RESOURCE POTENTIAL ASSESSMENT AND OPTIMAL DESIGN OF PV/WIND/BATTERY/ DEISEL GENERATOR BACK-UP HYBRID ENERGY SYSTEM FOR REMOTE AREAS

(CASE STUDY: ADDIS BODER VILLAGE, DAWURO ZONE, SOUTH WESTERN ETHIOPIA)

MSc. THESIS

BY

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HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

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A THESIS SUBMITTED TO THE

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING,

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EXAMINER'S APPROVAL SHEET

As members of the board of examiners of the final master's degree open defense. we certify that we have lead evaluated the thesis prepared by Mesfin Jariso under the title Resource Potential Assessment and Optimal Design of PV/Wind/Battery Storage/Generator Back up Hybrid Energy System for Remote Areas: Case Study: Addis Boder Village South Western Ethiopia and recommend that it be accepted as fulfilling the thesis requirement for the degree of M.Sc in Power system and Energy Engineering.

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DECLARATION

I, the undersigned, declare that this thesis is my own original work, and it has not been presented for in this or other university, and all sources of material used for thesis have been fully acknowledged.

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Date of Submission---------------------------------

This thesis has been submitted for examination with my approval as a university advisor.

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ABSTRACT

Off grid hybrid systems have been attracting to supply electricity to rural areas in all aspects like, reliability, sustainability and environmental protections, especially for communities living far in areas where grid extension is not appropriate. Hybrid renewable set-up indicates that combinations based on the renewable sources could be applied simultaneously to supply energy in the form employed in an off-gird supporting with battery storage and diesel generator as backup systems.

In this thesis photovoltaic-wind turbine-battery bank and diesel generator have been optimally sized, simulated and optimized for the rural community of Addis Boder village in the southern regional State, Ethiopia. Primary load demand of 142KWh/day, peak load of 26kW, deferrable energy is about 27kWh/day, and deferrable peak load of 3.6kW was involved during optimization of the power system. Well known HOMER modeling tool have been used to design the off-grid system. Solar and Wind 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. Regarding solar energy potential there is no accurately recorded solar radiation database in the country, instead only sunshine hour data was available. Empirical formulas are used to estimate the solar radiation from available sunshine duration data**.** This result is compared with the data collected from NASA and it is found to be nearly the same**.** Consequently, for this study the calculated solar radiation is used for modeling the hybrid system. During the design of this power system set-up, the simulation and optimization was done based on the electricity load, climatic data sources, economics of the power components and other parameters in which the NPC has to be minimized to select an economic feasible power system. The results obtained from the software give numerous alternatives feasible hybrid systems with different levels of renewable resources penetration which their choice is restricted by changing the net present cost of each set up Power schemes with less NPC, less COE, higher renewable fraction, less capacity shortage, smaller excess electricity and minimum fuel consumption would be suggested as optimum system.

It is concluded that besides electricity provisions, the role of a standalone hybrid system in protecting the environment from degradation, the improvement of life of people living in rural area, development of clean energy, and the future situation regarding fossil fuel sources should be taken in to account. Taking these issues into account the free solar and wind energy of the country should be utilized to improve the quality of life of the communities living in rural areas.

Keywords*: Hybrid energy, photovoltaic, wind energy, solar radiation, HOMER, standalone system, load demand, optimal design, resource potential*

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LIST OF ABBREVIATIONS

- ✓ AC — Alternating Current
- ✓ Ah — Ampere hour
- ✓ CC — Cycle charging
- ✓ CFL — Compact Fluorescent Lamp
- ✓ COE — Cost Of Energy
- ✓ DB — Distribution Board
- ✓ DC — Direct Current
- ✓ DOD — Depth of Discharge
- ✓ HPS — Hybrid power system
- ✓ HRE — Hybrid renewable energy
- ✓ HOMER — Hybrid Optimization Model for Electric Renewable
- ✓ I-V — Current-Voltage
- ✓ KWh — Kilo Watt hour
- ✓ LF — Load Following
- ✓ MPPT — Maximum Power Point
- ✓ NPC — Net Present Cost
- ✓ NASA — National Astronomical Service Agency
- ✓ NREL — National Renewable Energy Laboratory
- ✓ OCT — Operating cell temperature
- ✓ O&M — Operating and Maintenance
- ✓ PV — Photovoltaic
- ✓ P-V — Power-Voltage
- ✓ PMG — Permanent magnet generator
- ✓ VS — System Voltage
- ✓ Wh — Watt hour

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CHAPTER ONE
INTRODUCTION

1.1. Background

Energy requirement is becoming a prerequisite to enhance income, improved life quality for individuals no matter where they are and even when exactly the time would. Africa is a land of renewable energy source's opportunity. Africa's per capita energy consumption is only one third of the global usage; however the continent covers 15% of the planets population with 5% of the glob primary energy consumption. Developing countries in the line of growing economies are in a much demanding for electricity access to facilitate their industrial growth. Sustainable economic growth of such countries mainly depends on the supply of electricity infrastructure, as electricity is the heart and the driving engine of growing economy [3].

Ethiopia, despite being the one of Eastern African country, has a very poor electricity penetration rate. Electricity is available for 41% of the population and only 17% of the households are connected to the central grid; even the above coverage is confined to major towns and cities.

