and Solar and Wind Energy Resource Assessment (SWERA) to estimate the solar and wind energy potentials. The data needed for calculating the cost of extending the grid is taken from Ethiopian Electric Power Corporation (EEPCo) and is analyzed using interlinked Microsoft office excel spread sheet prepared by Universal Electric Access Program (UEAP). Electric load estimation and forecasting for the basic needs of the community, such as, for lighting, radio, television, water pumps and flour mills, is done. Primary school and health clinic are also considered for the community. The simulation results show many feasible hybrid system combinations having a cost of energy less than $0.295/KWh which is much lower than diesel generators and previously studied PV/Wind hybrid systems. The hybrid energy system optimized by HOMER for this village is cost effective as compared to the cost required to electrifying the village. The breakeven grid extension distance is found to be 14.9kms, which implies that this hybrid energy system is cost-effective for areas greater than the breakeven distance [23].

The thesis investigated by **Solomon Kiros**, focuses on comparing the economic performance of using various scenarios of stand-alone PV/Wind hybrid system, with battery storage and diesel as a backup, for electrifying Kutur village of Awlio kebele of the Axum district (which is 30kms away from the closest national grid) to the possibility of extending the grid. Axum district which is located at latitude of 14° 07' N and longitude of 38° 43' E is found to have 4.28m/s wind speed at a height of 10m, and 6.19KWh/m^2/day solar radiation. Two electric load scenarios are estimated by considering set of incandescent and efficient lamps for lighting for the existing 120 households. The over mentioned solar radiation and wind speed are then used as an input to simulate the hybrid setup for the high and low load estimation using HOMER software. Simulation result shows that the NPC corresponding to high and low load scenarios were $278,856 and $194,174, respectively [24].

Generally, all the researchers described above was used only HOMER software as a modeling, design and optimization tool to realize their study, the hybrid system set-ups were studied using different load demands and applications, location of studies as well as climatic data's they used were different. Some of the studies were employed in areas that have no electricity at all whereas the others in areas that have already accessed electricity which was provided by using diesel generator.

This thesis has been employed the HOMER software to model, design and optimize the off-grid hybrid power system. However, it is different from related studies in terms of application, load demand, climatic data and location of the selected area. In addition to this the thesis used MATLAB (Fuzzy Logic Controller) for energy manegnent system. So that no one use Fuzzy Logic Controller as an energy manegnent in the above studies.

2.2 Theories of Renewable Energy

Energy plays an important role in all types of development, including economic development. The world total energy annual consumption generally increases, with the vast majority of energy being produced by fossil fuels such as coal, oil and natural gas. In 2002 fossil fuels provided the three quarters of the total, With the current energy consumption rate, proven coal reserves should last for about 200 years, oil for approximately 40 years and natural gas for around 60 years [25, 26].

With constantly increasing development, diminishing fossil fuel resources and related environmental problems (e.g. emissions), sustainable development and the manner in which energy is produced and consumed is reconsidered. Renewable energy [1], i.e., energy generated from solar, wind, biomass, geo-thermal, hydropower and ocean resources, could increase the diversity of energy supplies and offer "clean"-environmental friendly energy. Although wind and solar energy sources are significantly less productive compared to fossil fuels, the use of PV cells and wind turbines [2] has increased rapidly during the last years, especially in developed countries. PV cells are electronic devices that are based on semiconductor technology and can produce an electric current directly from sunlight [27].

2.2.1 Basic Theory of Solar Energy

Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, solar PVs, solar thermal energy, solar architecture, molten salt power plants and artificial photosynthesis [19, 28].

It is an important source of renewable energy and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include the use of PV systems, concentrated solar power and solar water heating to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air [18, 29]. Generally, the sun is the largest energy source of life and at the same time it is the ultimate source of most of renewable energy sources that is why sun is considered as the mother or father of all renewable energy sources. Without sun; there is no wind, no water and no biomass energy. Energy from the sun has been used to provide heat and electricity for many years.

2.2.2 Solar Photovoltaic (PV) Systems

Solar PVs, by far the most important solar technology for distributed generation of solar power, use solar cells assembled into solar panels to convert sunlight into electricity. It is a fast-growing technology doubling its worldwide installed capacity every couple of years. PV systems range from distributed, residential, and commercial rooftop or building integrated installations, to large, centralized utility-scale solar PV power stations [24, 30].
The predominant PV technology is crystalline silicon, while thin-film solar cell technology accounts for about 10 percent of global PV deployment. In recent years, PV technology has improved its sunlight to electricity conversion efficiency, reduced the installation cost per watt as well as its energy payback time (EPBT) and levelised cost of electricity (LCOE), and has reached grid parity in at least 19 different markets in 2014 [18, 24].

2.2.3 Operation of Solar PV

The term PV means the direct conversion of light into electrical energy using solar cells. Solar cells are made up of Semiconductor materials such as silicon, gallium arsenide, cadmium, telluride or copper indium, diselenide, etc. Solar PV cells are the devices that are used for converting solar energy into electrical energy by utilizing the PV effect. These cells are used in many real-time applications such as railway signaling systems, street lighting systems, domestic lighting systems, and remote telecommunication systems. Solar PV effect is a process to convert solar energy into direct current (DC) electricity using an array of solar panels. This, DC electricity can be stored in batteries or can be used to feed DC loads directly or can be used to feed alternating current (AC) loads using an inverter that turns DC electricity into 220-volt AC electricity [24, 31, 32].
Solar PV cell consists of a P-type of silicon layer that is placed in contact with an N-type silicon layer. The electrons diffuse from the N-type material to the P-type material. The holes

in the P-type material accept the electrons but there are more electrons in the N-type material. So, with the influence of the solar energy, these electrons in the N-type material move from N-type to P-type.

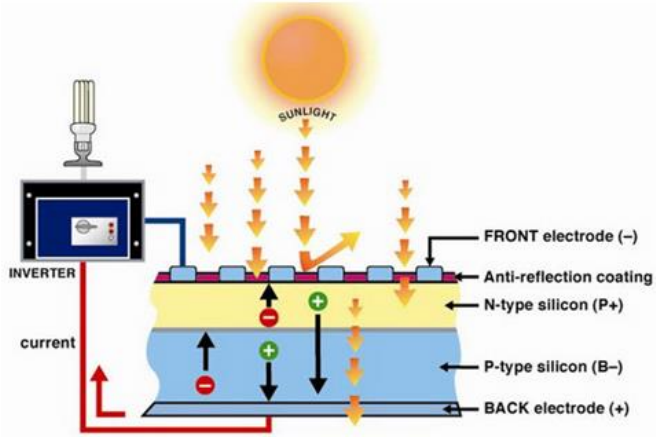


Figure 2. 1 Operation of Solar PV Cells [24]

Thus, these electrons and holes combine in the P-N junction. Due, to this combination a charge on either side of the P-N junction is created and this charge creates an electric field. This formation of electric field results in developing a diode like system that promotes the charge flow. This is called as drift current and the diffusion of electrons and holes is balanced by drift current. This drift current occurs in an area where mobile charge carriers are lacking and is called as the depletion zone or space charge region. Thus, during night time or in the darkness, these solar PV cells behave like reverse bias diodes [33, 34].

2.2.4 Solar PV Technologies

When we see physical characteristics of Solar cells for terrestrial applications are typically made from silicon as single-crystal, polycrystalline or amorphous solids.

Single-crystal or Monocrystalline Silicon Cell. - is the most efficient because the crystal is free of grain boundaries, which are defects in the crystal structure caused by variations in the lattice that tend to decrease the electrical and thermal conductivity of the material. These cells show efficiencies approximately 17 to 20% depending on the material quality and the specific cell technology [35, 36].

Polycrystalline or Multicrystalline Silicon. - has obvious grain boundaries; the portions of single crystals are visible to the naked eye. Slightly bigger solar panel for delivering the same amount of power that of Monocrystalline Silicon Cell. They demonstrate conversion efficiencies slightly lower than those of monocrystalline cells from 14 to 16% [13, 37].

Amorphous or thin film silicon (A-Si). - is the non-crystalline form of silicon where the atoms are arranged in a relatively haphazard way. Due to the disordered nature of the material, some atoms have a dangling bond that disrupts the flow of electrons. It has lowest power conversion efficiencies of the three types but is the least expensive to produce. Additionally, it absorbs light more effectively than crystalline silicon, which leads to thinner cells, also known as a thin film PV technology. The greatest advantage of these cells is that amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible. Their disadvantage is the low efficiency, which is approximately 5 to 7 % [38].

2.2.5 Components of PV Generator

To size the PV generator, the following components are required:

Solar cells. - are produced on silicon wafers. It is the oldest and the most popular technology due to high power efficiencies [39].

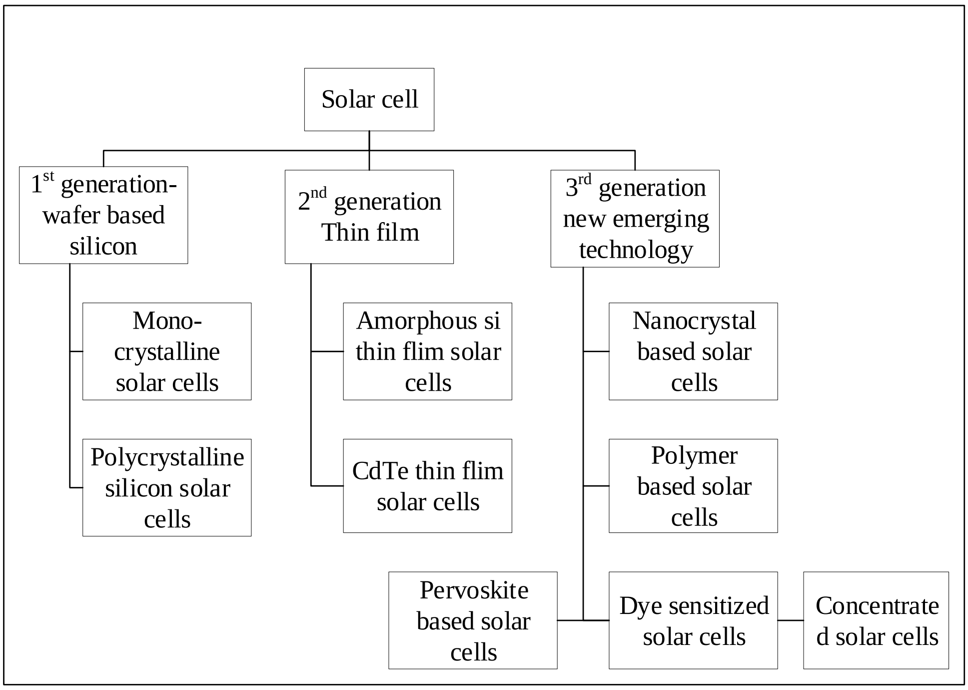


Figure 2. 2 Various types of solar cell technologies and current trends of development

PV Modules. - PV module or panel is a grouping of PV cells. The voltage generated by a single PV cell is inconveniently low. Several cells are always joined in series so that their voltages add up to a more useful value. The series connection of cells forms a unit called a PV module. The front consists of a window of low-iron glass with high transmission characteristic, which protects the surface of the PV material.

PV String. - is a group of modules which are wired either series or parallel. Series string is used to increase the voltage as modern solar electric DC systems operate minimum at 48 volts nominal, and for high-voltage grid-tied systems produce up to 600 volts [21].

Solar Panels. - are made up of solar modules or a group of solar modules and is used for converting solar energy into electrical energy. The solar panels utilize Ohmic material for interconnections and external terminals. Thus, the electrons produced in the N-type material are passed to the battery through electrode and wire. From the battery, electrons reach p-type material, where these electrons and holes are combined. Hence, the solar panel connected to the battery behaves like another battery, and hence, is comparable to the two serially connected batteries [35, 40].

PV Array. - One of the attractions of PV modules is that connecting modules to form array may increase the power rating of a system. Within a PV array, there are basically two methods of connection between modules. To increase the array voltage, modules are connected in series, known as series string. To increase the generating capacity without changing the array voltage, strings of modules are connected in parallel [39, 41].

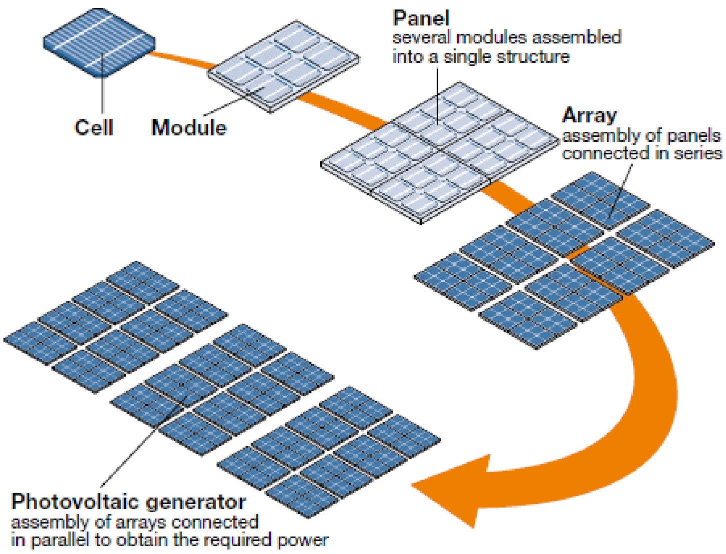
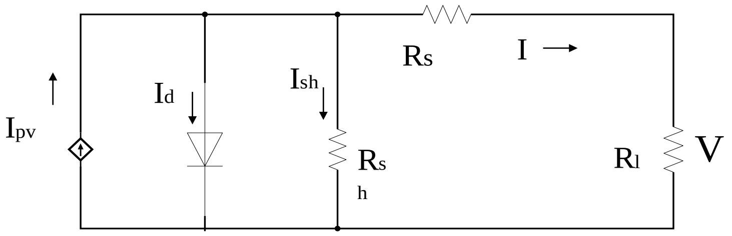


Figure 2. 3 PV field or generator

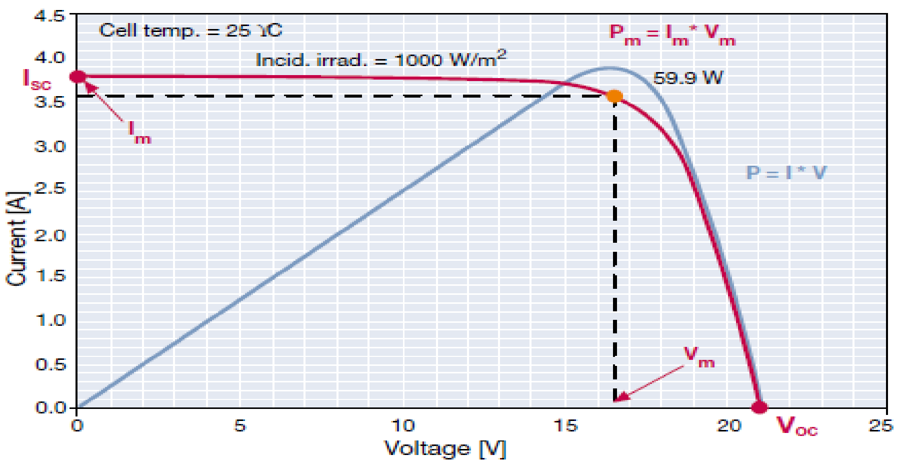
Generally, several panels electrically connected in series constitute an array and several arrays, electrically connected in parallel to generate the required power, constitute the generator or PV field.

2.2.6 Equivalent Circuit of PV System

The most popular circuit equivalent to a solar cell/panel is shown in Figure 2.4, it includes a current source, one diode and two resistors: one in series and the other is in parallel. Each element included in the equivalent circuit implies one parameter that has to be determined (two in the case of the diode whose behavior is represented by the Shockley equation). Therefore, five parameters need to be calculated when using this method. These representative points are, together with their variation as a function of the temperature, the normal information included in manufacturers' datasheets [8, 11, 15].



a)



b)

Figure 2. 4 a) Equivalent circuit and b) V-I characteristic of a solar panel

The fundamental parameters related to solar cell are short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power point (MPP), efficiency of solar cell and fill factor.

The circuit model formed by one diode and two resistors is defined by the following equation:

$$I = I_{PV} - I_O \left[\exp\left(\frac{V+IR_S}{\alpha V_T}\right) - 1\right] - \frac{V+IR_S}{R_{sh}} \quad (2.1)$$

Where, I_{pv} _ the photocurrent delivered by the constant current source;

I_o _ the reverse saturation current corresponding to the diode;

R_s _ series resistor that takes into account losses in cell solder bonds, interconnection, etc.;

R_{sh} _ shunt resistor that takes into account the current leakage through the high conductivity shunts across the p-n junction; and **a** _ ideality factor

V_T _ thermal voltage of the diode and depends on the charge of the electron, **q**; the Boltzmann constant, **k**; the number of cells in series, **n**; and the cell temperature, **T**:

$$V_T = n\frac{KT}{q} \tag{2.2}$$

Short circuit equation: I_{sc} is the current corresponds to the short circuit condition when the impedance is low and it is calculated when the voltage equals to zero.

$$I_{SC} = I_{PV} - I_O\left[\exp\left(\frac{I_{sc}R_s}{\alpha V_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \tag{2.3}$$

Open circuit equation: V_{oc} is the voltage when the open circuit occurs and there is no current passing through the cell. The V_{oc} is calculated when the current equals to zero.

$$0 = I_{pv} - I_o\left[exp\left(\frac{V_{0c}}{\alpha V_T}\right) - 1\right] - \frac{V_{0c}}{R_{sh}} \tag{2.4}$$

Maximum power point circuit equation:

$$I_{mp} = I_{PV} - I_O\left[\exp\left(\frac{V_{mp} + I_{mp}R_s}{\alpha V_T}\right) - 1\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{2.5}$$

2.3 Basic Theory of Wind Energy

Wind energy has been part of our life for thousands of years supplying energy in different forms and recently has become one of the most promising renewable sources of energy. In the past few decades, different researches have been carried out and an enormous potential of wind energy has been discovered across the globe. This worldwide wind energy potential is approximated to be about 278,000TWh per year of which about 39,000TWh supply per year could be sustainably used in the long run. This figure is more than double of the current global electricity demand [40, 42].

Generally, wind energy is a genuinely promising source of energy and it is one of the few green energy systems having an everlasting nature. As a result, proper use of the resource through sustainable project designs would significantly contribute in solving the energy crisis that the world is facing. It is basically a form of solar energy caused by uneven heating of the atmosphere by the sun, with the rotation of the earth along with the uneven surface of earth.

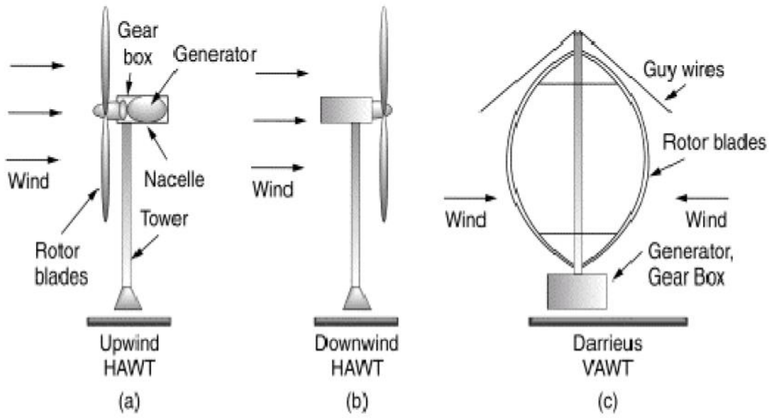
2.3.1 Wind Turbines

A wind turbine is a machine that converts the kinetic energy from the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator [29, 30].

There are a number of different wind turbine types available. The horizontal axis wind 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 wind turbine (VAWT) arrangement that uses drag and lift as the driving forces; the horizontal also uses drag and lift, but in other proportions [28, 25].

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 [19]. 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 [28, 31].

An advantage with **downwind** turbines is that the nacelle is selfadjusting 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.



(a) Upwind machine (b) Down wind machines (c) VAWT accept wind from any direction

Figure 2. 5 Types of wind turbines [31]

2.3.1.1 Horizontal Axis Wind Turbine (HAWT)

In order for a turbine to be defined as a HAWT, the rotor blades have to be connected to a horizontal shaft. These types of turbines are mainly for commercial usage. Critical components are the rotor, gearbox, anemometer, generator, yaw motor, control system and the foundation. The turbine can either be a rotor-upwind design or rotor-downwind design [3, 10, 13].

Upwind rotor design currently dominates the market. Even though the downwind rotor design adjusts automatically to wind direction, an important safety and operational feature, it does not adjust under abrupt or sudden changes in wind direction. This can be overcome with three-blade upwind rotor, making it more desirable than the downwind rotor [27, 32].

The main advantages of HAWT are high generating capacity, improved efficiency, variable pitch blade capacity, and tall tower to capture large amount of wind energy. There are also disadvantages such as consistent noise, killing of birds, interference with radio, TV transmission and radar, land use, maintenance worker hazards and visual impacts [33, 34].

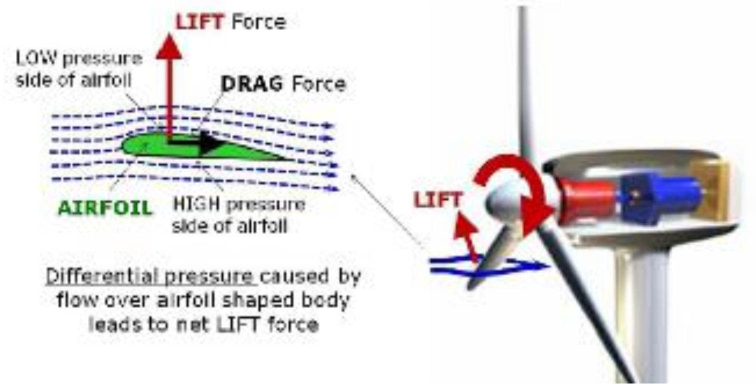


Figure 2. 6 Lift-based HAWT concept [7]

In HAWT the dominant driving force is lift force. The **Lift Force** is perpendicular/ right-angled to the direction of motion. This force is wanted to be strong. The **Drag Force** is parallel to the direction of motion. This force is wanted to be weak [33].

There are critical components when it comes to HAWT that need to be considered when it comes to design. A cut-view (Figure 2.7) helps the reader to get familiar with the components of a wind turbine.

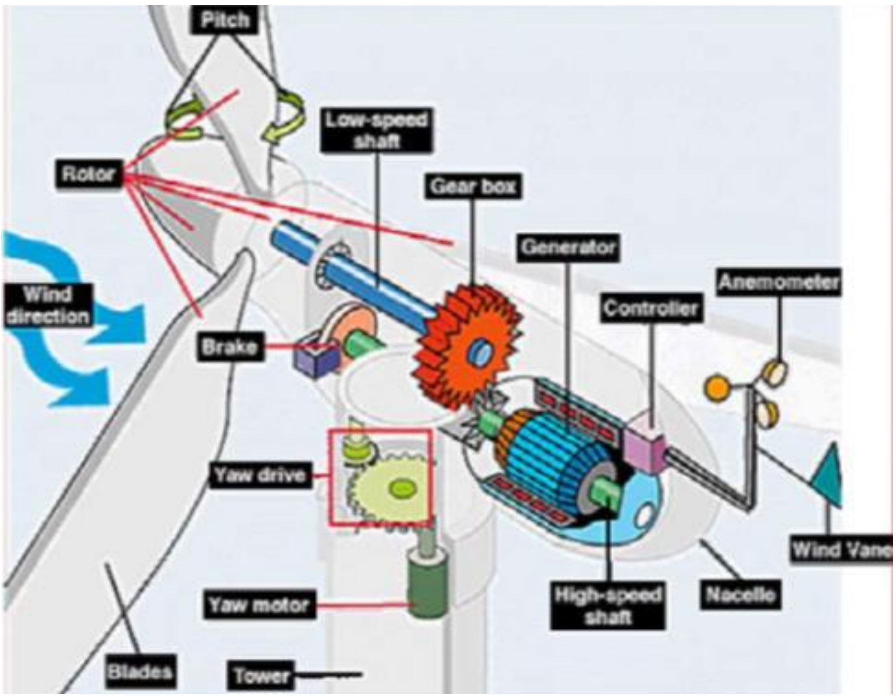


Figure 2. 7 Cut-view of a wind turbine. [32]

<u>Wind direction</u>.- This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.

Wind vane.- Measures wind direction and communicate with the yaw drive to orient the turbine properly with respect to the wind. 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 [32]

Yaw motor.- Powers the yaw drive.

Tower. - Towers are made from tubular steel, concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity [7].

Rotor. - The blades and the hub together are called the rotor. It is a critical element of a wind turbine. The power production is dependent on its interaction with the wind. The swept area, or surface area swept by the rotating blades, is the parameter that decides the size of the wind turbine. Equation 2.6, show the relationship between the swept area (S) of the rotor and the diameter (D) of the rotor:

$$S = \pi \frac{D^2}{4} = 0.785D^2 \qquad (2.6)$$

Rotor Blades. - Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate.

Rotor Hub. - Hub height is the height from the ground to the center of the rotor and is a heavy component of the wind turbine. The hub connects the blades to the main shaft and drive train and must withstand all loads from the blades.

The hub is rigid, hinged or teetering and is usually made of ductile cast iron. The hub is covered by a cone in order to prevent from the environment and for visual effects. The material used for constructing the cone has similar composites as used in the blades [2].

Controller.- The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds [10].

Pitch. - Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity [32].

Anemometer. - Measures the wind speed and transmits wind speed data to the controller. There are two types of anemometer that are used: cup or ultrasound anemometers. The **cup anemometer** consists of three cups placed on a small vertical shaft. When the wind blows the device rotates and the wind speed conducts the speed of revolution. At the end of the shaft is a DC device that generates signal of a different voltage, where the voltage is used as a measurement of the wind speed. The **ultrasound anemometer** is in no danger of freezing because it has no moving parts. It works based on the speed of sound. The speed of sound, or ultrasound, in the air is affected by the wind speed. At any given temperature value, the wind speed is known. So, if the temperature value changes, the wind speed are known due to that any changes represent the wind speed [13].

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 1000 to 1800 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 [34].

Nacelle. - The nacelle sits top of the tower and contains the gear box, low-speed and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on. Heat Exchanger the components and systems inside the nacelle are necessary to convert mechanical energy into electricity. These systems and components generate a lot of heat inside the nacelle and need cooling. Excessive heat causes lubrication to break down and materials to expand, which in turn causes more friction and heat, leading to frequent lubricant replacement and gearbox repair [35]. **Brake** A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Low-Speed Shaft. - The rotor turns the low-speed shaft at about 30 to 60 rpm.

High-speed shaft. - It drives the generator.

Electrical Generator. - Electrical generators convert mechanical power into electrical power. The generators that are used in HAWT are synchronous or induction generators, but induction generators are usually chosen because of torsional compliance and extraction of damping energy in the drive train. The reason why is the cyclic variations in the torque developed in the aerodynamic rotor [42]. The induction generator has a non-rotating component called stator which is connected to the network or load. In order to reduce noise and electrical losses, the stator has a three-phase winding on a laminated iron core. Their function is to produce a magnetic field that rotates at a constant speed. Though the induction generator and the synchronous generator have similar stators, their rotor configurations are very different.

Induction generators are more reliable and are not expensive. They also have some mechanical properties that suit wind turbines. The rotor has a number of aluminum bars and those bars are connected to electricity by aluminum end rings. The speed of the generator changes according to the rotor speed. Induction generators also go under the name asynchronous generators because they operate asynchronous to the synchronous speed.

When the torque changes the generator will increase or decrease its speed. Because of this, there is less wear and tear on the tower, gearbox and other components in the transmission line, or lower peak torque, that is one of the most important reasons for choosing an asynchronous generator rather than synchronous generator. The smaller wind turbines also use induction generators for the same reasons but mainly because they are inexpensive [6].

Synchronous Generators. - The synchronous generator also has a stator with the same function as the induction generator. The rotor for this type of generator has field winding to carry DC, which creates a magnetic field. The rotating field, which is created by the stator winding, interfaces into the magnetic field. This leads to the rotor rotating at a constant speed with the stator field and the frequency of the network [40, 41].

2.3.1.2 General Working Principles

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 used to 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 [37].

In off-grid application it is difficult to keep the frequency of the resulting current constant, as it depends on wind speed which is highly variable. Therefore the current is usually rectified to give DC [19, 30].

Most wind turbines have two or three blade. Two blade machines are somewhat less expensive. Three bladed machines suffer less mechanical stress and are less vulnerable to fatigue problem. The Yaw bearing allows a wind turbine to rotate in order to face to the wind from any direction. A tower support wind turbine and places it above any obstruction [35].

2.3.1.3 Wind Turbines Efficiency and Power Curve

The theoretical limit of power extraction from wind, or any other fluid was derived by the German aerodynamicist Albert Betz. Betz law, states that 59% or less of the kinetic energy in the wind can be transformed to mechanical energy using a wind turbine. In practice, wind turbines rotors deliver much less than Betz limit. The factors that affect the efficiency of a turbine are the turbine rotor, transmission and the generator. Normally the turbine rotors have efficiencies between of 40% to 50%. Gearbox and generator efficiencies can be estimated to be around 80% to 90%. Also efficiency of a turbine is not constant. It varies with wind speeds. Many companies do not provide their wind turbine efficiencies, instead they provide the power curve [33, 34, 38].

A power curve is a graph that represents the turbine power output at different wind speeds values. The advantage of a power curve is that it includes the wind turbines efficiency. The power coefficient and efficiency of wind turbines vary greatly from manufactures to manufacturers [39, 40]. As a result, the power output of wind turbines varies from turbine to turbine and is given by power curve which plots the output power of a turbine against wind speed (see Figure 2.8).

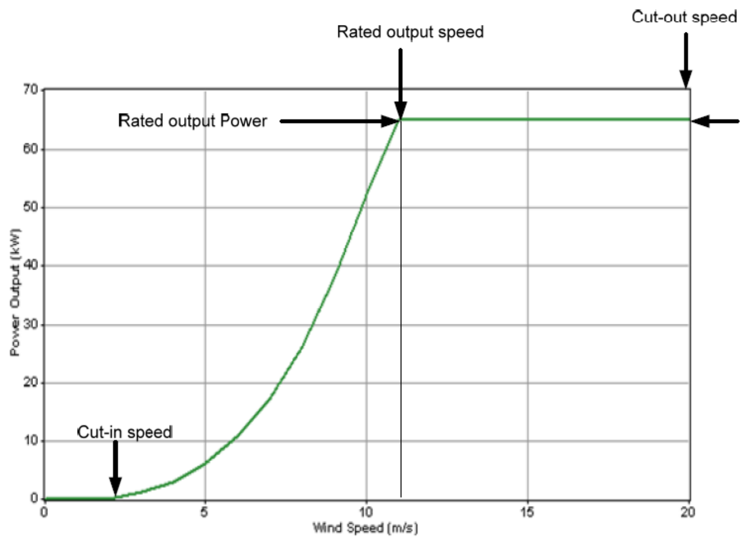


Figure 2. 8 Characteristic power output (kw) vs wind speed (m/s) curve [17]

From the above characteristic curve, there are three important points at which much attention is paid for the speeds and the corresponding turbine output powers for every wind turbine.

Cut-in speed.- at very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate is called the cut-in speed and is typically between 3 and 4 meters per second [32].

Rated output power and rate output wind speed.- as the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly. However, typically somewhere between 12 and 17m/s, the power output reaches the limit that the electrical generator is capable. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed [19].

<u>Cut-out speed</u>.- as the speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cutout speed and is usually around 25 m/s [41].

<u>A furling speed (u_f)</u>.- is approximately twice that of the rated speed (u_R).This means the turbine control system is able to maintain a constant power output over an eight to one range of wind power input [22, 24].

$$u_f = 2 * (u_R) \tag{2.7}$$

2.3.2 Wind Speed Height Correction

For idealized smooth plane surface, the average wind speed increases with height approximately as the 1/7th power:

$$\frac{v(z_2)}{v(z_1)} = (\frac{z_2}{z_1})^a \tag{2.8}$$

Where, $\mathbf{v}(\mathbf{z_2})$ the wind speed at the desired height is $\mathbf{z_2}$

$\mathbf{v}(\mathbf{z_1})$ is the wind speed measured at a known height $\mathbf{z_1}$, and

a is a coefficient known as the wind shear exponent. The wind shear exponent varies with pressure, temperature and time of day. A commonly use value is one-seventh (1/7) and which is more applicable over open land surfaces [25, 27].

There is also another formula that wind speed on height correction. As you know wind speed always affected by local factor which are hills, building and topography where the wind turbine install. This formula is best estimation of the wind speed at hub height. For this thesis it uses logarithmic law of wind speed correction since it include local factor which affect the wind speed. The most general equation to calculate wind speed at hub height is as follow:

$$\frac{\mathrm{v}(\mathrm{z_{hub}})}{\mathrm{v}(\mathrm{z_{anem}})} = \frac{\ln(\mathrm{z_{hub/z_o}})}{\ln(\mathrm{z_{anem/z_o}})} \tag{2.9}$$

Where, $\mathbf{v}(\mathrm{z_{hub}})$ - the wind speed at the desired hub height is $\mathrm{z_{hub}}$

$\mathbf{v}(\mathrm{z_{anem}})$ - the wind speed measured at a known anemometer height $\mathrm{z_{anem}}$

2.3.3 Wind Power

The power (P) in the wind is a function of air density (ρ), the area intercepting the wind (A), and the instantaneous wind velocity (V), or the speed. Increasing these factors will increase the power available from wind. Equation 2.10 shows the relationship between these parameters but all this parameters is included on the power curve of any wind turbines.

$$P = \frac{1}{2}\rho A v^3 \qquad (2.10)$$

Where, P is the power output in (watts), ρ is the air density in (kg/m^3), A is the area where wind is passing (m^2) and V is the wind speed in (m/s).

The air density under standard conditions (sea level, 15^0C) is $1.22kg/m^3$. The average power output from a wind turbine is the power produced at each wind speed times the fraction of the time that wind speed is experienced, integrated over all possible wind speeds [28, 39].

The electric power output of a wind turbine generator (WTG) in the up state depends strongly on the wind regime as well as on the performance characteristics and the efficiency of the generator [41]. This function is described by the operational parameters of the WTG. The parameters commonly used are the cut-in wind speed, the rated wind speed and the cut-out wind speed. The hourly output of a WTG can be obtained from the simulated hourly wind speed by applying Equation 2.9. The following equations for the electrical power output of a model wind turbine are given as follows [31, 36]:

$$\left.\begin{array}{ll} P_e = 0 & (u < u_c) \\ P_e = a + bu^k & (u_c \leq u \leq u_R) \\ P_e = P_{eR} & (u_R \leq u \leq u_f) \\ P_e = 0 & (u > u_f) \end{array}\right\} \qquad (2.11)$$

Where, P_e - electrical power output, P_{eR} – rating output power, U – wind speed, U_c – cut-in wind speed, U_R -rating wind speed, and U_f - furling speed which is approximately twice rated wind speed.

The coefficients a and b are given by: $a = \frac{P_{eR}u_c^k}{u_c^k - u_R^k}$

$$b = \frac{P_{eR}}{u_R^k - u_c^k}$$

The Rayleigh distribution is a special case of the Weibull distribution with k = 2 and is often sufficiently accurate for analysis of wind power systems. This value of k should be used if the wind statistics at a given site are not well known. If Weibull k is not known, use k = 2 for inland sites, use 3 for coastal sites, and use 4 for island sites [26, 29].

2.4 Energy Storage System

A wide range of energy storage technologies exist today. In general, energy storage technologies are classified into two categories based on the form of the stored energy: direct energy storage and indirect energy storage technologies [20, 27]. The former store the energy as electrical energy and do not require any conversion to other forms. In contrast, the indirect energy storage technologies require converting electrical energy from/to mechanical energy or chemical energy. The need of energy storage is to transfer the excess power during weak loads or excess supply from RESs to the peak periods [14, 15]. The energy from the RESs has to be transformed into a storable energy form first and then transformed when storing is needed. Technologies of each type are presented in Figure 2.9.

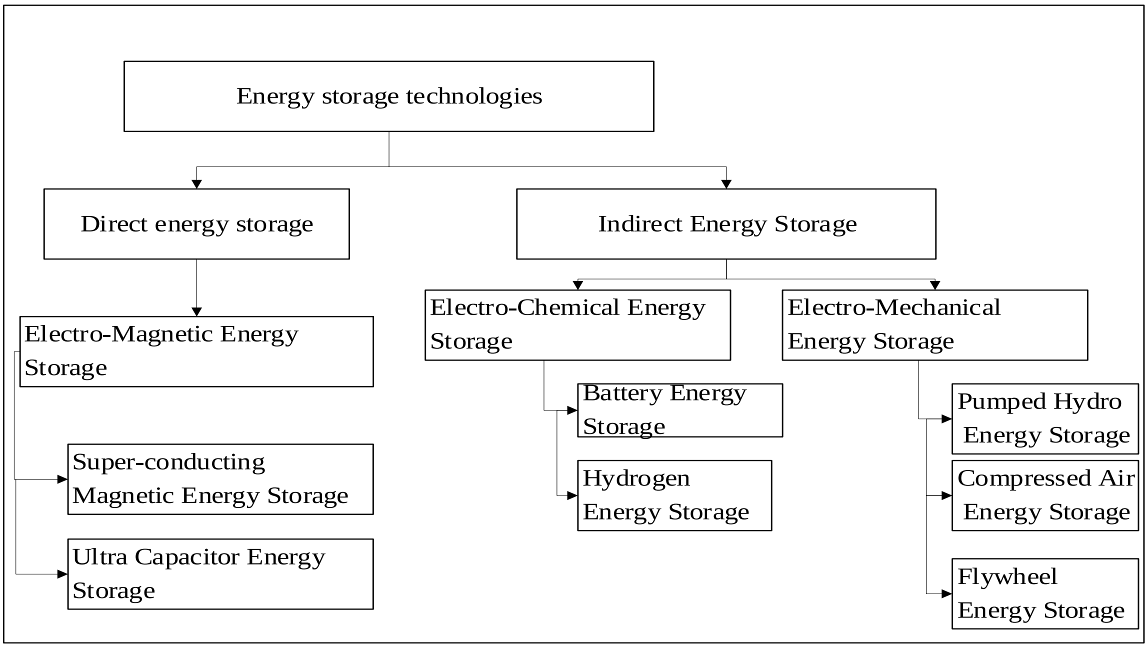


Figure 2. 9 Classification of energy storage technologies [36]

The energy storage element can act as a load or a generator depending on the supply to demand ratio. Ideally, at any instant of time, there should be a zero-net exchange between the energy sources and the energy sinks (both real and reactive power) [16, 18, 21]. If this balance is not achieved, the voltage and frequency of the system changes to maintain equilibrium. In the above Figure 2.9 there are many energy storage techniques from which the good hybrid energy storage system is battery bank. Some types of storage battery bank:

Lead Acid Battery. -When a lead acid battery is fully or partially discharged, lead sulphate forms at the electrodes. If the battery is allowed to remain for a prolonged period in a discharged state or with a very low state of charge the lead sulphate may form into large crystals which are very difficult to convert back into lead and sulphuric acid by the charging process. The formation of these crystals is called sulphation and causes a permanent loss of capacity of the battery. To avoid this problem, lead acid batteries should therefore only be stored in a fully charged condition and the charge should be topped up from time to time during storage to compensate for the self-discharge of the cells [37, 39].

To prolong shelf life without charging, the batteries should be stored at 10°C or less but the electrolyte should not be allowed to freeze. When the battery is fully charged the electrolyte is sulphuric acid solution and the freezing point is -36°C but it rises to 0°C in the fully discharged state when the electrolyte is simply water.

The electrodes of the cells in a lead storage battery consist of lead grids. The anode is filled with spongy (porous) lead. The cathode is filled with lead dioxide {PbO_2}. Dilute sulfuric acid {H_2SO_4} serves as the electrolyte. During the battery recharge cycle lead sulfate (sulfation) begins to reconvert to lead and sulfuric acid. During the recharging process as electricity flows through the water portion of the electrolyte and water, (H_2O) is converted into its original elements, hydrogen and oxygen.

Nickel Cadmium Battery. -Nickel Cadmium batteries can be stored in either a charged or discharged state. Long term storage can accelerate battery self-discharge, and lead to the deactivation of reactants. Although the cells can be stored at temperatures between -20°C and +45°C, as with almost all batteries heat can cause deterioration of the active chemicals and it is better to keep the cells in a cool, clean, dry, non-corrosive environment. After prolonged storage, two or three deep discharge cycles may be needed to restore full capacity.

Nickel Metal Hydride Battery. -A nickel–metal hydride battery, abbreviated NiMH or Ni–MH, is a type of rechargeable battery. The chemical reaction at the positive electrode is similar to that of the nickel–cadmium cell (NiCd), with both using nickel oxide hydroxide (NiOOH). NiCd batteries use Cadmium, a highly toxic heavy metal, that can damage the environment if not disposed of properly. (They should be recycled not discarded). NiMH batteries usually have a higher capacity than NiCd batteries of the same size.

The negative electrode reaction occurring in a NiMH cell is

$$H_2O + M + e^- \rightleftharpoons OH^- + MH$$

The charge reaction is read left-to-right and the discharge reaction is read right-to-left.

On the positive electrode, nickel oxyhydroxide, NiO(OH), is formed:

$$Ni(OH)_2 + OH^- \rightleftharpoons NiO(OH) + H_2O + e^-$$

The metal M in the negative electrode of a NiMH cell is an intermetallic compound. When overcharged at low rates, oxygen produced at the positive electrode passes through the separator and recombines at the surface of the negative electrode. Hydrogen evolution is suppressed, and the charging energy is converted to heat. This process allows NiMH cells to remain sealed in normal operation and to be maintenance-free [9, 18].

Table 2. 1 Characteristics of storage battery

Parameter \ Battery	Lead acid	Nickel Cadmium	Nickel Metal Hydride
Commercialization	1881	1956	1990
Cell voltage (V)	2	1.2	1.2
Energy by weight (Wh/Kg)	30 to 40	40 to 60	30 to 80
Specific power (W/Kg)	180	150	250 to 1000
Energy by volume (Wh/L)	60 to 75	50 to 150	140 to 300
Max. discharge rate	10^0C		20^0C
Recharge time	>10Hours	8Hours	6Hours
Life Cycle	500-800	2000	1500
Self-discharge pre-month	3% to 4%	20%	30%
Temperature range ^{0}C	-20^0C to +50^0C	-40^0C to +60^0C	-20^0C to +60^0C
Best Charging Technique	Constant Voltage -constant current	Constant Current	Constant Current
Average energy cost ($/Kwh)	$150	$400-800	$250

Based on the above Table 2.1 characteristics of different types of storage battery bank, Lead-acid (S4KS25P) batteries are used for this thesis work. Because, Lead acid batteries are familiar with the optimization tool that is Homer software, low average energy cost, low self-discharge when compare with the other battery energy storage system. In addition to this reliable, over 140 years of development, Robust, Tolerant to overcharging, Low internal impedance, can deliver very high currents, Indefinite shelf life if stored without electrolyte, can be left on trickle or float charge for prolonged periods, Wide range of sizes and capacities available, The world’s most recycled product. And also, Flooded lead acid cells are one of the least expensive sources of battery power available, Deep cycle cells may cost up to double the price of the equivalent flooded cells [19, 20].

2.4.1 Battery Characteristics

Battery capacity. - is a measure of how much energy that the battery can store. The amount of energy that can be extracted from a fully charged battery basically depends on temperature, rate of discharge, battery age and battery type. The three main ratings to specify the capacity of a battery are [17, 18]:

Ampere-hour (Ah). - the current at which a battery can discharge at a constant rate over a fixed interval of time.

Reserve capacity. - the length of time (in minutes) that a battery can produce a specified level of discharge.

KWh capacity. - a measure of energy required to fully charge a depleted battery. A depleted battery is not usually a fully discharged battery.

Autonomy. - This variable is defined by the ratio of restorable energy capacity to maximum power discharge [17]. It refers to the maximum amount of time the system can continuously release energy. The autonomy of a system depends on the type of storage and the type of application.

$$\alpha = \frac{E_{restore}}{P_{discharge}} \quad (2.15)$$

Where, $E_{restore}$- stored energy (whr), $P_{discharge}$- discharge power (w), and α- Number of days of autonomy (hr).