Since the Ethiopian Government advocates Green Economy Renewable energy sources (solar, wind, hydropower etc.) are attracting and got more attention as an alternative energy sources than conventional biomass based energy system it accounts 88 % of the total primary energy consumption in the country [22].

Ethiopia's government has already started to apply the growth and transformation plan strategy for the country to become a middle income nation until 2030. This target would be expected to achieve by transforming into industrial development moreover to mechanized agriculture. Thus sustainable and reliable supply of electricity is a requirement. Renewable sources use environmentally friendly technologies to produce energy; they are inexhaustible at all, and are non-polluting. The application of renewable energies in off-grid systems however is challenging due to the nature of intermittence of the sources, the dependence on geographical and weather conditions. The electrification of the villages is an important step for the improvement of the individual's economic condition and for the country in general.

Utilization of renewable energy resources such as solar, wind, small hydro and bio energy for rural electrification has become an attractive solution for those areas where grid electricity is not feasible or cost of the grid extension is relatively large.

But the main difficulty of using these renewable energy systems is that they cannot provide reliable electricity due to the intermittent nature of these resources [4].Generally these systems are used with batteries. In order to get a reliable supply of electricity even within the worst condition of renewable source, it might be required to install a system with large capacity, which requires high capital investment.

Hybrid energy systems are combinations of two or more energy conversion devices (e.g. Diesel/Wind with storage devices), or two or more Renewable energy resources (e.g. PV/wind/Hydro). Hybrid systems provide a high level of energy security, and reliability through the integrated mix of complementary generation methods, and often will incorporate a storage system (battery, fuel cell) and backup system (Generator) to ensure consistent supply.

Therefore hybrid systems have been identified as a better solution for rural electrification. Hybrid systems use multiple energy sources for generating electricity some kind of energy storage medium. Other than renewable energy systems, using diesel generators has become popular in hybrid systems. The generator is important to ensure quality of the service when the output from other sources are low or when the demand is high. A significant reduction in the system cost can be expected by using this kind of conventional source in combination with renewable sources.

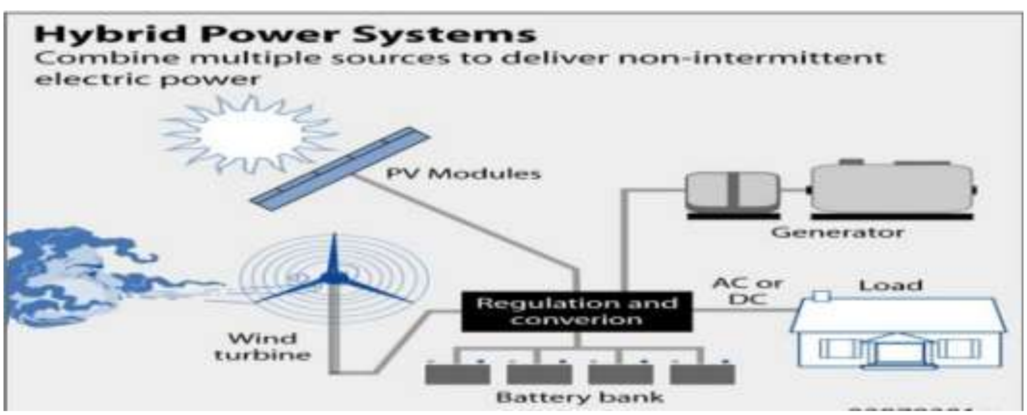

Figure-1.1: Typical hybrid power system incorporating wind turbines, PV panels and battery storage

1.2 Statement of Problem and Motivation of the Study

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.

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.

In addition to above issues, the role of a standalone hybrid system in protecting the environment from degradation, the improvement of life of people living in rural area, development of clean energy, and the future situation regarding fossil fuel sources should be considered. Taking these issues into account the free solar and wind energy of the country should be utilized to improve the quality of life of the communities living in rural areas.

The rural areas of Loma Woreda is among the villages of Ethiopia facing similar problems due to the difficulty of giving electric access by extending the grid, of which Addis Boder Village is one of the village that does not have access to electricity, in spite of having different renewable resource potential. This can be minimized by looking for alternative resources which can be used as a stand-alone to give electric access to the community. This thesis proposes hybrid of solar, wind and Generator as back up energies as option for electrification.

1.2.1 Research question

In general, the research and analysis has been guided by addressing and answering the following questions:

1. **Resource Assessment** - has the village exploitable and feasible solar and wind resource potential? Can it produce an optimal combination for electrification?
2. **Hybrid optimal design and power option** - Can designed system satisfy the load demand and alleviate the electricity problem? Is it technically and economically feasible?

1.3 Objectives

The thesis work comprises the following general and specific objectives:

General objective

- The main aim of this thesis is assessment and technical study of resource potential and optimal design of off grid hybrid renewable energy system that can generate and provide cost effective electricity to satisfy load demand of the village

Specific objectives:

- ✓ To assess potential of renewable energy resource of the area; wind speed and solar radiation potential
- ✓ To estimate the monthly average daily solar radiation based on sunshine hour data from meteorological stations in the region with the required record
- ✓ To estimate electricity energy required for domestic uses, commercial sectors (flour milling machine) and community services like, school and health clinic
- ✓ To select appropriate solar modules, wind turbines and batteries depending on the energy demand
- ✓ To design optimal hybrid system to meet the electrical energy demand of the community
- ✓ To evaluate the technical and economic performance of PV/wind Hybrid System
- ✓ To provide valuable information to the government and Non-government organization (NGO) about the potential of technology in the country for a rural electrification project in Ethiopia.