Durability (cycling capacity). - Energy storage system is designed to release the energy stored after each recharge in a fixed time. The number of times the energy storage can release the energy level it was designed for after each recharge is referred to as durability or cycling capacity. It is expressed in number of cycles, N_{cycles}. The cycling capacity mainly depends on the depth of discharge (DOD). The number of cycles versus the DOD of lead acid (S4KS25P) batteries is shown by Figure 2.10 below.

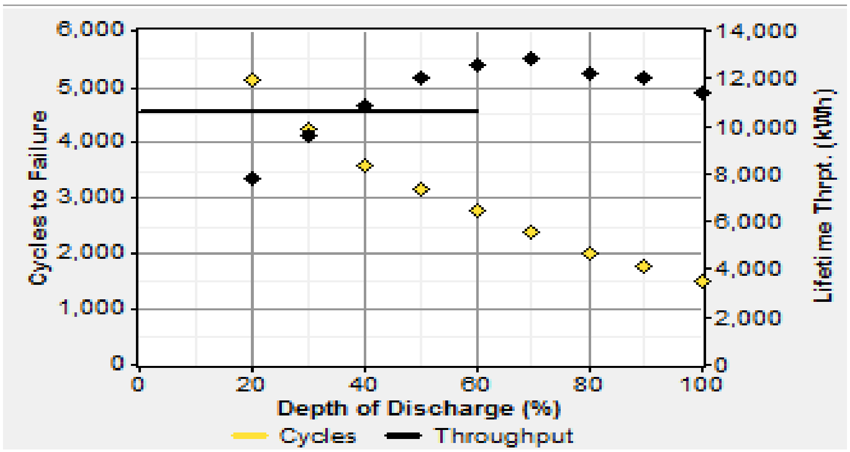


Figure 2. 10 Cycling capacity Vs depth of discharge for lead acid battery [10]

The higher the DOD, the lower will be the cycles and the lifetime of the batteries (can be seen from Figure 2.10).

Self-discharge. - This refers to the portion of energy which was initially stored and dissipated in a given non-use period of time. The battery cycles depend on the DOD and End of Life (EOL) [6, 17].

$$\text{Cycles} = f\,(\text{DOD, EOL}) \tag{2.16}$$

The smaller the DOD, the more cycles can be provided by the battery but not in a linear relationship because of the EOL criterion. The EOL, in general, is a decrease of 80% of its capacity [6, 17]. The normal capacity needed can be given [6] as:

$$BC_{nom} = 1.25BC_{calculated} \tag{2.17}$$

2.5 Converters

The power conditioning units are electronic devices and grouped into DC - DC/AC, AC/DC. The DC/DC converters are electronic devices used to change DC voltage or current into needed voltage and frequency outputs. This type of converter is required since DC voltage cannot easily be stepped-up or down with transformers. The DC/AC converter uses to switch the DC voltage or current produced by the hybrid system to the AC type voltage output. This type of power converter is called power inverter. The AC/DC power converter functions as an inverse of the inverter and it is called rectifier. It converts the AC input voltage to rectified DC output voltage [5, 9].

In this thesis bi-directional DC/AC or AC/DC converter type was considered as part of the hybrid system component. The incorporation of the bi-directional converter is used to switch the DC voltage that comes from battery and PV, moreover to change the AC voltage from the wind into DC when it is needed to charge the battery. In order to determine the size of an inverter, the determination of all the demanding loads from all consumers which are likely to function at the same time is an important step, however in this thesis case since power is provided from wind turbine directly to the consumers so inverter size can be smaller than the load to be supplied at one time. The rectifier and the inverter are the two main power electronics components of the solar PV and wind power systems. DC electricity generated from PV is converted into AC electricity by using an inverter, and hence, this electricity is the one connected to individual household's appliances [17, 25].

2.6 Charge Controller

Charge controller is an essential component in hybrid systems where a storage system is required. In other words, the battery charge controller works as a voltage regulator. It protects the battery against both excessive overcharge by a generating unit system and deep

discharge by a load. Charge controller shall switch off the load when a certain state of discharge is reached, also shall switch off the battery from the DC bus when it is fully charged [31, 36]. Charge controller can be adjusted to deal with different charging and discharging conditions. The controllers average efficiencies range from 95% to 98% [8].
There are two types of **charge controllers**. These are pulse width modulation (PWM) and Maximum power point tacker (MPPT). The first one or PWM controller is most simple, less expensive, the source voltage and also battery voltage are the same. The MPPT controller is most expensive and more efficient. The cost difference is may be 30 - 60% and also the source voltage is bigger than the storage batteries voltage [39, 42].

CHAPTER THREE

MATERIALS AND METHODS

3.1 Data Collection and Assessment

3.1.1 Primary and Secondary Data Collection

Primary data. - It is a data that are collected by myself by conducting field survey. During the field survey, the primary data necessary for this thesis were the number of religious institutes and type of community services, such as, one primary school, one health center, one church and one FTC.

Secondary data. - It was a data that is not collected by the researcher for him purpose; others collect it for other purpose. For this thesis were solar radiation, wind speed and direction data at different height levels, Population size and number of households, energy equipment cost related to the proposed RHS configuration and technologies.

Solar radiation and wind speed and direction data are collected from NMSA and NASA Surface metrology; whereas the population size and number of households are taken from Delanta Woreda Administration office. The potential of solar resource, and wind resource for the village was assessed. The solar radiation and clearness index for 22 years average, and wind speed and wind direction for 10 years average was obtained from NASA surface meteorology, solar and wind map of Ethiopia was obtained from Solar and Wind Energy Resource Assessment (SWERA). And also, the recent actual data for the selected site from 3 to 5 years were obtained from NMSA at Adama branch.

3.1.2 Assessment of Solar Energy Potential in the Case Study

For Ethiopia as a whole, the yearly average daily radiation is 5.26 kWh/m^2. This varies significantly during the year, ranging from a minimum of 4.55 kWh/m^2 in July to a maximum of 5.55kWh/m^2 in February and March. On a regional basis, the yearly average radiation ranges from values as low as 4.25kWh/m^2/day in the areas of Itang in the Gambella Regional State (Western Ethiopia), to as high as 6.25kWh/m^2/day around Adigrat in the Tigray Regional State (Northern Ethiopia).

Solar energy was the current source of Off-grid rural applications in homes, rural telecoms and in the social sectors (water pumping, health services, schools). The current total installed PV power in Ethiopia is about 3.5MW (three-quarters installed in telecom stations, mostly in mobile towers but also in other stations).

3.1.3 Solar Resource Assessment of the Village

The 22 years' monthly average solar resource of the village varies from 6.93kwh/m^2/day in January to 4.38kwh/m^2/day in August, which is the winter of Ethiopia, and clearance index are obtained from NASA. An average solar radiation for the village is 6.49kWh/m^2/day. The clearance index and daily radiation of the village is obtained from NASA surface metrology at the center latitude 11.35N and longitude of 39.13E which is a western boundary of 39, northern boundary of 12, eastern boundary of 40 and also southern boundary of 11in degree. For a PV system to supply sustainable power, the daily radiation should be greater than 4kWh/m^2/day. Table 3.1 shows the solar resource profile for Tikishign village.

Table 3. 1 Clearance index and daily radiation of the village (Source: NASA)

Month	Clearance Index	Daily radiation (kwh/m^2/day)	Temperature (^{0}C)	Average daylight hours (Hours)
January	0.68	6.93	9.61	11.5
February	0.67	6.87	10.2	11.7
March	0.66	6.52	9.82	12.0
April	0.66	6.08	8.80	12.3
May	0.64	6.30	9.22	12.6
June	0.61	5.33	8.40	12.7
July	0.60	4.42	7.69	12.7
August	0.59	4.38	8.36	12.4
September	0.62	5.44	10.2	12.2
October	0.66	5.95	11.3	11.8
November	0.67	6.85	10.7	11.6
December	0.67	6.07	9.77	11.4
Annual Average	**-**	5.93	9.51	

3.1.4 Solar Radiation Variation

January is the sunniest month of the year, at which time solar energy resource is 8.20kWh/m^2/day, while in August it drops to 4.38 kWh/m^2/day as shown in Table 3.1. In the months of, January, February, March the clearance index decreases with differences from month to month as (0.68), (0.67) and (0.66) respectively. In these months, the wind power can compensate. Where as in the months of September, October and Novembers the clearance index increases from month to month as (0.62), (0.66), and (0.67) respectively.

3.1.5 Solar Radiation Potential

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 neighbouring structures. Figure 3.1 shows below 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 eastwards. For a horizontal surface, γ is always 0^0.

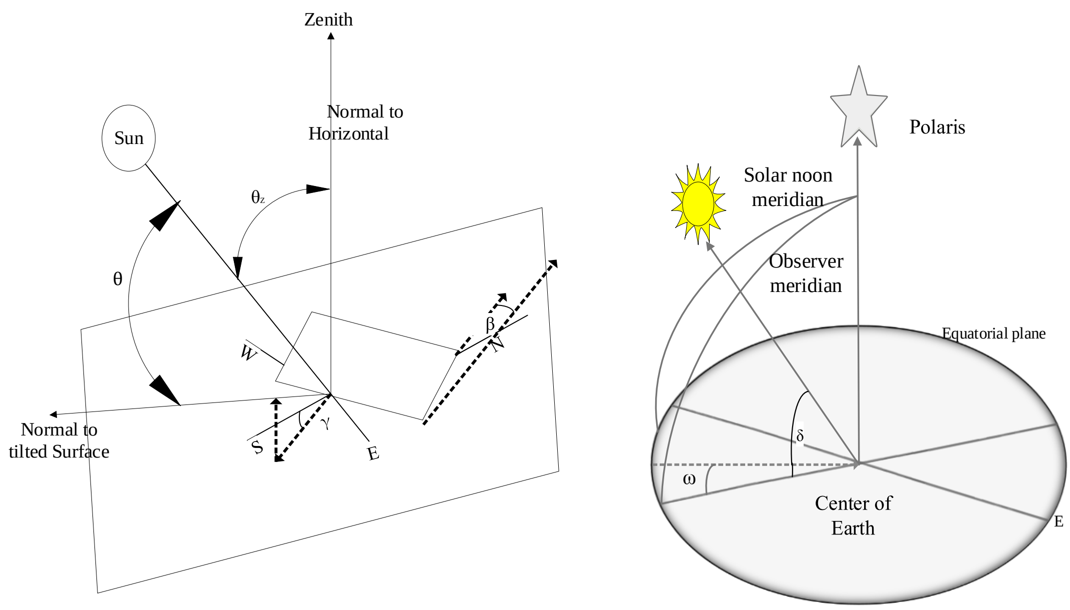


Figure 3. 1 Geometry of solar collector and location of sun relative to earth

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,∅), 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 [Source: HOMER software].

$$\delta = 23.45\sin\left(360^0 \frac{284 + n_d}{365}\right) \quad (3.1)$$

Where: δ is solar declination angle (^{0})

n_d is day number of the year starting at January 1st as 1

$$\omega = (12 - t_L)15^0) \quad (3.2)$$

Where, t_L = local solar time in hours.

ω = solar hour angle (^{0})

$$\sin(\alpha_s) = \sin(\emptyset)\sin(\delta) + \cos(\emptyset)\cos(\delta)\cos(\omega) \quad (3.3)$$

Where, α_s = solar altitude (^{0}), $\emptyset$ =latitude (^{0})

$$\sin(\gamma_s) = \frac{\cos(\delta)\sin(\omega)}{\cos(\alpha_s)} \quad (3.4)$$

Where: γ_s = solar azimuth (^{0})

The sunset/sunrise angle is given by

$$\omega_s = \cos^{-1}\left(-\tan(\emptyset)\tan(\delta)\right) \quad (3.5)$$

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

$$\begin{aligned}\text{Cos}(\theta_i) &= \sin(\delta)\sin(\emptyset)\cos(\beta) - \sin(\delta)\cos(\emptyset)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\emptyset)\cos(\beta)\cos(\omega) \\ &+ \cos(\delta)\sin(\emptyset)\sin(\beta)\cos(\gamma)\cos(\omega) \\ &+ \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega) \quad (3.6)\end{aligned}$$

The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (about 1.5 * 10^{11}m), measured outside the earth's atmosphere is called the solar constant, G_{sc} (1367W/m^2). 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:

$$G_{on} = G_{sc}\left(1 + 0.033 * \cos\frac{360 n_d}{365}\right) \quad (3.7)$$

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

$$G_o = G_{on}\cos(\theta_z) \quad (3.8)$$

Where, θ_z = 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. By integrating the solar constant (extraterrestrial irradiance) over the day length gives us the daily solar radiation on the horizontal surface.

$$H_o = \frac{24 * 3600 * G_{sc}}{\pi}\left(1 + 0.033 * \cos\left(\frac{2\pi n_d}{365}\right)\right) \quad (3.9)$$

Where, H_o is the average extraterrestrial horizontal radiation for the day [kwh/m^2/day]

n_d - Day number starting from January 1st as 1,

G_{SC} -1.367KW/m^2, the solar constant,

$\emptyset$ -Latitude of the location (11.35^0),

δ -Declination angle (^{0}) given by equation 3.1, ω_s- 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.

$$H = H_o\left(a + b\frac{n}{N}\right) \quad (3.10)$$

Where, H- monthly average daily radiation on horizontal surface (kwh/m^2)

H_0 - monthly average daily extraterrestrial radiation on a horizontal surface (kwh/m^2)

N - the maximum possible daily hours of bright sunshine given by equation

n - monthly average daily number of hours of bright sunshine

a and b - are regression coefficients having average value of a = 0.33 and b = 0.43.

The day length, N, is the maximum possible daily sunshine hour is given by equation 3.11.

$$N = \frac{2}{15}\omega_s \quad (3.11)$$

3.1.6 Estimation of PV Output of the Village

<u>The steps to calculate approximately the output power of solar PV are as follows</u>. -

- Determine the radiation at the horizontal surface based on the day of the year and the site latitude and then establish a clearness index.
- The clearness index is then used to calculate the direct, diffuse and random components of the radiation on a horizontal surface.
- The total radiation is then calculated from the direct, diffuse and random values obtained.

- Finally, the radiation on the surface of the panel is determined. It requires monthly average meteorological data at a specific site location as its input for the simulation of the solar radiation process at that site. The necessary data is the monthly average values of solar radiation on the horizontal surface, if temperature effect ignored.

The monthly average values of solar radiation (kWh/m^2/day) on the horizontal surface data obtained from NMSA at Adama branch which is measured one times per day.

Table 3. 2 Monthly average solar radiation [Source: NMSA at Adama branch]

Year	2012 kwh/m^2	2013 kwh/m^2	2014 kwh/m^2	2015 kwh/m^2	2016 kwh/m^2	**Monthly average**	**Annual average**
January	5.13	5.65	5.18	4.62	5.10	**5.14**	**5.013**
February	6.22	6.00	5.80	5.58	5.27	**5.77**	
March	5.79	6.35	4.68	5.32	5.35	**5.50**	
April	6.16	5.29	5.95	6.01	5.44	**5.77**	
May	5.60	5.45	5.12	5.51	5.71	**5.47**	
June	5.02	5.08	4.34	4.58	4.79	**4.76**	
July	3.97	4.25	3.90	4.64	3.86	**4.12**	
August	4.25	3.94	3.96	4.59	4.06	**4.16**	
September	4.56	4.58	4.66	4.63	4.78	**4.64**	
October	4.15	4.54	5.18	5.56	5.63	**5.01**	
November	5.44	4.63	5.03	5.37	5.19	**5.13**	
December	5.07	4.76	4.73	4.39	4.90	**4.77**	

3.1.7 Wind Power Potential Assessment

Once an area has been chosen for assessment, it is necessary to collect wind speed and direction data. A complete wind resource assessment involves a dense network of anemometers (wind monitoring stations) recording continuous wind data for at least one year. Since such wind monitoring efforts are time consuming and costly, wind researchers often obtain data sets that have been previously recorded. The wind resource can be obtained either from NMSA or from selected sites like NASA, SWERA, etc. The average wind speed data obtained from Ethiopian NMSA of Adama branch which is conventional wind resource measured five times a day (at 6:00, 9:00, 12:00, 15:00 and 18:00) and also automatic data logger wind resource measured at each fifteen minutes' time interval per day.

The 10 years' monthly average wind speed (m/s) resource of the village varies from 5.76m/s in February to 4.57m/s in October at 10m and also 6.76m/s in February to 5.25m/s in October at 50m are obtained from NASA. An average wind speed at 10m and 50m for the village is 5.17m/s and 6.11m/s respectively.

Table 3. 3 Ten years' monthly average Wind resource profile [source: NASA].

Month	Wind speed at 10m (m/s)	Wind speed at 50m (m/s)	Wind speed at 100m (m/s)	Wind direction at 50m (degree)
January	5.71	6.70	7.21	132
February	5.76	6.76	7.28	135
March	5.59	6.54	7.03	137
April	5.21	6.05	6.50	137
May	5.03	5.83	6.24	136
June	5.52	6.46	6.94	144
July	5.49	6.42	6.90	162
August	5.18	6.01	6.46	182
September	4.77	5.50	5.88	198
October	4.57	5.25	5.60	196
November	4.97	5.76	6.17	184
December	5.21	6.09	6.53	172
Annual average	5.17	6.11	7.56	

Table 3. 4 Conventional average wind speeds measured five times per day at 10m [Source: NMSA Adama branch]

Month	2015 (m/s)	2016 (m/s)	Wind direction (degree)
January	4.57	4.74	126
February	4.63	5.10	130
March	5.72	5.03	132
April	6.12	4.91	132
May	5.76	5.38	131
June	5.44	5.59	139
July	5.19	4.59	157
August	4.68	4.68	167
September	6.26	4.87	193
October	5.18	5.90	191
November	6.75	5.20	179
December	5.10	5.20	167
Annual average	5.45	5.10	

Table 3. 5 Automatic data logger average wind speed [Source: NMSA Adama branch]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annu.Ave.
2016	5.15	5.58	6.00	6.99	8.21	6.86	4.04	4.90	3.72	8.98	6.10	5.15	5.97
2017	6.09	5.35	6.78	8.16	9.19	7.59	6.03	x	x	x	x	x	

By nature, wind speed is directly proportional with altitude. As altitude increase the wind speed also increase. Hence using the power law formula, the wind speed at any height can be determined by using mathematical Equation or calculate by using wind speed distribution.

3.1.8 Wind Speed Distribution

The distribution of wind is expressed by Weibull distribution which is called a Raleigh distribution for K = 2. It is given by equations (3.13 to 3.15).

$$f(v) = \frac{\pi v}{2\tilde{v}^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\tilde{v}}\right)^2\right] \quad (3.13)$$

$$\text{Prob}\,(v \le V) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{v}{\tilde{v}}\right)^2\right] \quad (3.14)$$

$$\text{Prob}\,(v \ge V) = \exp\left[-\frac{\pi}{4}\left(\frac{v}{\tilde{v}}\right)^2\right] \quad (3.15)$$

Where, f (v)= Weibull probability density function of wind distribution

$\tilde{v}$ = mean wind speed (m/s), v = instantaneous wind speed (m/s)

Prob (v ≤V) = probability of instantaneous wind speed is less than V

Prob (v ≥ V) = probability of instantaneous wind speed is greater than V

Wind speeds are always measured at 10m height anemometer. But, wind turbines are installed at higher elevations at which the wind speed is completely different from the 10m measurement. This variation of wind speed with height can be expressed with equa. (3.16).

$$V(z) * \ln\left(\frac{z_r}{z_o}\right) = v\,(z_r) * \ln\left(z\,\frac{z_r}{z_o}\right) \quad (3.16)$$

Where, Z_r - Reference height (m), Z - Height where wind speed is to be determined (m)

Z_0 - Measure of surface roughness (0.1 to 0.25)

V (z) -Wind speed at height of Z m (m/s), $v(z_r)$ - Wind speed at the reference height (m/s)

3.1.9 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 equa. (3.17).

$$P_w = \frac{1}{2}\rho A V^3 \qquad (3.17)$$

Where, ρ = Density of air (kg/m^3), A = the swept area (m^2), P_w = 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, C_p as given by equa. (3.18).

$$C_P = \frac{\text{rotor power}}{\text{power in the wind}} \qquad (3.18)$$

The power coefficient, C_P 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). Thus, the electrical power output from the wind turbine can be expressed by equa. (3.19).

$$P_{wout} = \eta_t C_p \frac{1}{2}\rho A V^3 \qquad (3.19)$$

Where: P_{wout} = output power of wind turbine, C_p= the power coefficient

η_t = Overall efficiency of the transmission system/power train

The C_p and efficiency of wind turbines, η_t vary greatly from manufactures to manufacturers.

3.2 Load Estimation

The load estimation is mainly concerned with calculating the power and energy demand of the community. The primary and deferrable load estimation is performed for a village with 720 households by considering the basic needs of the community. The primary load contains lighting, radio receiver, TV and DVD player. In addition to these, the community has school, health clinic, animal clinic, church, farmers training center (FTC), flour mill, etc.

3.3 Energy Demand of the Village

3.3.1 Energy Demand Assessment and Load Scheduling of the Village

Energy is the oxygen of the economy and the blood live of the growth. To improve the life of the society energy is very important and crucial. Due to the low income of the society, scattered placement, the house hold energy demand of the village is lower than that of in the urban area. The electrical energy produced from the proposed hybrid system is supplied to home appliances, community service, and religious institute and for agricultural activities. In this thesis the electric load demand of the village community is divided into the following four major categories like:

Household/domestic load, Commercial loads, Community load (Primary school load, Health clinic load, Animal clinic load, Church load, FTC load) and Deferrable load. The total electric load estimated for the listed appliances above were summed up to get the required load to be supplied by the system. Despite of the present situation is below the poverty line; Peak operation hours of the appliances have been proposed based on the current living condition of the community and the current growth trend of the country. To design an off-grid hybrid power system for a specific area community the establishment of information's like the load profile of the community, climatic data of the area, initial cost of the components, etc. are the important parameters to be accounted.

3.4 Estimation of Primary Load

Primary load is the load that should meet by the energy providing system as it requires immediately; which includes lighting, baking, vaccine refrigeration, TV, radio, computer, printer, simple laboratory equipment's and others. Here the electricity load consumption in each household is considered to be the same and constant throughout the year. The load determination of the village was performed for 720 household numbers with average of five family members per household. During load estimation, the nature of load has been thoroughly analyzed to come up with sustainable energy demand satisfaction since electric load is vary hourly, daily and seasonal bases. The rural economic situation of the country is below the poverty line and thus in this energy system design the selection of appliances was reflected for the low wattage for the affordability of the provided electric energy. The electricity load estimation is made according to the following approach.

Annual Energy consumption (KWh) = [(number of appliance used * power rating of each appliance (w) * hours of operation * number of days)/1000]/7 days.

3.4.1 Domestic Load

Table 3. 6 Households Electricity Consumption Features

Appliances	Quantities	Capacity (w)	Operation (hrs)	Total no. of customers (720)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
CFL	4	11	3	720	18:00-21:00	31.68	95.04
	2	11	1	100	21:00-22:00	2.20	2.20
	2	11	1	40	22:00-23:00	0.88	0.88
	1	11	6	10	23:00-5:00	0.110	0.660
Television				250			
	3	100	5	250	12:00-14:00	28.5	53.5
Radio				700			
	3	10	3	640	7:00-10:00	5.40	5.40
	1	10	2	120	19:00-21:00	1.20	2.40
Baking machine				50			
	1	2500	1	15	11:00-12:00	37.50	37.50
	1	2500	1	20	14:00-15:00	50	50
	1	2500	1	15	15:00-16:00	37.50	37.50
DVD player				100			
	1	15	1	50	7:00-8:00	0.75	0.75
	1	15	1	75	12:00-13:00	0.375	0.375
	1	15	2	50	19:00-21:00	0.75	1.5
Charger	1	10	1	670		6.70	6.70
Total per household per day						203.54	294.405

3.4.2 Commercial Load

Table 3. 7 Electric Load Consumption Characteristics of commercial load

Appliances	Quantities	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
Flour mill	1	12,500	2	12:00-14:00	12.5	25.00
	1	12,500	1	15:00-16:00	12.50	12.50
CFL	2	11	3	18:00-21:00	0.022	0.066
Fluorescent lamp	2	11	3	21:00-00:00	0.022	0.066
Total per commercial per day					25.041	37.6316

3.4.3 Community Load

School Load. - July, August and the semester break were in January. For school total energy requirements for the year computed as daily demand times 160 days per year (8 months per year and 20 days per month). In other words, the total daily electricity consumed by the school except for January, July and August is shown below in Table 3.8.

Table 3. 8 Electric Load Consumption Characteristics of school load

Appliances	Quanti-ties	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
Class-room (CFL)	10	11	2	18:00-20:00	0.11	0.22
For staff (CFL)	4	11	3	18:00-21:00	0.044	0.132
Fluorescent lamp	4	11	6	19:00-23:00	0.044	0.132
Radio	1	10	2.4	9:00-11:40	0.060	0.042
Printer	1	330	1	10:00-11:00	0.330	0.330
	1	330	1	15:00-16:00	0.330	0.330
Computer	1	300	2	10:00-12:00	0.300	0.600
	1	300	2	14:00-16:00	0.300	0.600
Copy machine	1	900	1	10:00-11:00	0.900	0.900
	1	900	1	16:00-17:00	0.900	0.900
Electric stove	1	1500	1	10:00-11:00	300	1.50
	1	1500	1	12:00-13:00	1.500	1.500
Electric siren/bell	2	40	1/2		0.080	0.040
Total per school per day					7.898	7.226

Health Clinic Load

Table 3. 9 Electric Load Consumption Characteristics of health center load

Appliances	Quantity	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
CFL	8	11	2	18:00-20:00	0.088	0.176
	4	11	2	20:00-22:00	0.044	0.088
	2	11	3	22:00-1:00	0.022	0.066
Vaccine refrigerator	1	100	24		0.100	2.400
Microscope	1	20	1		0.020	0.020
Radio	2	10	3	9:00-12:00	0.020	0.060
	1	10	3	14:00-17:00	0.010	0.030
Computer	1	300	1	9:00-11:00	0.300	0.300
	1	300	1	15:00-16:00	0.300	0.300
Printer	1	330	1	11:00-12:00	0.330	0.330
	1	330	1	14:00-15:00	0.330	0.330
Electric siren	3	40	2		0.120	0.240
Television	1	100	10		0.100	1.00
Electric stove	4	1500	3	10:00-14:00	6	4.5
Total per clinic per day					7.284	98.32

Animal Clinic Load

Table 3. 10 Electric Load Consumption Characteristics of animal clinic load

Appliances	Quantity	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
CFL	4	11	2	18:00-20:00	0.044	0.088
	2	11	1	20:00-21:00	0.022	0.022
Vaccine refrigerator	1	100	24		0.100	2.400
Radio	1	10	2	9:00-11:00	0.010	0.020
	1	10	2	14:00-16:00	0.010	0.020
Computer	1	300	1	11:00-12:00	0.300	0.300
	1	300	1	15:00-16:00	0.300	0.300
printer	2	330	1	10:00-11:00	0.660	0.330
Electric stove	3	1500	2	10:00-12:00	4.5	3
Electric siren	1	40	1		0.080	0.040
Total per clinic per day					6.26	6.7

Church Load

Table 3. 11 Electric Load Consumption Characteristics of church load

Appliances	Quantity	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
CFL	4	11	2	18:00-20:00	0.044	0.088
Fluorescent lamp	2	11	2	19:00-21:00	0.022	0.044
Radio	1	10	6		0.010	0.060
Microphone	1	15	3		0.015	0.045
Electric stove	1	1500	1		3	1.5
Computer	1	300	1		0.300	0.300
printer	1	330	1		0.660	0.230
Electric siren	1	40	1		0.080	0.040

Farmers Training Center (FTC) Load

Table 3. 12 Electric Load Consumption Characteristics of FTC load

Appliances	Quantity	Capacity (w)	Operation (hrs)	Time interval (hrs)	Power (kw)	Energy (kwh/day)
CFL	4	11	2	18:00-20:00	0.044	0.088
Fluorescent lamp	2	11	4	20:00-00:00	0.022	0.088
Radio	1	10	6		0.010	0.060
Microphone	1	15	2		0.015	0.030
Computer	1	300	3		0.300	0.900
Printer	1	330	1		0.330	0.330
Electric siren	1	40	2		0.040	0.080
Total per church per day					0.7608	1.607

3.5 Estimation of Deferrable Load

Deferrable load is electrical load that must be met within some time period, but the exact timing is not important. Loads are normally classified as deferrable because they have some storage associated with them. Water pumping is a common example - there is some flexibility as to when the pump actually operates, provided the water tank does not run dry. Other examples include ice making and battery charging.

Water Pump. - Water pumping in small communities are used for the following purposes:

- Remove water from the source, such as a river, lake, reservoir, well, spring, etc.

- Move water from the treatment plant to the distribution system or irrigation system.
- Circulate water through a distribution system.
- Maintain pressure in the distribution system.
- Circulate glycol through heat exchanger or heating loop.
- Pump chemicals into the system.

Generally, water pumping system is required for the households, the schools and health care centers. About 125L of water per day per family and 2400L/day for each pair of one health center and one primary school, etc is suggested. During the rainy season (summer) delivery of water to distribution center with the aid of pumps is expected to decrease and to be shared by rain water, moreover, the amount of water to be covered by the rain water was assumed about 30% of the deferrable load. Whereas in June since it is the beginning month to the rainy season only 15% reduction is being suggested. There are no classes in July and August (annual break) and in January (semester break).

The average water requirement in developing country is about 125lit/day. This village has 720 households total amount of water consumption can be calculated as follows:

720*125 = 90000lit/day = 90m^3

For considerable depth of 20m**,** the pump average operating time is 6hours/day

The flow rate (Q) = 90*1000/ (6*3600) = 4.17lit/sec = 25lit/min

The electric power capacity of pump can be calculated as follows.

$$P = \frac{gQh}{\eta} (\text{watt}) \tag{3.20}$$

Where, g is Gravitation force of earth [9.81m/s^2], Q is flow rate

h is considerable height (depth) and η is efficiency of pump typically 90%.

$$P = \frac{9.81*4.17*20}{0.9} = 910\text{watt} \cong 1000\text{watt}$$

For this case water storage capacity for 3 - 5 days is also recommended. The energy storage capacity can be calculated as follows:

Energy storage capacity = No. of pumps rating * capacity of pumps storage days * running hours per day.

3.6 Modeling of Hybrid Energy System Components

3.6.1 Mathematical Modeling of PV System

As the operation and the performance of PV generator is interested to its maximum power, the models describing the PV module's maximum power output behaviors are more practical for PV system assessment. Using the solar radiation available on the tilted surface, the ambient temperature and the manufacturers data for the PV modules as model inputs, the power output of the PV generator, P_{PV}, can be calculated according to equa. (3.21)

$$P_{pv} = \eta_g N A_m G_t \quad (3.21)$$

Where, η_g **-** is the instantaneous PV generator efficiency, $\mathbf{A_m}$ **-** is the area of a single module (m^2), $\mathbf{G_t}$ **-** is the global irradiance incident on the titled plane (KW/m^2) and
N - is the number of modules.

All the energy losses in a PV generator, including connection losses, wiring losses and other losses, are assumed to be zero. The instantaneous PV generator efficiency is represented by the following equation:

$$\eta_g = \eta_r \eta_{pt}[1 - \beta_t(T_c - T_r)] \quad (3.22)$$

Where, η_r is the PV generator reference efficiency, η_{pt} is the efficiency of power tracking equipment which is equal to 1, T_c is the temperature of PV cell (°C), T_r is the PV cell reference temperature and β_t is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 per °C for silicon cells.

Based on the energy balance the PV cell temperature can be expressed as follows:

$$T_c = T_a + G_t\left(\frac{\tau\alpha}{U_L}\right) \quad (3.23)$$

Where, T_a is the ambient temperature (°C), U_L is the overall heat loss coefficient ($W/m^2/$°C), τ and α represent the transmittance and absorptance coefficients of PV cells respectively.

The overall heat loss coefficient $\tau\alpha/U_L$ can be estimated from the nominal operating cell temperature (NOCT) as follows:

$$\left(\frac{\tau\alpha}{U_L}\right) = \frac{NOCT - 20}{800} \quad (3.24)$$

Consequently, the instantaneous PV generator efficiency can be expressed as follows:

$$\eta_g = \eta_r \eta_{pt}\left\{1 - \beta_t(T_a - T_r) - \beta_t G_t\left(\frac{NOCT - 20}{800}\right)(1 - \eta_r \eta_{pt})\right\} \quad (3.25)$$

Where, η_{pt}, $\boldsymbol{\beta_t}$, NOCT, $\mathbf{A_m}$ were parameters that depend on the type of module and given by the manufacturer of the modules. Using the solar radiation available the hourly energy output of the PV generator ($\mathbf{E_{PVG}}$) can be calculated according to the following equa. (3.26)

$$E_{PVG} = G(t) * A * P_{PV} * \eta_{PVG} \quad (3.26)$$

Where, G (t) is the hourly irradiance in kWh/m^2, A is the surface area in m^2, P_{PV} is the PV penetration level factor and η_{PVG} is the efficiency of PV generator.

3.6.2 Mathematical Model of Wind Energy Generator

Hourly energy generated by wind generator (E_{WEG}) with rated power output (P_{WEG}) is defined by the following expression:

$$P_{WEG} = \frac{1}{2}\rho_{wind} AV^3 C_p(\lambda, \beta) * \eta_t * \eta_g \quad (3.27)$$

$$E_{WEG}(t) = P_{WEG} * t \quad (3.28)$$

Where, ρ_{wind} - is the density of air in $1.22 kg/m^3$, A- is the swept area (m^2)

v - is the wind speed (m/s), C_p - is the performance coefficient of the turbine

λ - is the tip speed ratio of the rotor blade tip speed to wind speed

β - is the blade pitch angle (deg) as 0^0, η_t - is the wind turbine efficiency

η_g - is the generator efficiency

The power density of wind (power per unit area)

$$\text{power density of wind} = \frac{P}{A} = \frac{1}{2}\rho v^3 \quad (3.29)$$

$$A = \pi R^2 \quad (3.30)$$

Where, R is radius of the rotor

3.6.3 Mathematical Model of Converter

In the proposed scheme, a converter contains both rectifier and inverter. PV and battery sub-systems are connected with DC bus while wind energy generator unit sub-system is connected with AC bus. The rectifier is used to transform the surplus AC power from the wind energy generator to DC power of constant voltage. The wind energy generator will be powering the load and at the same time charging the battery. The rectifier model is given below:

$$E_{rec-out}(t) = E_{rec-in}(t) * \eta_{rec} \quad (3.31)$$

$$E_{rec-in}(t) = E_{sur-ac}(t) \quad (3.32)$$

At any time, t,

$$E_{sur-ac}(t) = E_{weg}(t) - E_{load}(t) \quad (3.33)$$

Where, $E_{rec-out}(t)$ is the hourly energy output from rectifier, KWh

$E_{rec-in}(t)$ - is the hourly energy input to rectifier, KWh

η_{rec} - is the efficiency of rectifier

$E_{sur-ac}(t)$ - is the amount of surplus energy from AC sources, KWh

$E_{weg}(t)$ - is the hourly energy generated by wind generator

Here converter is used which can work both as an inverter and rectifier depending on the direction of flow of power.

3.6.4 Mathematical Model of Charge Controller

To prevent overcharging or discharge of a battery, a charge controller is used to sense when the batteries are fully charged and to stop or reduce the amount of energy flowing from the energy source to the batteries. The model of the charge controller rating is given below:

$$\text{solar charge controller rating} = I_{sc} * \text{Total number of modules} * 1.3 \quad (3.34)$$

Where: 1.3 - is charge controller oversizing factor, I_{sc} - Total short circuit current, of PV array

The energy of the charge controller is also given as:

$$E_{cc-out}(t) = E_{cc-in}(t) * \eta_{cc} \quad (3.35)$$

$$E_{cc-in}(t) = E_{rec-out}(t) + E_{sur-dc}(t) \quad (3.36)$$

Where, $E_{cc-out}(t)$ - is the hourly energy output from charge controller, kWh

$E_{cc-in}(t)$ - is the hourly energy input to charge controller, kWh

η_{cc} - is the efficiency of charge controller

$E_{rec-out}(t)$ - is the hourly energy output from rectifier, kWh

($E_{sur-dc}(t)$ - is the amount of surplus energy from DC sources, kWh

3.6.5 Mathematical Model of Battery Bank

The battery state of charge, SOC is the cumulative sum of the daily charge/discharge transfers. The battery serves as an energy source entity when discharging and a load when it charging. At any time, t the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t. The net capacity that the battery can store in Ah/day must be:

$$BC_n = \frac{E_{Tot}}{V_{nom,batt}} \quad (3.37)$$

Where, BC_n – net capacity of the battery, E_{Tot} – total energy

$V_{nom,batt}$ – nominal battery voltage i.e $48V_{DC}$

To calculate the number of batteries connected in parallel to reach the Ah required by the system.

$$B_P = \frac{B_c}{B_R} \tag{3.38}$$

Where, B_P – is batteries connected in parallel, B_R – is required battery bank capacity in Ah, B_C – is battery capacity

To calculate the number of batteries to be connected in series to reach the voltage required by the system.

$$B_S = \frac{V_{nbatt}}{V_{batt}} \tag{3.39}$$

Where, B_S – is number of series connected batteries, V_{nbatt} – is nominal battery voltage V_{batt} – is battery voltage

During the charging process, when the total output energy of all generators exceeds the load demand, the available battery bank capacity at time, t can be described by using:

$$E_{bat}(t) = E_{bat}(t-1) - E_{cc-out}(t) * \eta_{chg} \tag{3.40}$$

Where, $E_{bat}(t)$ – is the energy stored in battery at hour t, kWh

$E_{bat}(t-1)$ -is the energy stored in battery at hour t-1, kWh

η_{chg} -is the battery charging efficiency

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at time, t, can be expressed as:

$$E_{bat}(t) = E_{bat}(t-1) - E_{needed}(t) \tag{3.41}$$

Where, $E_{needed}(t)$-is the hourly load demand or energy needed at a particular period of time. Let d be the ratio of minimum allowable SOC voltage limit to the maximum SOC voltage across the battery terminals when it is fully charged. So, the Depth of Discharge (DOD)

$$DOD = (1 - d) * 100 \tag{3.42}$$

DOD is a measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity. The maximum value of SOC is 1, and the minimum SOC is determined by maximum DOD,

$$SOC_{min} = 1 - \frac{DOD}{100} \tag{3.43}$$

3.6.6 Power Generation Model

Total hybrid power generated at any time t, is given by:

$$P(t) = \sum_{weg=1}^{N_w} P_{weg} + \sum_{pvg=1}^{N_p} P_{pvg} \tag{3.44}$$

Where, N_w is the number of wind generators unit, N_p is the number of PV cells unit

This generated power will feed to the loads. When this generated power exceeds the load demand then the surplus of energy will be stored in the battery bank. This energy will be used when deficiency of power occurs in order to meet the load demand. The charged quantity of the battery bank has the constraint $SOC_{min} \leq SOC(t) \leq SOC_{max}$. The dump load will draw excess energy produced by the renewable generators but unused when the load does not need all the energy and the battery has reached its maximum capacity and cannot store more energy. The approach involves the minimization of a cost function subject to a set of equality and inequality constraints.

3.6.7 Mathematical Cost Model of Energy Systems

This work developed a mathematical model of a system that could deploy the best renewable energy options available at any base station located in any part of a country in the world; where the term Best represents the integral (total sum) of the minimum economic and environmental (health and safety) costs of the considered options. For this purpose, the thesis adopts the Hybrid Optimization Model for Electric Renewable (HOMER).

The Annualized Cost of a Component. - The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual operation and maintenance (O&M) cost and emissions cost. Operation cost is calculated hourly on daily basis.

Annualized Capital Cost. - The annualized capital cost of a system component is equal to the total initial capital cost multiplied by the capital recovery factor. Annualized capital cost is calculated by using:

$$C_{acap} = C_{cap} * CRF(i, R_{proj}) \qquad (3.45)$$

Where, C_{acap} – is annualized capital cost, $CRF(i, R_{proj})$ – is capital recovery factor, i – is interest rate, R_{proj} – is project lifetime, C_{cap} – is initial capital cost of the component

Annualized Replacement Cost. - The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project minus the salvage value at the end of the project lifetime.

Annualized replacement cost, C_{arep} is calculated by using:

$$C_{arep} = C_{rep} * f_{rep} * SFF(i, R_{comp}) - S * SFF(i, R_{proj}) \qquad (3.46)$$

Where, C_{rep} – is replacement cost of the component, SFF ( ) – is sinking fund factor

R_{comp} – is lifetime of the component, S – is salvaged value of the component

f_{rep} – is replacement factor

f_{rep} , a factor arising because the component lifetime can be different from the project lifetime, is given by:

$$f_{rep} = \begin{cases} \frac{CRF(i, R_{proj})}{CRF(i, R_{rep})}, & R_{rep} > 0 \\ 0 & R_{rep} = 0 \end{cases} \quad (3.47)$$

Where, R_{rep}-is replacement cost duration which is given by:

$$R_{rep} = R_{comp} * INT\left(\frac{R_{porj}}{R_{comp}}\right) \quad (3.48)$$

Where, INT () is the integer function, returning the integer portion of a real value.

SFF (), the sinking fund factor is a ratio used to calculate the future value of a series of equal annual cash flows, is given by:

$$SFF(i, N) = \frac{i}{(1+i)^{N}-1} \quad (3.49)$$

Where, *N* = number of years

The salvaged value of the component at the end of the project lifetime is proportional to its remaining life. Therefore, the salvage value *S* is given by:

$$S = C_{rep} * \left(\frac{R_{rem}}{R_{comp}}\right) \quad (3.50)$$

Where, R_{rem} – is remaining life of the component

The remaining life of the component, R_{rem} at the end of the project lifetime is given by:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (3.51)$$

Annualized Operating Cost (C_{aop}). - The operating cost is the annualized value of all costs and revenues other than initial capital costs and is calculated by using:

$$C_{aop} = \sum_{t=1}^{365}\{\sum_{t=1}^{24}[C_{oc}(t)]\} \quad (3.52)$$

Where, $C_{oc}(t)$ – is the Cost of operating component.

Total cost of a component = Economic cost + Environmental cost

Where, Economic cost = Capital cost + Replacement cost + O & M cost

Environmental cost = Emissions cost ≅ 0

Annualized cost of a component is calculated using:

$$C_{ann} = C_{acap} + C_{arep} + C_{aop} + C_{emissions} = C_{acap} + C_{arep} + C_{aop} \quad (3.53)$$

Annualized total cost of a component is calculated using:

$$C_{ann,tot,c} = \sum_{c=1}^{N_c}(C_{acap,c} + C_{arep,c} + C_{aop,c}) \quad (3.54)$$

Where, $C_{ann,tot,c}$ – is Annualized capital cost of a component

$C_{arep,c}$ – is Annualized replacement cost of a component

$C_{aop,c}$ – is Annualized operating cost of a component

From equa. (3.53), the Economic and Environmental cost model through Annualized Total Cost of different Configurations of Power System were derived as follows:

Economic and Environmental cost model of running **Solar Power only** is calculated as:

$$C_{ann,tot,s} = \sum_{s=1}^{N_s} (C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) \tag{3.55}$$

Where, $C_{acap,s}$ – is annualized Capital Cost of solar Power

$C_{arep,s}$ – is annualized Replacement Cost of solar Power

$C_{aop,s}$ – is annualized Operating Cost of solar Power

Economic and Environmental cost model of running **Wind Power only** is calculated as:

$$C_{ann,tot,w} = \sum_{w=1}^{N_w} (C_{acap,w} + C_{arep,w} + C_{aop,w} + C_{emissions}) \tag{3.56}$$

Where, $C_{acap,w}$ – is annualized Capital Cost of Wind Power

$C_{arep,w}$ – is annualized Replacement Cost of Wind Power

$C_{aop,w}$ – is annualized Operating Cost of Wind Power

Economic and Environmental cost model of running **Batteries** is calculated as:

$$C_{ann,tot,b} = \sum_{b=1}^{N_b} (C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \tag{3.57}$$

Where, $C_{acap,b}$ – is annualized Capital Cost of batteries Power

$C_{arep,b}$ – is annualized Replacement Cost of batteries Power

$C_{aop,b}$ – is annualized Operating Cost of batteries Power

Economic cost model of **Converter** is calculated as:

$$C_{ann,tot,c} = \sum_{c=1}^{N_c} (C_{acap,c} + C_{arep,c} + C_{aop,c} + C_{emissions}) \tag{3.58}$$

Where, $C_{acap,c}$ – is annualized Capital Cost of Converter Power

$C_{arep,c}$ – is annualized Replacement Cost of Converter Power

$C_{aop,c}$ – is annualized Operating Cost of Converter Power

Hybridizing the renewable energy generators (PV and Wind) results in three (3) different topologies as:

Economic and Environmental cost model of running **Solar only + Batteries + Converter** is calculated as:

$$C_{ann,tot,s+c+b} = \sum_{s=1}^{N_s}(C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) + \sum_{c=1}^{N_c}(C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}) + \sum_{b=1}^{N_b}(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \quad (3.59)$$

Economic and Environmental cost model of running **Wind only + Batteries + Converter** is calculated as:

$$C_{ann,tot,w+c+b} = \sum_{w=1}^{N_w}(C_{acap,w} + C_{arep,w} + C_{aop,w} + C_{emissions}) + \sum_{c=1}^{N_c}(C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}) + \sum_{b=1}^{N_b}(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \quad (3.60)$$

Economic and Environmental cost model of running **Hybrid (Wind and Solar) + Batteries + Converter** is calculated as:

$$C_{ann,tot,s+w+c+b} = \sum_{s=1}^{N_s}(C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}) + \sum_{w=1}^{N_w}(C_{acap,w} + C_{arep,w} + C_{aop,w} + C_{emissions}) + \sum_{c=1}^{N_c}(C_{acap,c} + C_{rep,c} + C_{aop,c} + C_{emissions}) + \sum_{b=1}^{N_b}(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions}) \quad (3.61)$$

The mathematical model derived estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The output when run with HOMER software will give us the optimal configuration of the energy system that takes into account technical and economic performance of supply options, the 10-year life cycle cost (LCC) of equipment, locally available energy resources (hourly solar insolation data (KW/m^2), hourly wind speed (m/s)), and system reliability.