1.4 Scope of the study

The scope of this study is to assess resource potential and the technical and economic design of a standalone PV/wind/Gen-set/battery hybrid energy system to supply the rural community detached from national grid. This study shall collect and analyze relevant data and information to examine and select the most suitable systems configuration, recommend necessary action, necessary measures that configure a system to accommodate the electrical energy demand for the village. The study only focuses on solar energy and wind resource assessment of among different renewable energy resource in the village. The limitations of this research shall clearly be told as to give a way to next coming researchers and those who are interested in the area.

1.5 Study Area (Addis Boder village) Background

The study area is located in the South Nation Nationalities and People Region, (SNNPR) Dawuro Zone Loma woreda. The Dawuro Zone is among 14 zones in SNNPR covers a total area of 446082 hectare. The administrative capital city of this zone is Tarcha. Loma woreda is one of the five woredas of Dawuro zone found in South 492 km across Shashemene and 439 km across Hosana from Addis Ababa the Capital City of Ethiopia at the main road 267 km South West of the regional state of Hawassa and 36 km East from Zonal administrative town Tarcha. According to the Finance and Economic Development Department Documents the woreda is situated at the eastern tip of the zone. . The mean annual temperature varies from 16^0c and 29^0c, and average temperature of 20.5^0c.

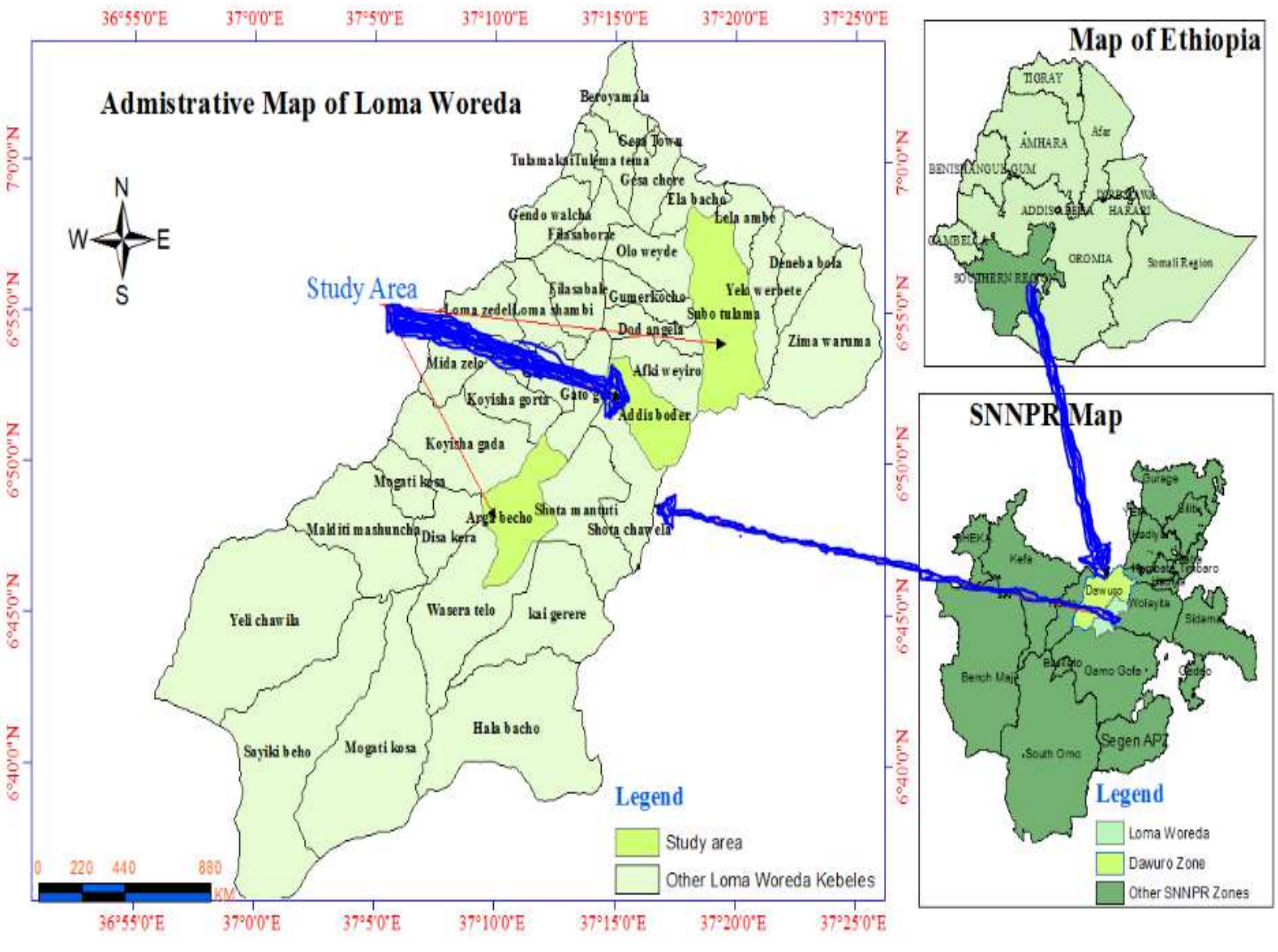

Figure-1.2 Study area map

1.6 Data sources and Methods

1.6.1 Data Sources

Availability of solar and wind energy in terms of potential convertible energy is highly dependent on location, and studying the expected annual availability is extremely important and should be the first step before the actual system design. As it is mentioned in the introduction section, this research is mainly concerned to looking in- to better option of energy sources to electrify villages in remote areas of Ethiopia which are isolated from the national grid. The main concern was the assessment of resource potential and modeling of the hybrid system by analyzing the data taken from different sources.