3.7 The Energy Optimization Model

The process of optimization had been of concern for man for many ages. Previously there were no defined and scientific rules for optimum conditions. But with the passage of time and advancement in science and technology, everything was considered to be based on certain reasons or logics. Mathematical calculations involving process of optimization have become more famous in recent years. True meaning of optimization is to find the best answer for a particular problem. For example, problems dealing with the cost will require the best cost to be as less as possible. On the other hand, problems dealing with profit will see the maximum value as the best answer. So ‘Optimum’ is the word which is used to demonstrate the meaning of best, and the process of finding the best solution to a particular problem is known as the process of optimization. To solve an optimization problem, we require an optimization algorithm. An optimization algorithm is the algorithm which is used to define an optimized solution for a particular function. Thus, for the stand-alone PV and Wind hybrid system with constraints under study, we have the following optimization algorithm.

Minimize

$$\mathrm{Cost} = \sum_{i} C_{PVi} N_{PVi} + \sum_{j} C_{Wj} N_{Wj} + \sum_{m} C_{Bm} N_{Bm} + \sum_{n} C_{Cn} N_{Cn} \quad (3.62)$$

Subject to the constraints

$$\mathrm{Load} \le \sum_{i} E_{PVi} N_{PVi} + \sum_{j} E_{Wj} N_{Wj} \quad (3.63)$$

$$\text{Maximum Power Wattage} \le \sum_{n} P_{Cn} N_{Cn} \quad (3.64)$$

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (3.65)$$

Where, C_{PVi} – is Cost of a PV module, C_{Wj} – is Cost of wind turbine

C_{Bm} – is Cost of a battery, C_{Cn} – is Cost of a converter, N_{PVi} – is Number of PV modules

N_{Wj} – is Number of wind turbines, N_{Bm} – is Number of battery bank to be use.

N_{Cn} – is Number of converters, E_{PVi} – is kWh generated by PV module i

E_{Wj} – is kWh generated by wind turbine j, P_{Cn} – is Maximum output power of converter

SOC_{min} - is State of battery charge at minimum,

SOC_{max} - is State of battery charge at maximum

3.8 Population Growth and Load Forecasting

The population of Ethiopia accounts all residents regardless of legal status/citizenship except for refugees not permanently in the country of asylum, which are generally considered part of the population of the country of origin. The average annual population growth rate of Ethiopia was 2.65% from 2005 to 2017 G.C. (source: www.google.com)

The formula used for population forecasting is:

$$P_n = P_o(1 + \frac{r}{100})^n \quad (3.66)$$

Where: P_n – is population at the n^{th} year, P_0 – is the current population and r – is annual population growth rate in %.

3.8.1 Load Forecasting

The load forecasting was done for the two load estimations separately. It was obvious that previously recorded data was required as an input to conduct load forecasting using different techniques. But since the selected area were not electrified so far, the previous data were extracted by using the load forecasting method which was in use by UEAP. This was a governmentally owned company endowed in supplying electric access to rural areas by extending the national grid. The annual load growth rate was about 5% which was calculated by considering the data taken from previously electrified areas. Hence, a primary load forecasting for the first ten years were done using equa. (3.67) given below. The current electric load was taken to be 260kWh/day which was calculated by considering the total primary load of the community.

$$E_n = E_o(1 + \frac{r}{100})^n \quad (3.67)$$

Where: E_n - is electric load at the n^{th} year, E_0 - is the current electric load and

r - is the annual electric load growth (i.e. 5%)

The result of this analysis was shown in Table 3.13 below. These values are then used as input to forecast for the coming 10 years (2027) using the exponential method of forecasting.

Table 3. 13 Results of primary load forecasting

Year	2017(0)	2018(1)	2019(2)	2020(3)	2021(4)
Load	260 kw	273 kw	286.65 kw	300.98 kw	316.03 kw

Thus, the principle of regression theory was used to forecast the load for the coming ten years by using the results in Table 3.13 as a previous data. Its principle was that any function y = f(x) can be fitted to a set of points (x_1, y_1), (x_2, y_2) so as to minimize the sum of errors squared at each point, i.e.

$$\sum_{i=1}^{n}\{y_i - f(x_i)\}^2 = \text{minimum} \tag{3.68}$$

Among the different typical regression curves used in power system forecasting the simple least square line was used for forecasting the load in this thesis. The line y = a_0 + a_1x was fitted to the sets of points (x_1, y_1), (x_2, y_2) … (x_n, y_n).

Where, y - is dependent variable, a_1 - is slope, x - is independent variable, a_0 - is y-intercept and n are number of years.

$$\varepsilon^2 = \sum_{i=1}^{n}[y_i - (a_0 + a_1 x_i)]^2 = \text{minimum} \tag{3.69}$$

Partial differentiation with respect to the regressions coefficients (a_0 and a_1) is made and the equations set to zero to obtain the minimum error criterion. This gives us a set of simultaneous equations in a_0 and a_1:

For $\quad a_0: 2\sum[y_i - (a_0 + a_1 x_i)] = 0,$ We get,

$$\sum a_0 + a_1 \sum x_i = \sum y_i$$

$$Na_0 + a_1 \sum x_i = \sum y_i$$

For $\quad a_1: 2\sum[y_i - (a_0 + a_1 x_i)]x_i = 0$

$$a_0 \sum x_i + a_1 \sum x_i^2 = \sum x_i y_i$$

Which yield

$$a_0 = \frac{(\sum y)(\sum x^2) - [\sum(x)].\sum xy}{N\sum x^2 - (\sum x)^2} \tag{3.70(a)}$$

$$a_1 = \frac{N\sum xy - (\sum x).(\sum y)}{N\sum x^2 - (\sum x)^2} \tag{3.70(b)}$$

Table 3. 14 Results of the analysis

Year	Peak demand (kw)	x_i	$pDi = \frac{\text{Peak demand}}{10}$	Y_i = InpDi	$x_i y_i$	x_i^2
2017	260	-2	26.0	3.25809	-6.51618	4
2018	273	-1	27.3	3.30689	-3.30689	1
2019	286.65	0	28.665	3.35568	0	0
2020	30098	1	30.098	3.40446	3.40446	1
2021	316.03	2	31.603	3.45325	6.9065	4
		$\sum x_i = 0$		$\sum y_i = 16.7784$	$\sum x_i y_i = 0.4879$	$\sum x_i^2 = 10$

a_0	a_1	x_i
3.35568	0.04879	5

Finally, the values in Table 3.14 are used to determine the load of the selected area in 2027 G.C. The forecasting is then done using equation 3.71 (a) and (b) shown below by considering 2017 as a reference year. Therefore, the load is obtained to be 365.85kWh/day.

$$Y = a_0 + a_1 . x_i \quad (3.71(a))$$

$$E_n = 10e^Y \quad (3.71(b))$$

3.9 Hybrid System Designing and Sizing

3.9.1 Design Methodology

In this thesis the main system design methods based on the daily energy demand assessment of Tikishign village that is the peak load of 49 kw/day and total energy of 260kwh/day were estimated. The work also dealt with the sizing and specifying of PV array, wind energy blade radius, Battery bank, and converter.

3.9.2 Designing and Sizing of Solar PV

Based on the above data about 48% of the system at peak time the total power supplied by solar PV to the cluster of villages is 23.52 kw, neglecting losses in the energy and delivery system. The design requirement was thus for a PV system delivering 400 Vac (V_{rms}) three-phase.

Selection of PV module to be used

Module type: Solar Liberty SLX-320 watt

Number of cells per module: 72

Lifetime: 90% power output over 20 year, 80% power output over 30 year

PV Control

Derating factor	95%
Tracking system	No Tracking
Slope	4 - 13 deg
Azimuth	0 deg
Ground reflectance	20%

Specifications of considered PV system under standard test condition (STC):

V_{oc} = 49.7 V

I_{sc} = 54.58 A

Voltage (V_{mp}) = 43.2 V

Current (I_{mp}) = 49.43 A

Module parameters for one module

R_p = 993.51 Ω

T_{sat} =1.1753 e^{-8}°C

I_{ph} = 5.9602 A

Q_d = 1.3 J/S

PV system design for 23.52kw at 49 kWp, the calculation of the number of modules

$$\text{Total number of panels } = \frac{\text{peak power}}{\text{rating per panel}} = \frac{23520 \text{ watt}}{320 \text{ wa}tt} = 73.5$$

0.5 fractional panels are not possible so panels rounded up to 74

Therefore, total number of panels = 74

3.9.3 Designing and Sizing of Wind Turbine Power Rating

Based on the given data above 52% of daily energy requirement of a village supplied by wind energy is 135.2 KWh/day, calculate the size of wind turbine i.e required to be installed to meet the energy requirement. The parameters were given below which determine wind energy:

- ✓ Daily energy requirement – 135.2 KWh/day
- ✓ Propeller type wind machine is used
- ✓ Coefficient of performance – 0.40
- ✓ Annual average wind speed (m/s) at 10m, V_{ave}(m/s) = 7.09 m/s (if the turbine hub is placed at the height other than 10meter, the wind speed should be estimated as shown in ‘vertical’ wind speed variation section).

- ✓ Density of air, $\rho = 1.22 kg/m^3$
- ✓ Capacity factor – 0.30 (i.e. 30% of the time, wind machine is producing energy at rated power)
- ✓ Number of hours in a day 24hours.

The power density of wind (power per unit area)

$$= \frac{P}{A} = \frac{1}{2}\rho v^3 = 0.5 * 1.22 * (7.09)^3 = 217.405 w/m^2$$

Actual power density that will be converted to useful energy = Cp * transmission loss * generator loss

Considering losses: Coefficient of performance C_p = 0.40, Transmission losses (rotor to generator) = 0.90, Generator losses = 0.90

Overall loss factor = 0.40 * 0.90 * 0.90 = 0.324

Actual power density = power density of wind * Overall loss factor

= 217.405 * 0.324 = 70.44 W/m^2

Daily energy density (useful) = Actual power density * number of hours per day

= 70.44 * 24 = 1.69 kWh/m^2

The rotor size and turbine power rating equation:

$$A = \frac{\text{Total daily energy required}}{\text{Useful energy density}} = \frac{135.2}{1.69} = 80 \ m^2$$

Radius of the rotor blade, (R):

$A = \pi R^2 = 80 \ m^2$

R= 5.05 meter.

Power rating of the turbine = Actual power density * area of the rotor

= 70.44w/m^2 * 80 m^2 = 5.64 kw

Actual rated power of the turbine rating should be = power rating / capacity factor

= 5.64 kw/0.30 = 18.8 kw ~ 19KW

Therefore, around 19KW rated power wind turbine were provide for the desired daily energy under the given situation.

3.9.4 Battery sizing and specifying

The final battery capacity will depend on the following:

1. The total energy that the battery bank must supply to loads.
2. Maximum power demand
3. Maximum depth of discharge

4. System voltage

5. Charge current and recharge time.

Determining the required battery capacity.- Batteries used in all solar systems are sized in Ah under STCs (Temperature: 25^0C). Battery manufactures usually specify the maximum allowable DOD for their batteries. The DOD is a measure of how much of the total battery capacity has been consumed. For most batteries, the maximum allowable DOD is about 60%. Based on the above equation the net capacity that the battery can store in Ah/day must be:

$$BC_n = \frac{E_{Tot}}{V_{nom,batt}} = \frac{260\ kwh/day}{48V_{DC}} = 5416.667 Ah/day$$

The net capacity of the battery depends on the DOD of the battery and the DOD determines the life cycle of the battery. Deep cycle lead acid battery can store 40% to 90% depth taking an assumption of DOD = 60% then total commercial capacity of the battery is calculated as:

$$BC = \frac{BC_n}{DOD} = \frac{5416.667}{0.6} = 9027.778\ Ah/day$$

Considering, the battery must be at least three times big because of cloudy days, shadows, etc on solar PV and also low speed on wind case.

Therefore, BC = 9027.778 Ah/day * 3 = 27083.334 Ah/day. Hence, the capacity of the battery is taken as 30,000Ah. And also Selected Battery Ah Rating = 1900Ah. To calculate the number of batteries connected in parallel to reach the Ahs required by the system.

$$B_P = \frac{B_c}{B_R} = \frac{30{,}000}{1900} = 15.78 \sim 16 \text{ batteries}$$

And also calculate the number of batteries to be connected in series to reach the voltage required by the system.

$$B_S = \frac{V_{nbatt}}{V_{batt}} = \frac{48}{4} = 12 \text{ batteries}$$

Total number of batteries required by the system is B_P*B_S =16*12=192 batteries

3.9.5 Charge Controller Sizing and Specifying

The solar charge controller is typically rated against amperage and voltage capacity. The size of the controller depends on the total PV input current which is delivered to the controller and PV panel configuration.

$$\text{solar charge controller rating} = I_{sc} * \text{Total number of modules} * 1.3$$

= 9.58 * 66 *1.3 = 821.964A ~ 1000A

3.9.6 Converter Sizing and Specifying

Based on the above equation maximum power of ac loads supplied by the system = 49kW.
Converter size = maximum Power of Ac loads * 1.3 (oversize factor)
Converter size (kW) = 49 * 1.3 = 63.7kW
Available converter size were 100, 150, 200, 250kW. The chosen converter size for this thesis was a capacity of 100kW and the full load efficiency were greater than 90%.

3.10 Homer Software and Fuzzy Logic Controller

3.10.1 Overview of HOMER Software

Hybrid **O**ptimization **M**odel for **E**lectric **R**enewable (HOMER), is the micro power optimization model, simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. In designing power systems different decisions can be made about the configuration of the system, such as; what components to include in the system, the size and the quantity of the components and the cost of each components.
Incorrect power system design can lead to shorter life of battery, increase cost of energy production, insufficient supply of electricity demand. HOMER is a computer model developed originally by the National Renewable Energy Laboratory (NREL). It has different energy generating components in its library. The user must select the components from the library to represent the architecture considered. HOMER simplifies or helps the designer to compare various power systems options based on technical and economic aspects.

3.10.2 Modeling of Hybrid System with HOMER

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 was designed to overcome this uncertainty and also the complexity of the renewable energies being intermittent, seasonal, non-dispatchable and having uncertain availability.
The design of off-grid PV/wind with storage battery hybrid energy system to a community of 720 households, with average five members per family was carried out based on the theoretical background discussed so far. HOMER software is used as a tool to accomplish the thesis. As earlier, the main objective of the thesis was to design and model hybrid

PV/wind with storage battery based off-grid power generation systems to meet the load requirements of the community specified. A schematic representation of the off-grid hybrid energy system by HOMER is shown below in Figure 3.2 based on the previous mathematical design.

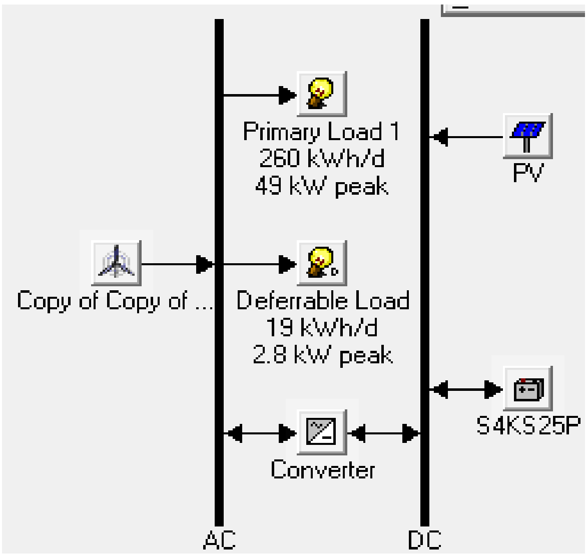


Figure 3. 2 HOMER diagram for the hybrid PV/wind/battery-converter set-up

Based on the above primary and deferrable load estimation of the village the HOMER optimization model diagram is given as follows respectively.

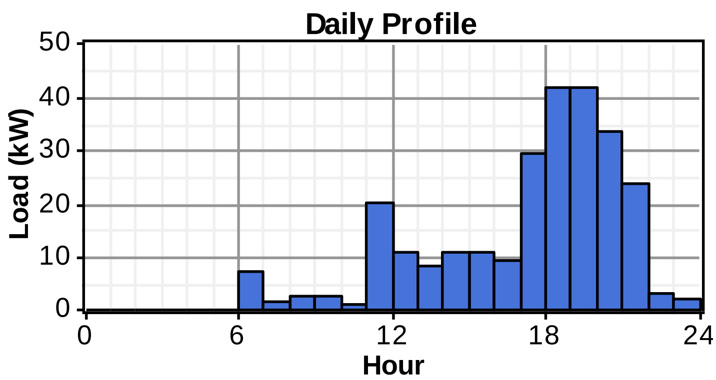


Figure 3. 3 Daily Primary Load

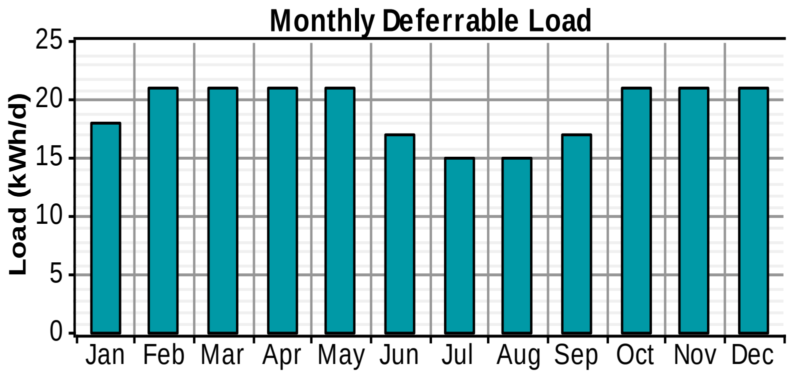


Figure 3. 4 Monthly Deferrable Load Profile

HOMER does three main tasks as indicated in Figure 3.5:

Simulation. - It compares the energy supply from the system and the load demand in 1 hour, of the 8,760 hours. During this time, it decides either to use load following or dispatch strategy to operate batteries and solar PV or wind power. For a system that contains battery, solar PV and wind power requires having dispatch strategy. Dispatch strategies are two types, load following and cycle charging strategies.

Optimization. - In this process, it simulates each different system configurations in search of the lowest NPC and lists each power systems that meet the load demand. The purpose of optimization is to determine the optimal system based on the decision variables imposed by the designer.

Decision variable is a variable that has control by the designer. HOMERs decision variables may include like; PV array size, wind turbine size, size of converter, quantity of batteries, dispatch strategy, and etc. Searching the optimal system includes deciding the mix of power components like size, quantity at the same time the dispatch strategy.

Sensitivity Analysis. - It examines the effect of external parameters and does optimization for each sensitivity variables. But first defining the variables that can affect the system over its entire life is mandatory to input into the software. The optimization process is repeated after specifying the sensitive parametric variables as an input in to the software. The sensitivity variables can be climatic data variations, components and fuel cost, interest rate, capacity shortages, operating reserves and others. HOMER does multiple optimizations using various sensitive inputs to see how sensitive output of the power system. The sensitivity results from HOMER are displayed in tabular and graphical forms.

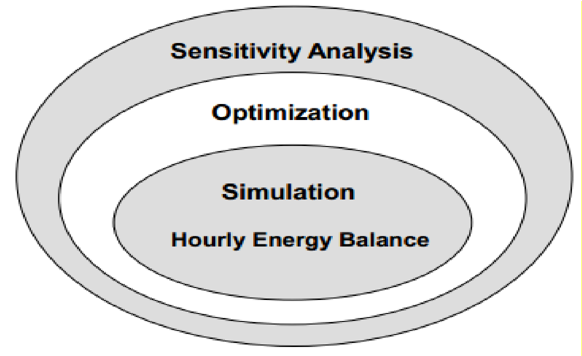


Figure 3. 5 Interactions between Simulation, Optimization and Sensitivity Analysis [8]

3.11 Fuzzy Logic Control System

3.11.1 Fuzzy Inference Systems in MATLAB Tool Box

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules. There are two types of fuzzy inference systems that can be implemented in the MATLAB Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined. The most commonly used fuzzy inference technique is the so-called Mamdani method. In 1975, Professor **Ebrahim Mamdani** of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators.

In MATLAB fuzzy logic toolbox, there are five parts of the fuzzy inference process [35]:

***Fuzzification of the input variables*. -** The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. The input is always a crisp numerical value limited to the universe of discourse of the input variable and the output is a fuzzy degree of membership (always interval between 0 and 1).

***Application of the fuzzy operator (AND or OR) in the antecedent*. -** If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. Any number of well-defined methods can fill in for the AND operation or the OR operation. In fuzzy logic toolbox, two built -in **AND** methods are supported: min (minimum) and prod (product). Two built-in **OR** methods are also supported: max (maximum), and the probabilistic OR method prober.

***Implication from the antecedent to the consequent*. -** The implication method is defined as the shaping of the consequent (a fuzzy set) based on the antecedent (a single number). The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication occurs for each rule. Two built-in methods are supported, min which truncates the output fuzzy set, and prod (product) which scales the output fuzzy set.
***Aggregation of the consequents across the rules*. -** Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set.
***Defuzzification*. -** Input for defuzzification phase is unified fuzzy set formed by aggregation of consequents and output is crisp number. If there are more than one output variables, final output for each variable is a crisp number.
The most popular defuzzification method is the centroid calculation, which returns the center of area under the curve. There are five built-in methods supported: centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum.

3.11.2 Modeling of Fuzzy Logic Controller

Fuzzy logic is a derivative from classical Boolean logic and implements soft linguistic variables on a continuous range of truth values to be defined between conventional binary i.e. [0, 1]. It can often be considered a subset of conventional set theory. The fuzzy logic is capable to handle approximate information in a systematic way and it is suited for controlling non-linear systems and for modeling complex systems where an inexact model exists or systems where ambiguity or vagueness is common. It is advantageous to use fuzzy logic in controller design due to the following reasons.
It is simpler and faster methodology, reduces the design development cycle, simplifies design complexity, an alternative solution to non-linear control, improves the control performance, Simple to implement, Reduces hardware cost and so on.
A typical fuzzy system consists of a rule base, membership functions and an inference procedure which are explained in the following sections.
The fuzzy control systems are rule-based systems in which a set of fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimuli. With an effective rule base, the fuzzy control systems can replace a skilled human operator. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. This type of control, approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision and fuzziness in

the decision-making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system, just by incorporating the experts' knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations).

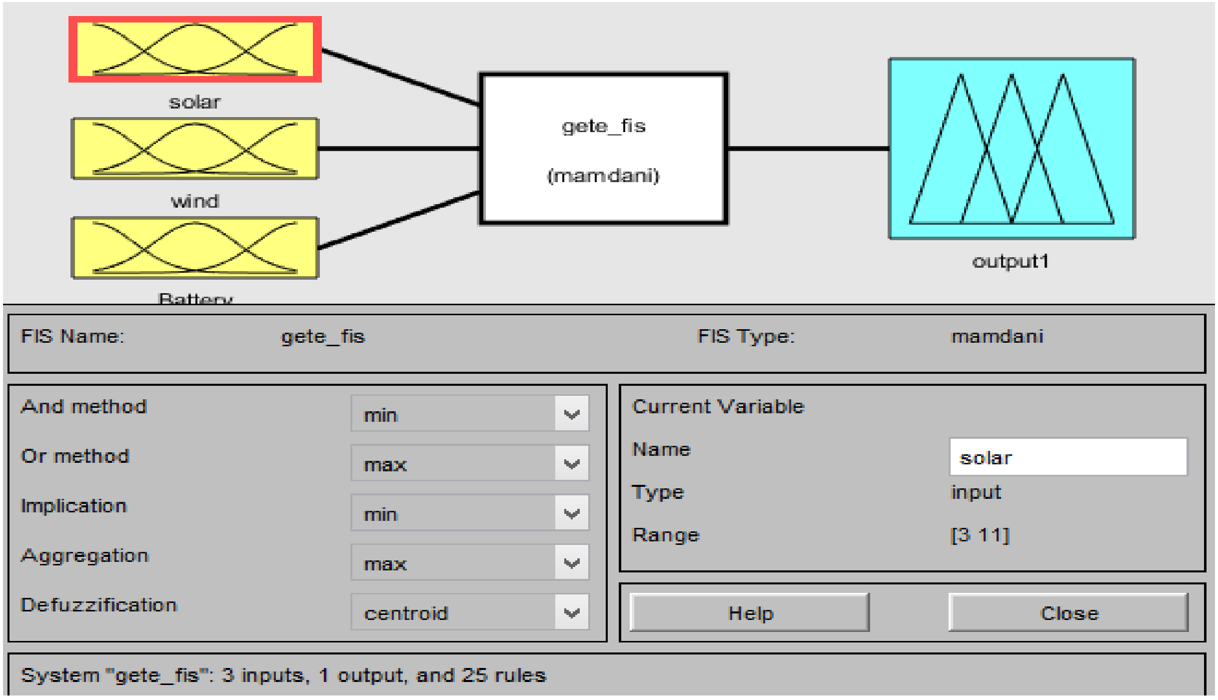


Figure 3. 6 Fuzzy models

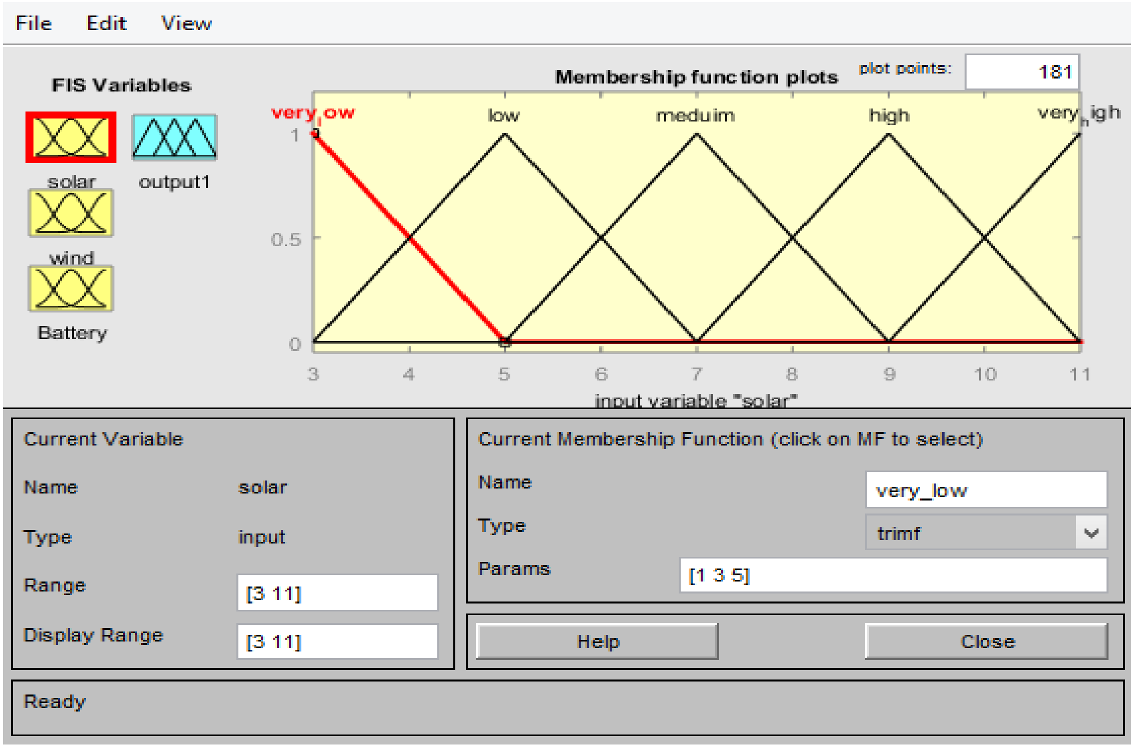


Figure 3. 7 Fuzzy logic membership function for solar input

3.11.3 Modeling of Fuzzy Logic Control Rules

Here is the model of fuzzy logic control having three inputs and one output. In the control box, a set of rules have been written. The system will operate in accordance to the rules set. The following Figure 3.8 shows the fuzzy logic rules and operation of the system in different operating conditions.

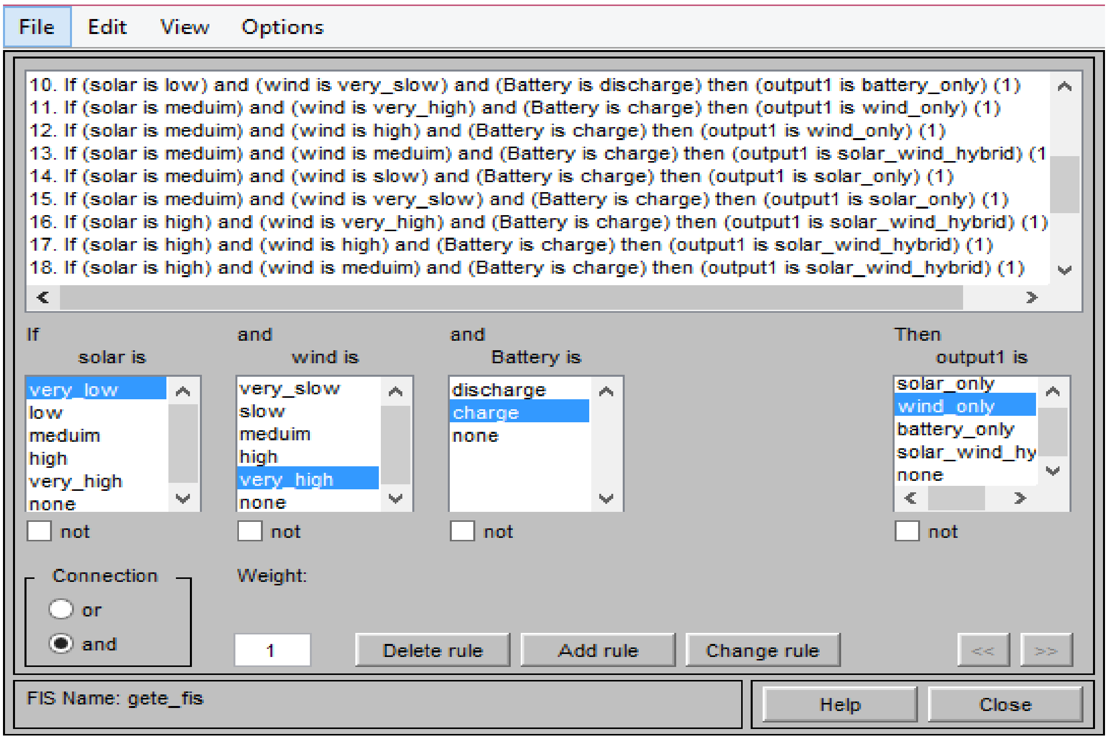


Figure 3. 8 Fuzzy logic rules

3.11.4 Overall Fuzzy Logic Control System

The overall fuzzy logic system consists of the PV system, wind turbine and storage battery bank. The separately modeled and simulated PV system, wind turbine and storage battery bank are the input parameters. According to the available energy resource, one or more of these resources will be subjected to supply the power. Hence in Figure 3.8, solar indicate the output from solar energy, wind indicates electric energy from the wind and storage battery bank indicates the battery energy that is stored during high renewable energy generation, minimum load and discharge during low generation of renewable energy. The multiport conditional switch will take an action according to the rules written in fuzzy logic control.

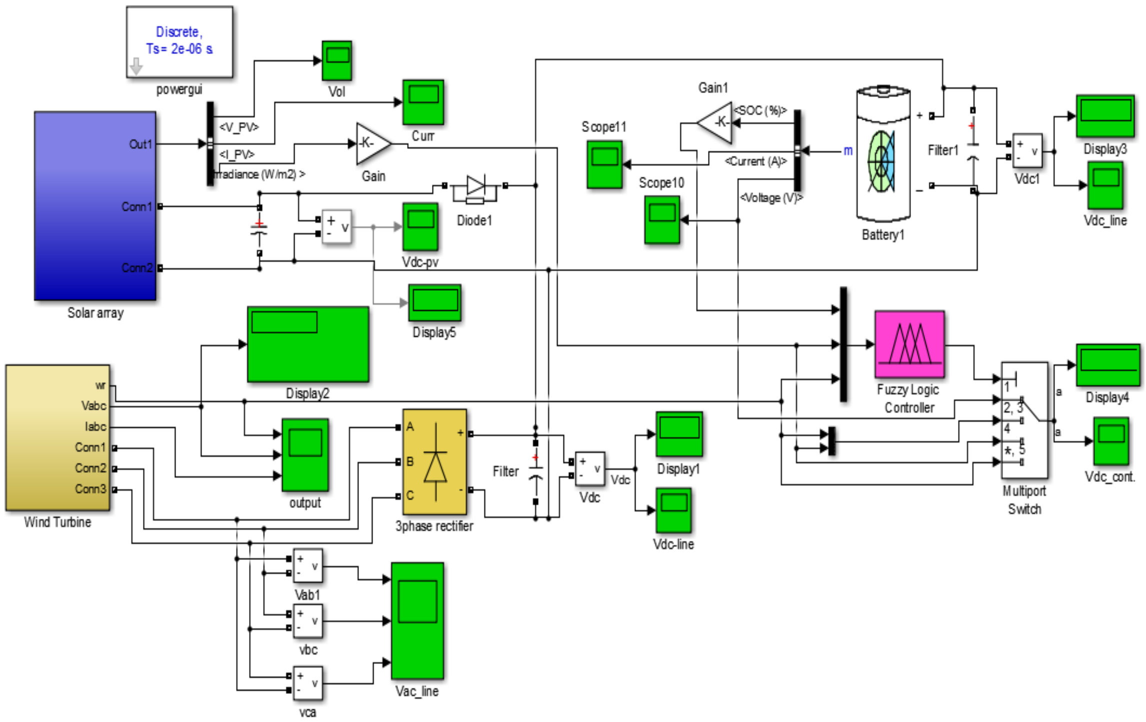


Figure 3. 9 Overall Fuzzy Logic Control System

SimPower systems library is a library which consists of power system equipment's. In the following MATLAB model, the separately modeled solar PV system, wind turbine, storage battery bank and inverter system were given below as follows.

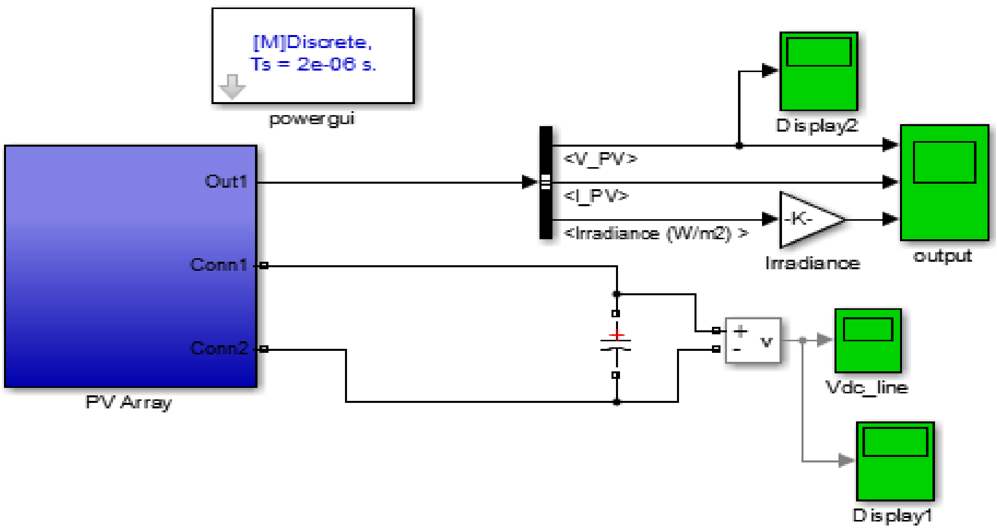


Figure 3. 10 MATLAB Simulink model of solar PV system

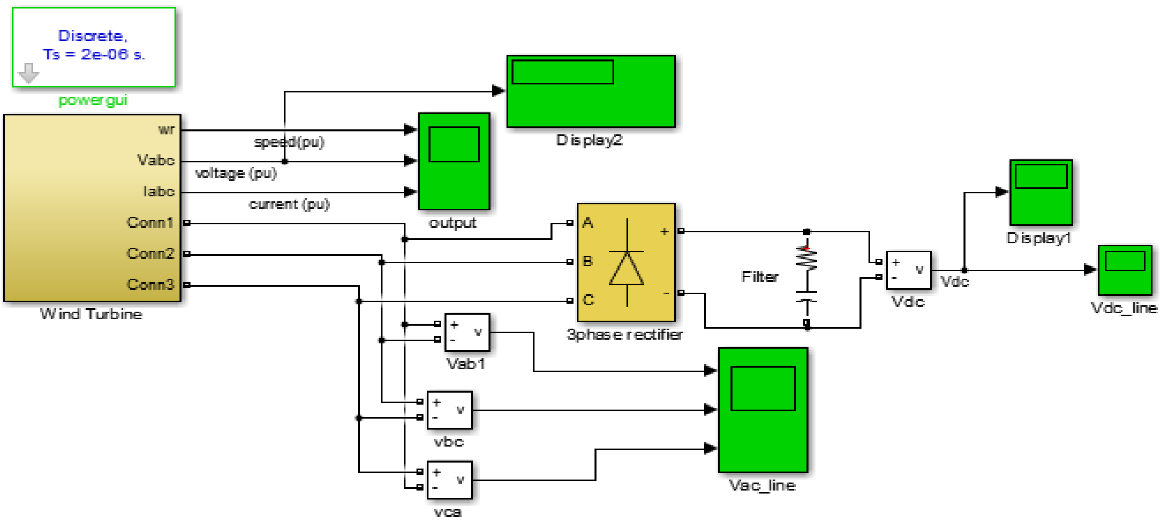


Figure 3. 11 MATLAB Simulink model of wind turbine system

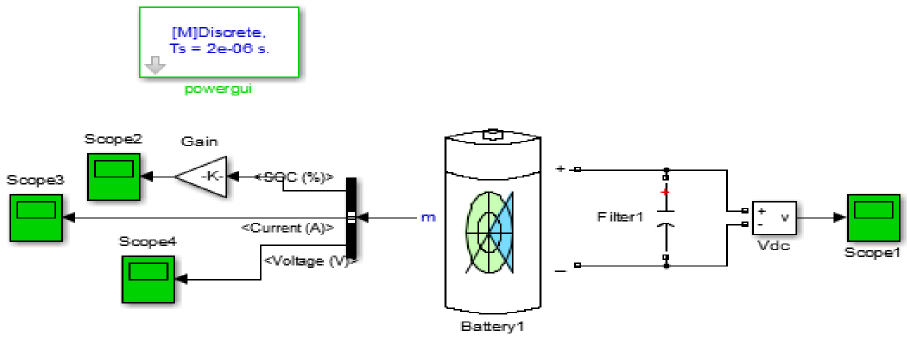


Figure 3. 12 MATLAB Simulink model of battery bank storage system

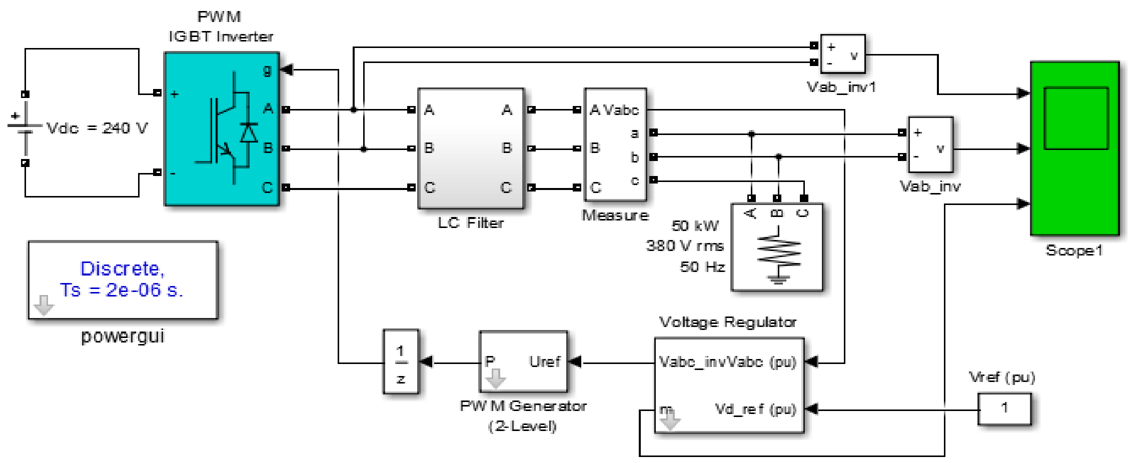


Figure 3. 13 MATLAB Simulink models of inverter

CHAPTER FOUR

RESULT AND DESCUSSION

4.1 Result

The optimal hybrid system is the one which can supply electricity needs at the lowest price or in other words, the system which is having the lowest total net present value, while supplying the electricity at the required level of availability. In this chapter the results of the feasibility of a **PV/Wind/Storage** battery hybrid power system is presented and discuss the results obtained from the HOMER simulations and the selection of the optimal system based on the simulation results. The chapter also discusses the performance of the optimal hybrid system, hybrid system design, economic viability of the thesis and a brief introduction to the energy management in the off-grid system. The main objective of this thesis was to model and design an optimized off-grid solar PV/Wind/storage battery hybrid power system with energy management to investigate alternative power supply option for rural area/village (**Tikishign)** detached from the main grid system. Then this input parameter used to generate simulation result using HOMER Software. Through the simulation work, **three different** scenarios are considered to increase the probability of finding the best energy system components. From the generated simulation results the combination of components which costs less (minimum total NPC and less COE) is considered as selected energy system for each scenario analysis. Then, finally from different scenario analysis, still the least cost scenario is considered as the best energy system by comparing scenarios with the same design parameter.

4.1.1 Optimization Results

During optimization all possible hybrid system configurations are listed in ascending order according to their total NPC. The best possible combination of solar PV/Wind/Batteries and Convertor is in the first row of the simulation results were able to fully meet **the village** load demands at the lowest cost, and the next best possible combination, is in the second row of the simulation results, includes the solar PV/Wind/Batteries and Converter. The simulation software provides the results in terms of optimal systems and the sensitivity analysis. The optimal system configuration for the first case study were mean output power of 23kW solar PV, 24kW Wind, 80 S4KS25P batteries and 100 kW Converter with a dispatch strategy of load following.

As indicated above in Figure 3.3 of the daily primary load profile of the village, the maximum load demand will cover between 18hr to 21hr which is around **41kW**. But this power is changed to **49kW** due the random variability of 3% for days to day and 5%-time step to time step as to be more realistic load demand growth. As it has been discussed in the preceding chapter three that the Solar PV and Wind turbine operate most efficiently when working near its full load.