The field data which includes the number of households and their daily activities related to energy consumption was collected by visiting the selected village. The wind speed and solar radiation/ Sunshine hour/ of the sites collected from NMSA, was compared with the NASA online website data. Specifications and current prices of the system components in the standalone systems were collected and compiled from websites of a number of manufactures and distributes.

1.6.2. Research Methodology

The methodology used for achieving the objectives of the thesis included:

- Different related literatures were reviewed
- The metrology data (solar and wind) of energy sources was collected from NASA and National Metrology agencies of near stations and calculated value were compared
- solar radiation from sunshine hours was estimated by empirical models
- Electricity load demand of domestic uses, commercial, school and health center and deferrable loads of village were estimated
- Optimal sizing and selection of hybrid system components was done based on load demand
- The cost data for each of the power system components had been thoroughly searched from different websites and publications
- Modeling, optimizing and simulating of system was done by Hybrid Optimization Model for Electric Renewable (HOMER) software tool

1.7 Thesis outline

This thesis is organized into seven chapters namely introduction, literature review, site inspection and data collection, design and sizing, optimization and simulation, result and discussion, and the last one is conclusion and recommendation.

Chapter one gives overview the background, the motivation and problem statement, objectives methodology of the study, the proposed area of study and boundaries is described in this chapter. **Chapter two** reviews related works and it includes the solar energy systems, wind energy systems and hybrid systems and components. It presents the, solar PV types, radiation incident to the PV surface, solar sources potentials, PV module and array, PV modeling methods and covers wind turbines, classification of wind turbines, the physics of wind energy, wind energy converters and regulation mechanisms and wind shear.

Chapter three explains about site inspection, data collection and resource potential assessment. It also describes load estimation of the village wind energy potentials of the study area.

Chapter four discusses design sizing and selection of hybrid system components. It explains the producers and methods of system selection and sizing.

Chapter five discuses, hybrid power system configurations, HOMER tool, HOMER inputs and optimization system components.

Chapter six presents the results and discussions of the research. It elaborates the results from HOMER simulation and manual calculated results.

Chapter seven concludes the thesis after providing recommendations and suggesting future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Related works

Several approaches have been used achieving the optimal configurations of the hybrid systems. Various optimization techniques have already been used to optimize the cost and efficiency of HRE systems, such as linear programing, Iterative technique dynamic programing, graphical construction technique, probabilistic approach & multi-objective.

G.J. Dalton et al [1] studied feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations. The study sites represented both small and medium-scale accommodation operations, and had a mix of RES/hybrid standalone systems using wind and pv.

Getachew B. et al [2] determined solar and wind potentials of selected locations in Ethiopia and studied feasibility of Wind/PV hybrid system to electrify 200 model families using HOMER for optimization and sensitivity analysis. The paper showed the most cost efficient combination from the hybridizing of diesel generator/battery and converter with no contribution of renewable sources fractions. It also presented other cost effective combinations of diesel generator/PV and converter; in this case the dispatch strategy applied was the load following strategy. The conclusion of the author is viable to deploy the above stated power configurations in the areas where these resources are stated.

Samir M. et al [3] studied hybrid PV-wind energy system to isolated micro-grid using HOMER software. Their main goal of this studies the effects of adding hybrid solar PV and WT systems to the micro-grid to improve the isolated operation of the micro grid. HOMER software is used to optimize the cost analysis of PV-wind- battery hybrid power system for rural place in Egypt\ considering the LPSP which is of great significance and can be regarded as an improvement combined with the previous works.

Balochistan et al [6] analyzed optimal Configuration of Hybrid Renewable Energy System for a remote area has been performed with the simulation tool HOMER. Its aim was to evaluate the system costs, the cost of energy generated by the PV-Wind- Hybrid systems, the effect of the load size and to what extent the combination of these two energy sources can reduce the costs compared to a PV-alone system. This simulation resulted in reduction of NPC, and showed stand-alone hybrid system applications have the potential to be more efficient compared to PV alone system. It has been proven that hybrid renewable electrical systems in off grid applications are economically viable, especially in remote locations. In addition, climate can make one type of hybrid system more profitable than another type.

K. M. Iromi et al [7] Performed techno-economic evaluation of hybrid renewable energy system for rural electrification. They analyzed solar radiation to asses' techno-economic feasibility of hybrid system for a typical remote village and the Simulation has been done by using HOMER software and the result indicates that PV/diesel/battery hybrid system is technically and economically feasible with levelized cost of energy of 0.170 $/kWh. The Study also indicates that the initial cost of Hybrid system is higher than standalone diesel generator system. The PV cost covers 78% of the total initial cost of the system. The increase in PV penetration decreases the operating hour of diesel generator which further augmented by including battery storage in the system. The running cost of diesel generator only system is much higher than that of hybrid system due to continuous cost of diesel fuel.