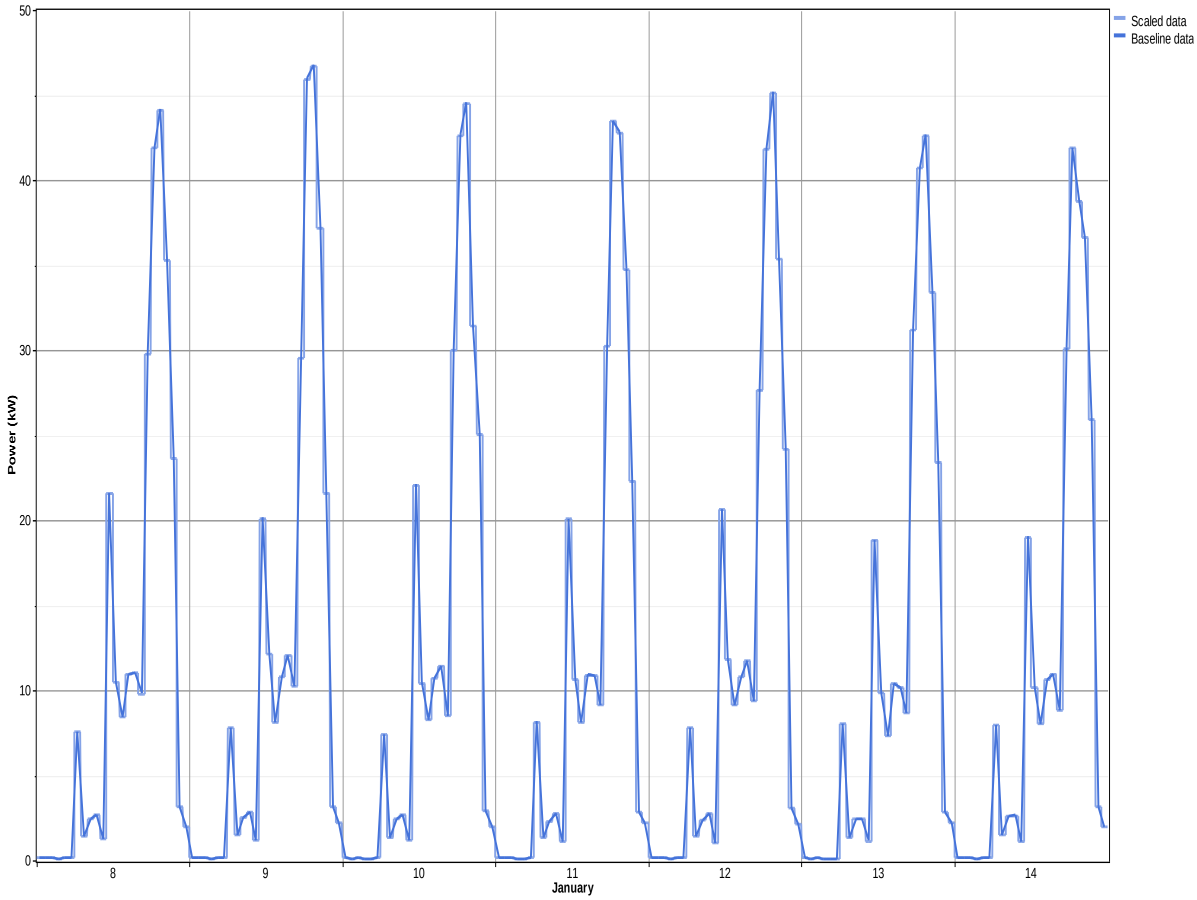


Figure 4. 1 Hourly load plot of the first month

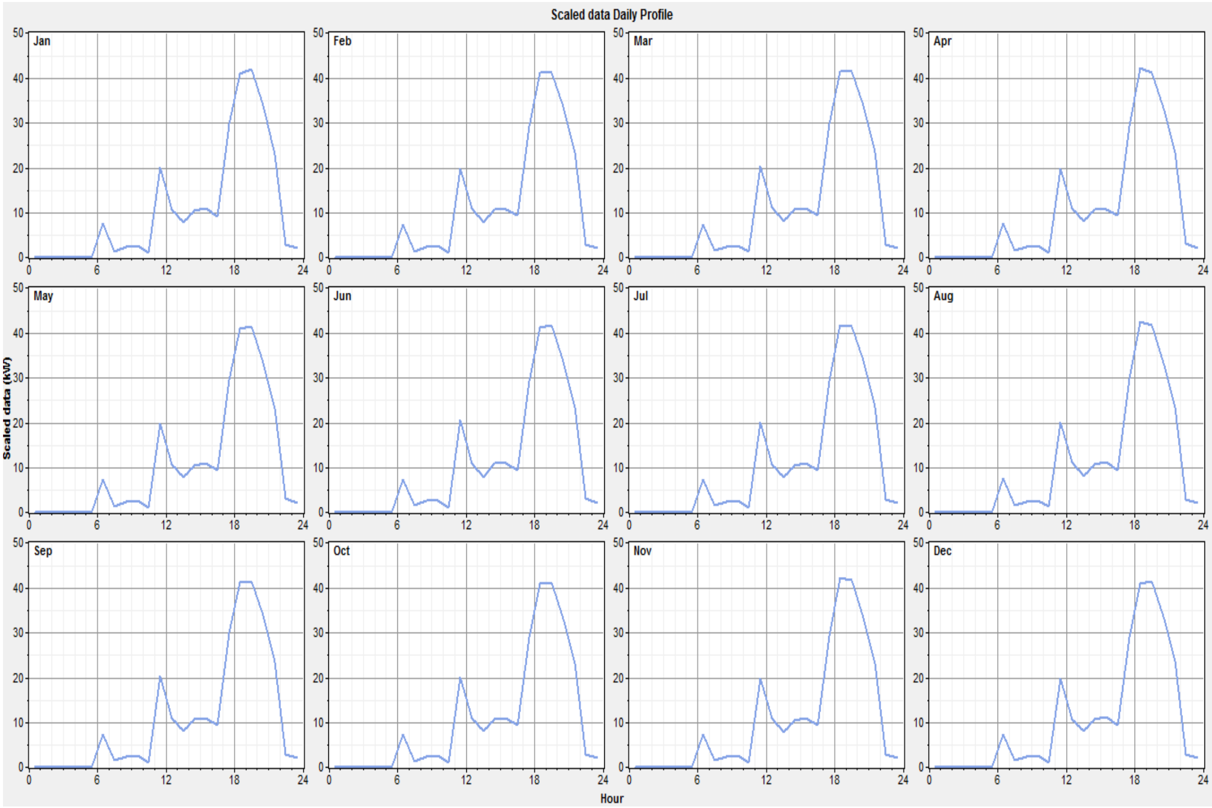


Figure 4. 2 Daily profile of Load (kw) vs hour (hrs) of each month

This system is considered 5.013kwh/m^2/day of average solar radiation for the solar PV and average wind speed of 5.45 m/s at 10 meter height. The total NPC, capital cost, operating cost and levelized COE for the given hybrid system are $138,848, $128,499, $1,213/year and $0.160/kWh, respectively.

The software displays the result for the inputs in either an overall form in which the top ranked system configurations are listed according to their NPC or in categorized form in which only the most cost effective configuration is considered from each system type.

Double click on a system below for simulation results. ◉ Categorized ○ Overall

PV (kW)	E33	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
95	1	80	100	$ 128,499	1,213	$ 138,848	0.160	1.00
	3	130	165	$ 137,910	1,140	$ 147,630	0.170	1.00

Figure 4. 3 Categorized simulation results of least cost-effective scenarios.

The overall optimization results below in Figure 4.4 shows that the total NPC increases from the first row to the last row. Because of the increment of total NPC, the first row is only the most cost-effective configuration for hybrid renewable energy generation. In addition to this the initial capital cost also increases from top to bottom when looking in the given figure.

Double click on a system below for simulation results. ◯ Categorized ◉ Overall

PV (kW)	E33	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
95	1	80	100	$ 128,499	1,213	$ 138,848	0.160	1.00
100	1	80	100	$ 128,580	1,212	$ 138,920	0.160	1.00
95	1	80	105	$ 128,609	1,212	$ 138,945	0.160	1.00
105	1	80	100	$ 128,661	1,211	$ 138,992	0.160	1.00
100	1	80	105	$ 128,690	1,211	$ 139,017	0.160	1.00
80	2	70	130	$ 128,776	1,201	$ 139,017	0.160	1.00
95	1	80	110	$ 128,719	1,210	$ 139,042	0.160	1.00
75	2	70	135	$ 128,805	1,200	$ 139,043	0.160	1.00
105	1	80	105	$ 128,771	1,210	$ 139,089	0.160	1.00
85	2	70	130	$ 128,857	1,200	$ 139,089	0.160	1.00
100	1	80	110	$ 128,800	1,209	$ 139,114	0.160	1.00
80	2	70	135	$ 128,886	1,199	$ 139,114	0.160	1.00
95	1	80	115	$ 128,829	1,209	$ 139,139	0.160	1.00
75	2	70	140	$ 128,915	1,199	$ 139,139	0.160	1.00
90	2	70	130	$ 128,938	1,198	$ 139,161	0.160	1.00
105	1	80	110	$ 128,881	1,208	$ 139,186	0.160	1.00
85	2	70	135	$ 128,967	1,198	$ 139,186	0.160	1.00
100	1	80	115	$ 128,910	1,208	$ 139,211	0.160	1.00
80	2	70	140	$ 128,996	1,198	$ 139,211	0.160	1.00
95	2	70	130	$ 129,019	1,197	$ 139,232	0.160	1.00
95	1	80	120	$ 128,939	1,207	$ 139,236	0.160	1.00
75	2	70	145	$ 129,025	1,197	$ 139,236	0.160	1.00
90	2	70	135	$ 129,048	1,197	$ 139,258	0.160	1.00
105	1	80	115	$ 128,991	1,206	$ 139,282	0.160	1.00
85	2	70	140	$ 129,077	1,196	$ 139,283	0.160	1.00
100	2	70	130	$ 129,100	1,196	$ 139,304	0.160	1.00
100	1	80	120	$ 129,020	1,206	$ 139,308	0.160	1.00
80	2	70	145	$ 129,106	1,196	$ 139,308	0.160	1.00
95	2	70	135	$ 129,129	1,196	$ 139,329	0.160	1.00

Figure 4. 4 Overall optimization results

4.1.2 Optimization Analysis of the Selected Scenario

The categorized optimization results summarized in Figure 4.3 above depicts the results from HOMER modeling for Tikishign village. The modeling simulates one year of operation and thousands of different system configurations. The system with the overall least cost of energy is the one highest on the list. The first four columns of the HOMER results in Figure 4.4 show graphic icons representing which components are present in the optimized system. The remaining columns show the optimized capacity of each component, the initial capital cost, the total NPC, the COE (in $ per kWh) and renewable energy fraction.

Based on the HOMER modeling, the optimal system for **Tikishign** village in categorized optimization results a first row, shows a hybrid solar PV/wind/battery, with mean output power of 23kW solar PV, 24.3kW wind power, 80 S4KS25P batteries (each of 1900Ah capacity) and 100kW bi-directional convertor (100kW rectifier, 100kW invertor) are required power supplied for the selected village. This "optimal" system uses 100% renewable energy and the COE is $0.160/kWh.

The system set-up in the first row of Figure 4.3 is the cost-efficient system composed of mean power output of 23kW PV panel, 24.3kW wind power, 80 S4KS25P batteries, and 100kW convertor. All of the power schemes remain producing electricity throughout the year.

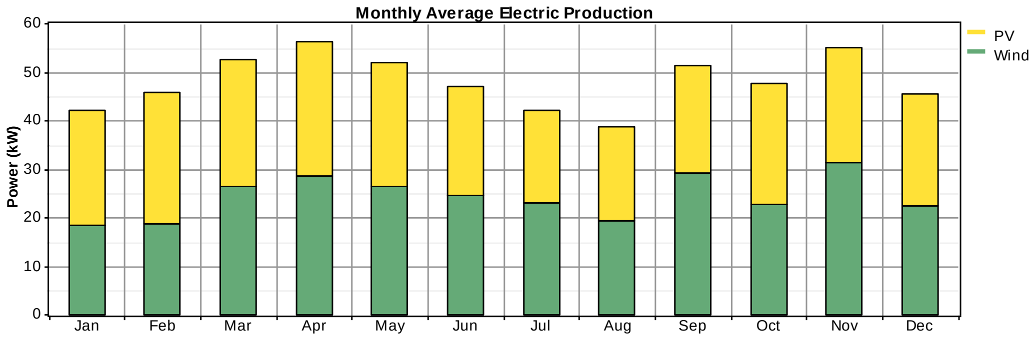


Figure 4. 5 Share of Electricity Generation

The electricity generation by individual power units of the hybrid system and consumptions by AC primary and deferrable load are given in Figure 4.5 PV array power production accounts for 48% (197,533kWh/year) whereas wind power generation covered 52% (212,853kWh/year) of total electricity produced by the hybrid scheme.

The total power generation of this power system setup were 410,386kWh/year (100%), whereas the total electric power consumption of the AC load was about 94,886kWh/year i.e 93% of the electricity consumed by AC load and the consumption of deferrable load 6,963kWh/year i.e 7% were consumed by deferrable load. In addition to this an excess electricity of 70.1%, a capacity shortage of (4.5%) and unmet electric load of (0.0%) were experienced during the year**.**

Actually, this power system architecture indicates that excess electricity would enable to supply the demand growth of the community in the future. In addition to this, excess electricity could provide to neighboring villages or introduce small businesses to increase the load factor of the power system; consequently, the cost of electricity will also decrease.

Similarly, the system set-up in the second row of Figure 4.4 is the cost-efficient system composed mean output power of 24kW PV panel, 24.3kW wind power, 80 S4KS25P batteries, and 100kW convertor. All of the power schemes remain producing electricity throughout the year.

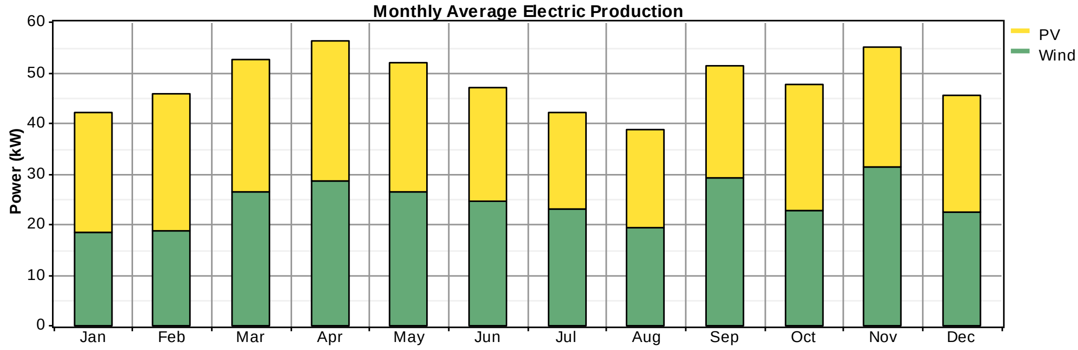


Figure 4. 6 Share of Electricity Generation

The electricity generation by individual power units of the hybrid system and consumptions by AC primary and deferrable load are given in Figure 4.6 PV array power production accounts for 49% (207,931kWh/year) whereas wind power generation covered 51% (212,853kWh/year) of total electricity produced by the hybrid scheme.

The total power generation of this power system setup were 420,784kWh/year, whereas the total electric power consumption of the AC load was about 94,886kWh/year i.e 93% of the electricity consumed by AC load and the consumption of deferrable load 6,963kWh/year i.e 7% were consumed by deferrable load. In addition to this an excess electricity of 70.8%, a capacity shortage of (4.8%) and unmet electric load of (0.0%) were experienced during the year**.**

Similarly, this power system architecture indicates that excess electricity would enable to supply the demand growth of the community in the future. In addition to this, excess electricity could provide to neighboring villages or introduce small businesses to increase the load factor of the power system; consequently, the cost of electricity will also decrease.

System load variation and generation of power from the renewable energy resource such as solar PV were given below in Figure 4.7. The generation capability of the solar PV varies based on the availability of solar irradiation. The Figure 4.7 shows that a solar PV generation in this hybrid power system generates mean power output of 84kW, minimum electrical output of 28kW.

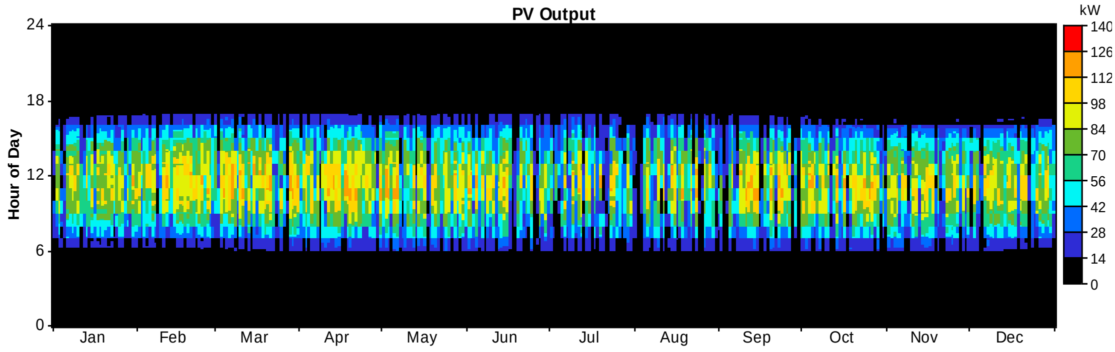
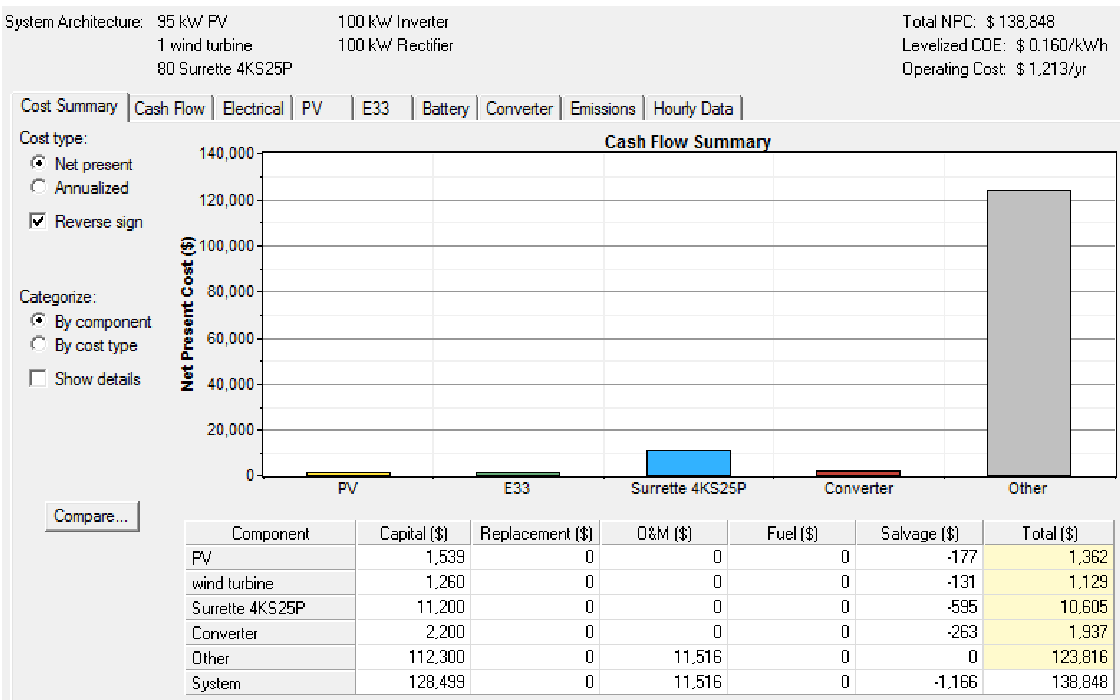


Figure 4. 7 Solar PV Power Productions

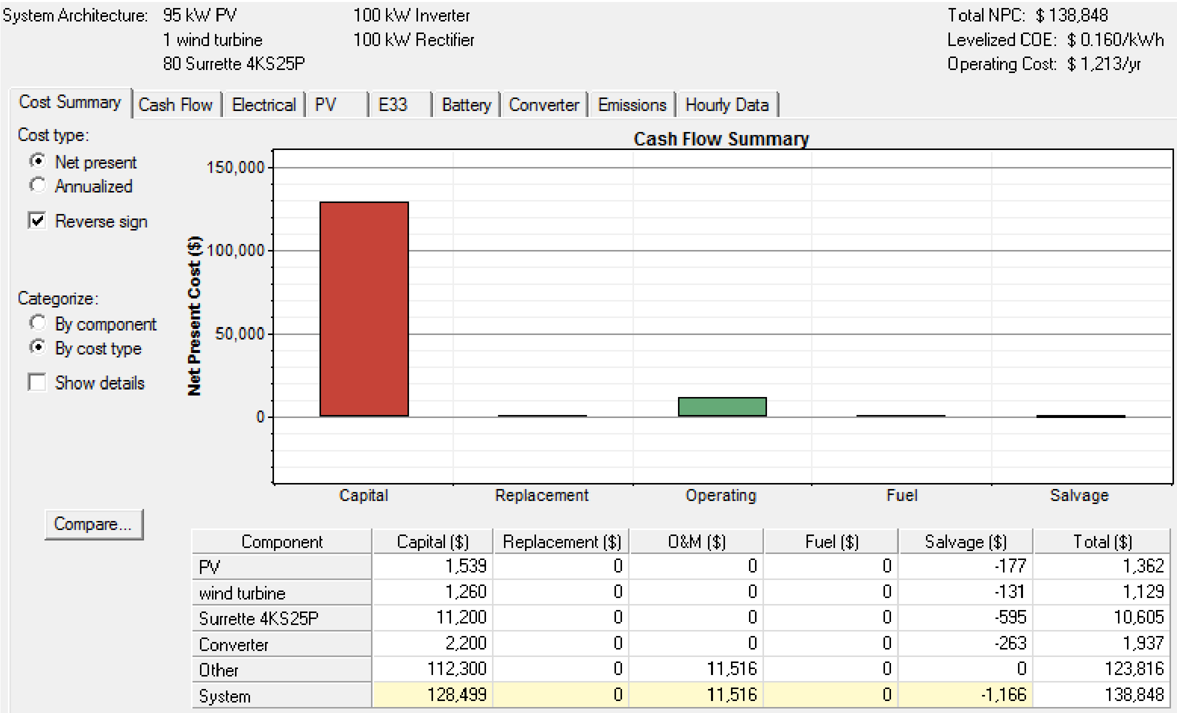
<u>Cost Summary in terms of NPC by Component Type</u>. - The following Figure 4.8 shows that the cost summary in terms of NPC by component type which were the system set-up in the first row of above Figure 4.3. it shows graphical representation of each component and also other required materials NPC ($). In addition to these, it shows table representation of the capital cost ($), replacement cost ($), O & M cost ($), salvage cost ($) and total cost ($) of each component as given below.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,539	0	0	0	-177	1,362
wind turbine	1,260	0	0	0	-131	1,129
Surrette 4KS25P	11,200	0	0	0	-595	10,605
Converter	2,200	0	0	0	-263	1,937
Other	112,300	0	11,516	0	0	123,816
System	128,499	0	11,516	0	-1,166	138,848

Figure 4. 8 Cost Summary in terms of NPC by Component Type

<u>Cost Summary of the System By Cost Type</u>. - The Figure 4.9 below displays cost break down summary of the components with 100% renewable fraction hybrid power scheme. It is clearly seen from the graph the total capital cost, NPC and COE of the optimal configuration of the hybrid system is calculated by the HOMER software to be $128,499, $138,848 and $0.160/kwh respectively.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,539	0	0	0	-177	1,362
wind turbine	1,260	0	0	0	-131	1,129
Surrette 4KS25P	11,200	0	0	0	-595	10,605
Converter	2,200	0	0	0	-263	1,937
Other	112,300	0	11,516	0	0	123,816
System	128,499	0	11,516	0	-1,166	138,848

Figure 4. 9 Cost summary of the system by cost type

4.1.3 Sensitivity Results Consideration

Sensitivity is a measure of how the optimal mix of components changes for any parametric variations in the lifelong of the system. The HOMER software simulates all the systems in their respective search space for each of the sensitivity values. An hourly time series simulation is performed for one complete year.

A feasible system is defined as the hybrid system which meet the required load under certain constraint the software eliminates all infeasible systems and presents the results in ascending order of NPC. In the present case, solar radiation ((6.28, 4.62, 5.12) kwh/m^2/day) and wind speed (5.45, 5.07, 5.57) m/s were given as follows below in Figure 4.10. The optimal system type, line graph, spider graph and surface plot were used to show sensitive results.

Sensitivity Results | Optimization Results

Tabular / Graphic

Export... Details...

Double click on a system below for optimization results.

Solar (kWh/m²/d)	Wind (m/s)		PV (kW)	E33	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
6.280	5.450		95	1	80	100	$ 128,499	1,213	$ 138,848	0.160	1.00
4.620	5.070		95	2	85	130	$ 131,119	1,184	$ 141,221	0.163	1.00
5.120	5.570		105	1	80	100	$ 128,661	1,211	$ 138,992	0.160	1.00

Figure 4. 10 All components of sensitivity results in tabular form

In Figure 4.11 the line graph below shows PV array capacity variations (KW) and wind speed (m/s) is displayed. Considering only two of the sensitivity cases (solar PV power (KW) and wind speed (m/s)) by keeping the other variables as fixed minimum renewable fraction were one), when wind speed varies from 5m/s to 6m/s, PV array capacity (kW) remain constant until wind speed reaches 5.45m/s which is best estimation of wind speed and after the PV array capacity rises from 95kW to 105kW. However, with the rise of PV array capacity and wind speed rises about 6 m/s.

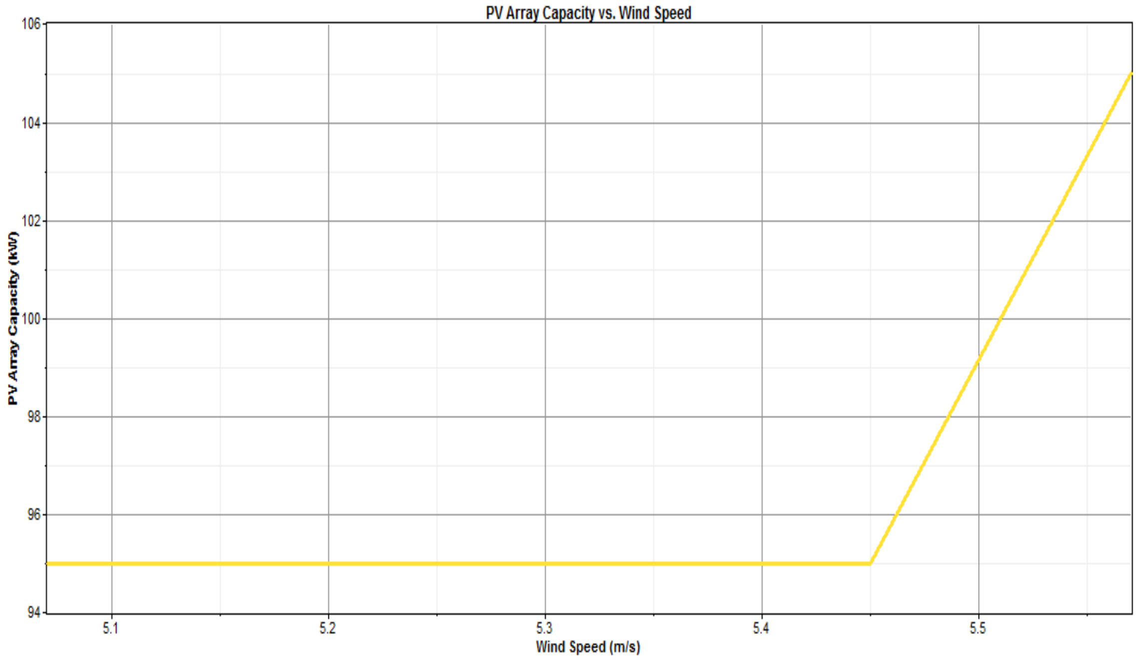


Figure 4. 11 PV array capacity vs. Wind speed

The above Figure 4.11 shows that the sensitivity analysis of sensitive variables given an input to HOMER from the wind speed data (5.45, 5.07, 5.57) m/s that is the best estimate wind speed is 5.45 m/s.

Below Figure 4.12 shows PV array capacity variations (kW), wind speed (m/s) and number of batteries were displayed. Considering three of the sensitivity cases (solar PV power (KW), wind speed (m/s) and number of batteries) by keeping the other variables as fixed minimum), when wind speed varies from 5m/s to 6m/s, PV array capacity (kW) remain constant until wind speed reaches 5.45 m/s which is best estimation of wind speed and after the PV array capacity rises from 95 kW to 105 kW. However, the number of batteries were decreases from 85 to 80 at wind speed equal to 5.45 m/s and remain constant.

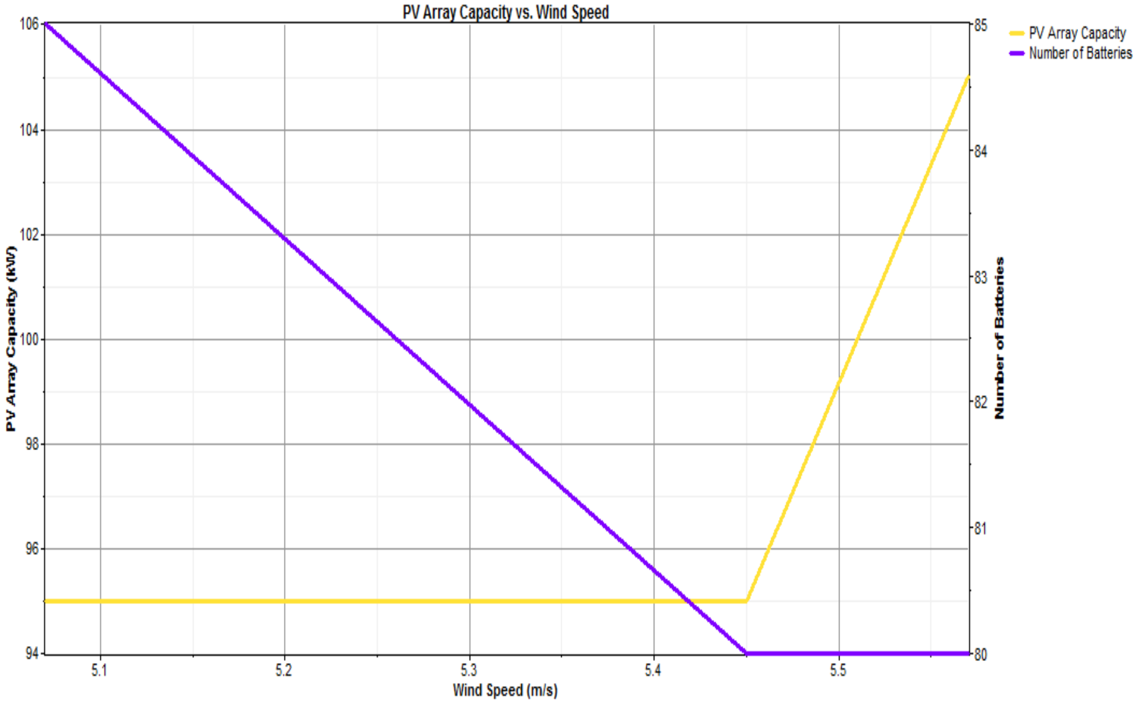


Figure 4. 12 PV array capacity, wind speed vs. number of batteries

The line graph for the number of batteries vs. wind speed with Levelized COE is presented in Figure 4.13 below. The number of batteries decreases from 85 to 80 when the wind speed increases from 5m/s to 5.45m/s in which at this point the number of batteries remain constant. However, levelized COE ($/kwh) decreases from 0.1626$/kwh to that of the optimized value 0.160$/kwh.

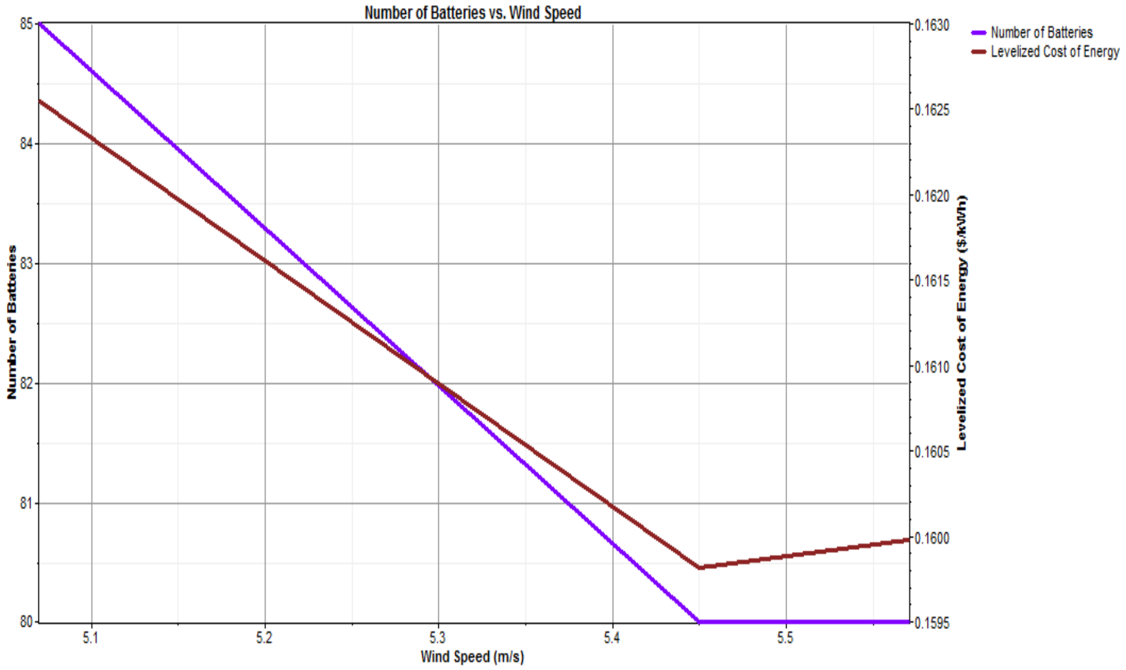


Figure 4. 13 Number of batteries vs. wind speed with Levelized COE

4.2 MATLAB/SIMULINK Simulation Result

The hybrid power generation system consists of PV system, Wind Energy Conversion System (WECS) and BESS. PV system is subjected to variable solar irradiance. WECS is also subjected by variable wind speed. The hybrid system is connected with the load which is also variable. So, these perturbances cause the difference in power supply as well as demand also. To take care of these perturbances fuzzy logic-based controller is used. Also, for getting the maximum output from the wind turbine and PV system their individual controllers are also used to extract maximum voltage.

After integrating with PV generator, Wind generator output such as three phase ac voltage (pu) and three phase ac current (pu) were given below in Figure 4.14.

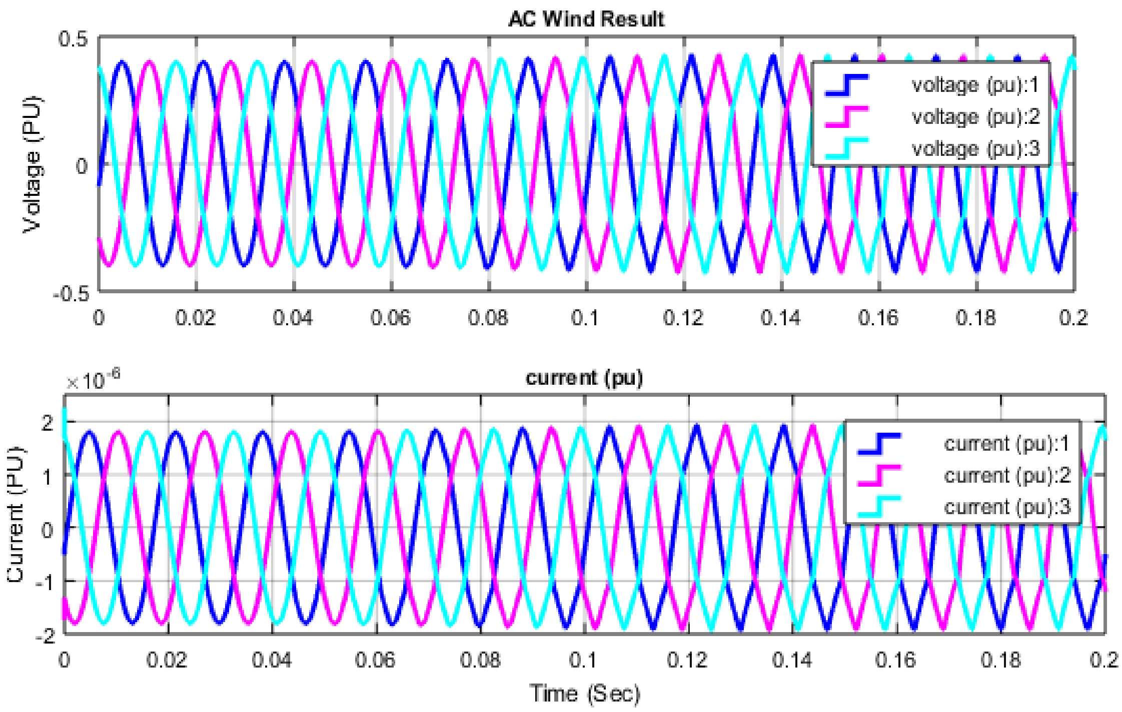


Figure 4. 14 Wind generator ac output when integrating with PV generator

MATLAB Simulation Result of Fuzzy Logic Control. - Since the simulation result depends on the availability of renewable energy resource, different cases have to be considered. For example, During high solar irradiation and low wind speed (During calm and sunny day).

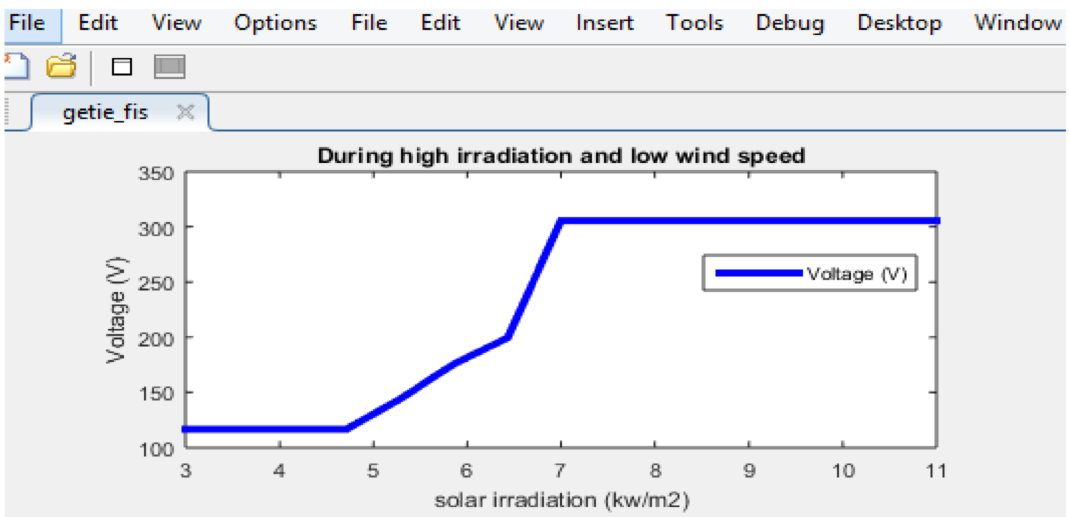


Figure 4. 15 Simulation result during calm and sunny day

During such kinds of days, the potential of solar energy is highly available and low wind energy is available. Hence from the simulation result indicated in Figure 4.15 shows the solar PV system is subjected to generate a DC voltage from the range 120 V to 300 V.
During windy and cloudy day i.e. when the solar energy was not available and wind energy were available.

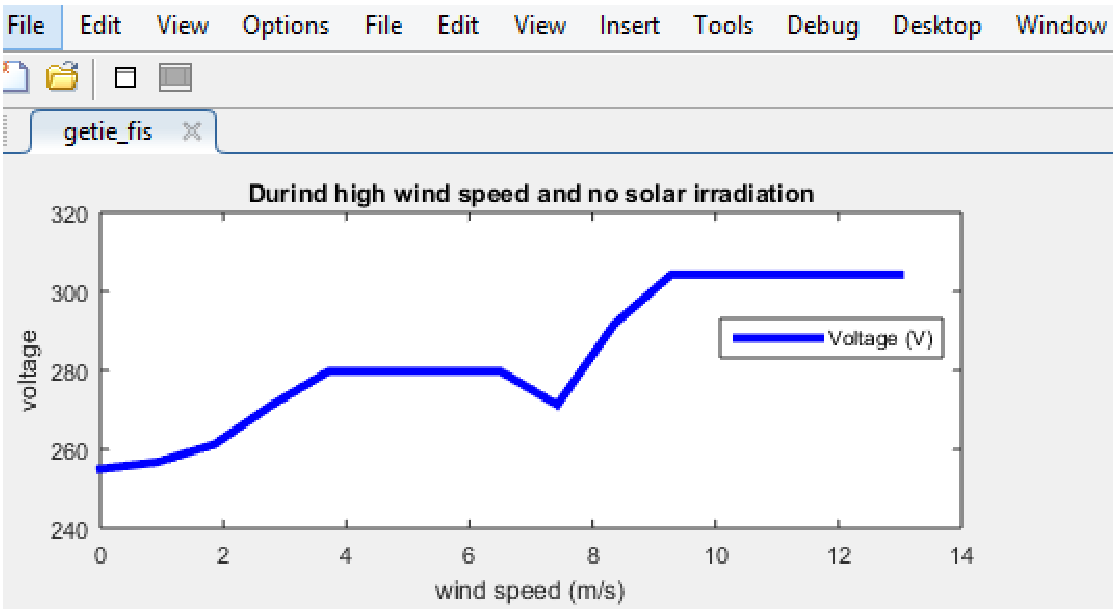


Figure 4. 16 Simulation result during cloudy and windy day

The simulation result indicated in Figure 4.16 above indicates the voltage output during windy day. The result shows that the output voltage was ranges from around 255 V to 305 V. This result shows the output voltage has been a little bit increased when wind speed was increased. Since the wind energy potential were available, wind turbine has been subjected to supply the intended demand.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The crucial objective of this thesis was to find a best techno-economic of an off-grid power system to supply a rural area in Tikishign Village with energy management system. In the design of solar PV/wind turbine and battery bank for Tikishign village, the thesis arrived at 6.28kWh/m^2/day scale annual average or 5.013 kWh/m^2/day average daily solar radiation and 5.45m/s scale annual average wind speed for a household with a total number of 720 households and the total average energy demand was about 260 kWh/day with maximum load of 49 kW.

Off-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium. Consequently, storage battery banks were added to the hybrid system. After selecting the appropriate components and studied their characteristics, the hybrid system has been modelled in HOMER, MATLAB/Simulink software and simulations have been made to determine the best system which can supply the village load with the required level of availability. The usefulness cost of all hybrid structure that can fulfil the continuous load demand has been calculated to determine the system which provides the lowest cost.

A solar PV/wind turbine/battery bank and converter hybrid system has been found as the optimum system with mean power output of 23kw, 24kw, 80 S4KS25P batteries and 100 kw converter respectively.

5.2 Recommendation

Furthermore, investigations need to be carried out to modify this thesis work the following recommendations are given by the author of this thesis.

- This thesis was deal to solve the electricity problem in the Tikishign village found in south Welo zone/Amhara region, Ethiopia. Other may work optimize to this system for rural electrification as well by integrated with micro hydro power and also extend the electrification to another area which were detached from the main grid.
- A major hindrance to use of renewable hybrid energy systems were high initial capital cost. so, the governmental and non-governmental organizations should subside to motivate and increase the interest of the community to use electricity.

- The implementation of hybrid solar PV/Wind turbine/storage battery bank systems in residential, non-governmental and governmental institutions and also commercial areas across Ethiopia would reduce unexpected power interruption, high power loss and blackouts on the national power grid.
- As far as the environmental aspects are concerned, this kind of renewable hybrid systems have to be wide spread in order to cover the energy demands of rural areas and used to apply green energy policy, by reducing the greenhouse gases emission and environmental pollutions were an important point taken to account.

5.3 Future Work

Since the issue of alternative energy source is worldwide and hot issue; a special attention was given to researches related to these areas since last few decades. In related with global warming, an environmental friendly energy source is highly needed. Besides, it can also be implemented and then compared with the simulation results.

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