Nurul A. et al [11] analyzed optimal sizing and operational strategy of hybrid renewable energy system using HOMER. The objective of this paper is to determine the best configuration of hybrid renewable system referring to the optimal sizing and operational strategy of diesel generator, wind energy and solar energy that can offer the lowest amount of Total Net Present Cost (TNPC). The Hybrid Optimization Model for Electric Renewable (HOMER) software has been used to perform random selection of sizing and operational strategy of generating system in order to obtain the finest solution of hybrid renewable energy with lowest TNPC. They performed by using the information collected based on the load profile, average monthly wind speed and solar radiation at the Pulau Perhentian Kecil, Terengganu in the year of 2004.

Solomon Netsanet [14] performed technical study on assessment of resource potential and technological options of solar energy and photovoltaic systems for Amhara Region, Ethiopia. The main task was assessment of the solar energy resource potential in Amhara region and performing a technical study on the possible technological options of photovoltaic systems that can be applied in the region. He performed a new topology dependent model of estimating global solar radiation from relative sunshine hour records is developed and applied to estimate the resource potential in the region. He compared the designed system was with the installed system and concluded that the initial design lacks accurate estimation of energy requirement and appropriate system sizing as a result. The economic and environmental advantages of PV system for rural institutions were proved by comparisons of a PV system with diesel generator and a hybrid one at Arsema Semaetat using HOMER. The results showed that a PV-only system is the best option with $11,366 NPC and a battery-free hybrid system is the worst one with $23,076 NPC.

F. Drake and Yacob Mulugeta [16] merged data from a variety of sources and presented new countrywide maps of the solar energy distribution over Ethiopia after predicting radiation from sunshine hours by employing empirical models. They used data from seven stations in Ethiopia, linear and quadratic correlation relationships between monthly mean daily solar radiation and sunshine hours per day. To produce a national solar-energy distribution profile, they carried out spatial extension of the radiation/sunshine relationships based on interpolation of regression coefficients of each of the seven linear regression equations and another six from previous studies, completed in neighboring Sudan, Kenya and Yemen. Subsequent to these procedures, 142 stations providing only sunshine data were assigned their appropriate ‘a’ and ‘b’ values to estimate the amount of solar radiation received.

In [15 and 17], the feasibility study, the optimal design and parametric study of hybrid renewables energy systems are analyzed based on available resources and energy demand requirements by analytical and HOMER optimization techniques.

Shuvankar Podder et al [20] used the sunshine duration to estimate monthly average daily solar radiation on a horizontal surface. After discussing one of the best models that used sunshine duration to estimate monthly average daily solar radiation, the Angström model, the correlation equations developed are employed to calculate the monthly average daily global solar radiation for various locations of Bangladesh by using the pyranometric stations solar radiation data and the daily sunshine hours from Meteorological Office, and then applying different equations and a regression relation for these five regions was obtained and Considering the sunshine hours which is the important factor for estimating global solar radiation and the fact that Bangladesh is a country in which sunshine hours are sensible, they suggested that Angstrom model could be the best for estimating the solar radiation.

Eyup Taymur, [21] carried out a comprehensive study on energy output calculation of a solar system. He modeled a graphical user interface by MATLAB GUI which calculates the energy yield by using data set for different PV module technologies to be presented to the end-users for decision making in PV energy investment. He used lots of expressions and equations for calculation of global solar radiation, beam irradiance, and diffuse irradiances. For planning a standalone PV system, he went through energy consumption calculation, PV generator sizing, consideration of cable and conversion losses, determination of Summer Excess and Winter Reserve, cable cross-section sizing, and sizing the battery and charge controller. PV array combiner box and grid-tied inverter are added in case of planning grid connected PV systems

Tamirat B. [37] has made a feasibility comparison of independent electrification at Dillamo and Gode sites in Ethiopia by either of the wind, solar PV or micro hydropower system. But, the author did not considered the possibility of combining the resources into hybrid system and the analysis is done manually without any computer tool.

In this thesis, Hybrid energy system of solar, wind and battery and, Diesel generator as back-up system for more reliable operation was analyzed. The main aim was assessment and technical study of resource potential as first part and optimal sizing of off grid hybrid energy system as second part.

To perform this task, site inspection and data collection was priory done In data estimation, different empirical models, autocorrelations methods, and different theories and standards were used and HOMER software were used to optimally size, decide optimal cost, show hourly dispatch, analyze operating strategy.

2.2 SOLAR ENERGY SYSTEMS

2.2.1 Introduction

The sun is the largest energy source of life at the same time it is the ultimate source of all energy (except tidal and geothermal power), even the energy in the fossil fuels ultimately comes from the sun. The sun radiates 174 trillion kWh of energy to the earth per hour. In other words, the earth receives 1.74 x 10 17 watts of power from the sun [13].

The sun is a typical star with mass 2×1030 kg, beam length 700,000 km and it has roughly 5 billion more years of life. Its surface temperature is about 5800 Kelvin while the internal temperature is approximately 15 million Kelvin. This temperature derives from reactions which were based on the transformation of hydrogen to helium, the process called nuclear fusion, which produces high temperature of the sun and the continuous emission of large amounts of energy. It is calculated that for each gram of hydrogen that is converted to helium sun radiates energy equal to 1.67×105 kWh. The solar energy is emitted to the universe mainly by electromagnetic radiation. Approximately one-third of energy radiated from sun is reflected back. The rest is absorbed and retransmitted to the space while the earth reradiates just as energy as it receives and creates a stable energy balance at a temperature suitable for life.

2.2.2 Solar Photovoltaic Energy

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. PV power generation uses solar panels comprising a number of cells containing a semi-conducting material. As long as light is shining on the solar cell, it generates electrical power. When the light stops, the electricity stops. Many PV have been in continuous outdoor operation on Earth or space for over 30 yrs. [4].

The solar cells that are used on calculators and satellites are photovoltaic cells or modules. This PV module consists of many PV cells wired in parallel order to increase current and in series to produce a higher voltage.

When we speak of a PV panel it means any number of PV modules and when we speak of array it means any number of PV panels. Individual PV cells are typically only a few inches in diameter, but multiple cells can be connected to one another in modules, modules can be connected in arrays, and arrays can be connected in very large systems. See Figure 2.1

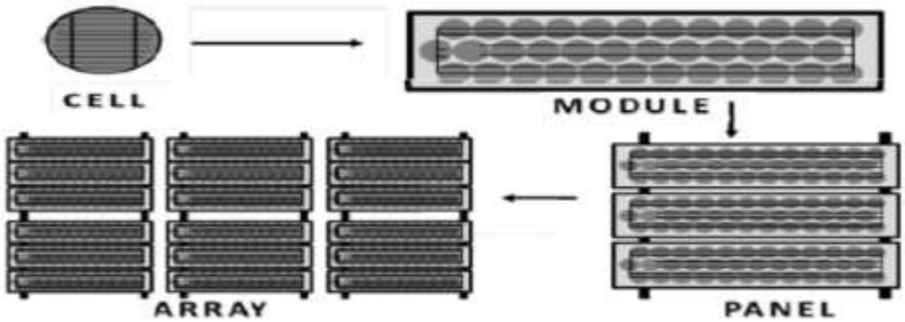

Figure- 2.1: PV Diagram

2.2.3. General Working Principles Photovoltaic Cells

PV cells convert sunlight directly into electricity by taking advantage of the photoelectric effect. Cells are constructed from semiconductor materials coated with light-absorbing materials. When photons in sunlight strike the top layer of a PV cell, they provide sufficient energy to knock electrons through the semiconductor to the bottom layer, causing a separation of electric charges on the top and bottom of the solar cell. Connecting the bottom layer to the top with a conductor completes an electrical circuit and allows the electrons to flow back to the top, creating an electric current and enabling the cycle to repeat with more sunlight. Figure 2.2 illustrates how photovoltaic cells work. [4]

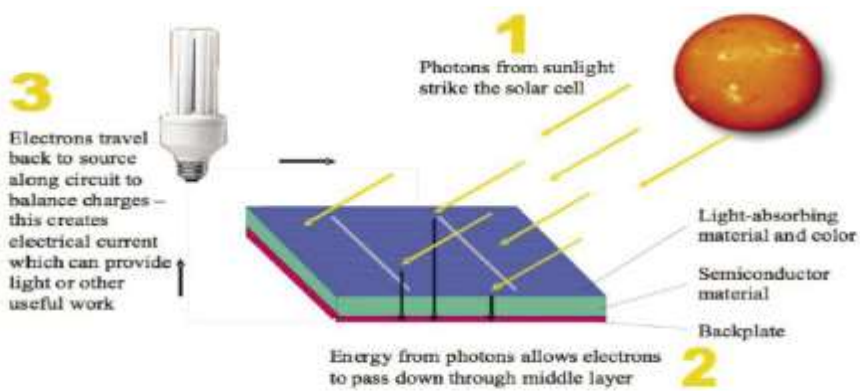

Figure 2.2 how photo cells work

2.2.4. Main PV Cell Types

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

1. **Single-Crystalline Silicon**:

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

2. **Polycrystalline or Multi-crystalline Silicon:**

The particular cell is relatively large in size and it can be easily formed into square shape which virtually eliminates any inactive area between cells. It has a slightly lower conversion efficiency compared to single crystalline and manufacturing costs are also lower. Cells efficiency oscillates between10% and 13% [4].

3. **String Ribbon:**

This is a refinement of polycrystalline silicon production. There is less work in its production so costs are even lower. Cells efficiency averages 8% to 10%**.**

4. **Technology which uses thin film solar cells**

Amorphous or thin film silicon cells are solids in which the silicon atoms are much less ordered than in a crystalline form. By using multiple junctions this kind of photovoltaic cells achieve maximum efficiency which is estimated at about 13% while the installation cost is reduced. The efficiency of this cell oscillates between 6% and 10% [15]. Furthermore the output of an amorphous silicon cell is not decreased as temperature increases and is much cheaper to produce than crystalline silicon. Cells efficiency decreases with increases in temperature. Crystalline cells are more sensitive to heat than thin films cells. The output of a crystalline cell decreases approximately 0.5% with every increase of one degree Celsius in cell temperature. For this reason modules should be kept as cool as possible. (4)

2.2.5 PV Module and Array

The solar cell is the basic building block of the PV power system. However, it rarely used individually because it is not able to supply an electronic device with enough voltage and power. For this reason, many photovoltaic cells are connected in parallel or in series in order to achieve as higher voltage and power output as possible. Cells connected in series increases the voltage output while cells connected in parallel increases the current. The solar array or panel is a group of several modules electrically connected in series-parallel combination to generate the required current and voltage and hence the power.

A typical photovoltaic system is made of 36 individual 100cm2 silicon photovoltaic cells and auxiliary devices which are lead-acid batteries with a typical voltage of 12 V. This system has the capacity of producing more than 13V during cloudy days and can charge a 12 V battery. While PV cells are connected in series, the output current remains the same but the output voltage will be the total summation of all cells formed the module. Schematic diagram on how PV cells connect to form module as well as modules to form array is shown in figure 2.3-

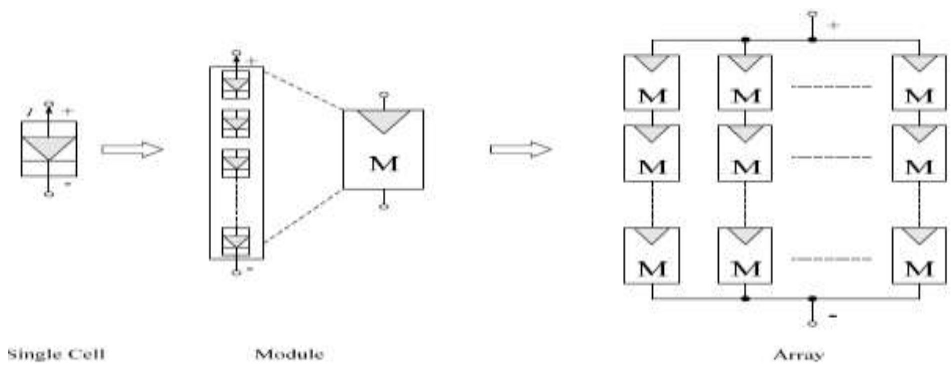

Figure-2.3 Schematic diagram on how PV cells connect to form module and array

The power rating of solar panel depends on the number of solar cells and the size of the panel. When the PV cells are assembled as module, they can be illustrated as having a nominal operating cell temperature. NOCT is the temperature of PV cell when operating at an open circuit at a temperature of 20 with air mass of 1.5, irradiance G = 800 W/m2 and a wind speed less than 1m/s [27, 38]. When large voltages or currents than single module are required, modules have to be connected together to form an array as indicated in figure 3-2. Arrays connected in series result higher voltages where as the ones connected in parallel has higher current.

When modules are connected in parallel they produce large power at the same voltage due to the increment of current, in a similar fashion when modules are connected in series; it is enviable to provide each module maximum power production at the same current due to the increment of voltage. When deciding to install solar panels, it is important to take into consideration the shading effects faced to the panels during the peak sun hours. The shading effect causes to the reduction of power production and it may even damage the cells. Generally, it is advisable to install PV panels free of trees, buildings, and other obstacles. The second important parameter to consider during solar panel installation is temperature. The heating up of solar panels cause a loss of power because solar cells efficiency is decrease as temperature increases. The mounting system of the panels should allow the air circulation system during the hot sun hour to cool the solar panel.

2.2.8 Solar PV Installation Methods

Solar energy exploitation depends on the tracking system that mounts the PV panel. The tracking system is basically applied to direct the panel to the direction of the sun light which enhances the radiation that strikes the surface of the PV module. Most PV arrays are typically mounted with no tracking systems. There is possibility to track the radiation of the sun for the power output maximization. Solar tracking systems are basically categorized according the number of axes of tracking and the time with which the adjustment is to be made. Below are the techniques to be considered during the design of the PV system [29, 31].

Horizontal axis monthly adjustment: This type of tracking system, it rotates horizontally from east to west direction. The angle of inclination of the PV is adjusted on the beginning of every month so that the beam strikes at 90 to the PV panel when sun is overhead.

Horizontal axis weekly adjustment: This type of mounting system, its axis of rotation is from east to west direction. The PV angle of tracking (slope) is adjusted on the first day of the week, thus solar radiation is at 90 to PV at noon of the corresponding day. The PV module slanted towards parallel the ground.

Horizontal axis daily adjustment: Axis of rotation is about a horizontal east-west direction to track the solar radiation. The slope is adjusted each day so that the sun's rays are at 90 degree to PV at noon of the corresponding day.

Horizontal axis continuous adjustment: It is a type of PV mounting system in which slope of photovoltaic is adjusted continuously and rotation is about a horizontal east-west axis. The slope is adjusted continually in order to minimize the angle on incidence.

Vertical axis continuous adjustment: PV axis of rotation is about a vertical with respect to the ground surface. The slope is fixed, but the azimuth is continually adjusted to minimize the angle of incidence.

Two axes: The panels are rotated about both to east-west and from north-south having two pivots to rotate. However, it is the most expensive method.

No tracking: Photovoltaic Panels are mounted at a fixed slope and azimuth; moreover it is the simplest and cheapest method. Preferable to orient the panel to the equator (south in the northern hemisphere) usually the angle of tilt is equal to the latitude of the specific site under study. A small increase and decrease from the latitude will be better for the winter and summer sun tracking respectively.

After the solar panels are installed on the mounting pole, the solar panels need to be tilted in order to produce the most power. Solar panels produce the most power when they are pointed directly at the sun. Since the solar panels will be attached to a permanent structure, the solar panels should be tilted at angle equal to the site's latitude in order to achieve the highest energy output.

2.2.9 Modeling of PV Cell

A Solar cell (also called a Photo-Voltaic cell) is an electrical device that converts the electrical energy of light directly into electricity. Equivalent circuit has a current source (photocurrent), a diode parallel to it, a resistor in series describing an internal resistance to the flow of current and a shunt resistance which expresses a leakage current. The current supplied to the load can be given as.

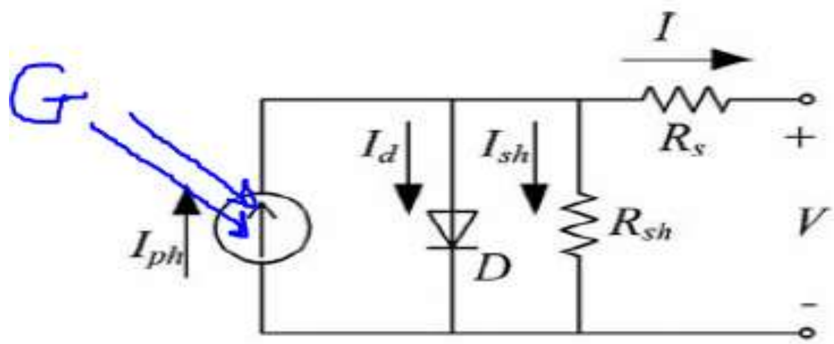

Figure: 2.4 Electrical PV cell model

$$I = I_{PV} - I_O\left[\exp\left(\frac{V + IR_S}{aV_T}\right) - 1\right] - \left(\frac{V + IR_S}{R_P}\right) \tag{2.1}$$

IPV–Photocurrent current,

IO–diode's Reverse saturation current,

V–Voltage across the diode,

a– Ideality factor

VT –Thermal voltage

Rs– Series resistance

Rp–Shunt resistance

PV cell photocurrent, which depends on the radiation and temperature, can be expressed as.

$$I_{PV} = \left(I_{PV\_STC} + K_I \Delta T\right)\frac{G}{G_{STC}} \tag{2.2}$$

KI– cell's short circuit current temperature coefficient

G–solar irradiation in W/m^2, G_{STC}–nominal solar irradiation in W/m^2

I_{PV_STC}– Light generated current under standard test condition

The reverse saturation current varies as a cubic function of temperature, which is represented as;

$$I_O = I_{O\_STC}\left(\frac{T_{STC}}{T}\right)^3 \exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right] \tag{2.3}$$

$\boldsymbol{I_{0\_STC}}$– Nominal saturation current

$\boldsymbol{E_g}$ – Energy band gap of semiconductor

T_{STC}–temperature at standard test condition and q – Charge of electrons

The reverse saturation current can be further improved as a function of temperature as follows

$$I_O = \frac{(I_{SC\_STC} + K_I \Delta T)}{\exp\left[\frac{(V_{OC\_STC} + K_V \Delta T)}{aV_T}\right] - 1} \tag{2.4}$$

I_{SC_STC} – short circuit current at standard test condition

V_{OC_STC} – short circuit voltage at standard test condition

K_V – temperature coefficient of open circuit voltage

As the total power generated by a single PV cell is very low, we used a combination of PV cells to fulfill our desired requirement. This grid of PV cells is knows as PV array. The equations of the PV array can be represented as;

$$I = I_{PV}N_P - I_O N_P\left[\exp\left(\frac{V + IR_S\left(\frac{N_S}{N_P}\right)}{aV_T N_S}\right) - 1\right] - \left(\frac{V + IR_S\left(\frac{N_S}{N_P}\right)}{R_P\left(\frac{N_S}{N_P}\right)}\right) \tag{2.5}$$

Where;

N_S– Number of series cells and N_P– Number of parallel cells

Open circuit voltage correspond to the voltage drop across the diode (p-n junction), when it is transverse by the photocurrent *Iph* (namely *IL* = *Iph*), namely when the generated currents is $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0}\right) = V_t \ln\left(\frac{I_L}{I_0}\right) \tag{2.6}$$

Where, $V_t = \frac{mkT_c}{e}$ is known as thermal voltage and *T* is the absolute cell temperature.

Maximum power is the operating point at (V_{max}, I_{max}), at which the power dissipated in the resistive load is maximum: $P_{max} = Vmax*Imax$. (2.7)

Maximum efficiency is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_a} \tag{2.8}$$

Where *Ga* is the ambient irradiation and *A* is the cell area

Fill factor is the ratio of the maximum power that can be delivered to the load and he product of *Isc* and *VOC::*

$$FF = \frac{P_{max}}{V_{OC} I_{SC}} = \frac{I_{max} V_{max}}{V_{OC} I_{SC}} \quad (2.9)$$

The open circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cell's temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with the cell temperature,

Temperature effect: This has an important effect on the power output from the cell. The temperature effect appears on the output voltage of the cell, where the voltage decreases as temperature increases. This decrease for silicon cell is approximately 2.3 mV per 1°C increase in the solar cell temperature.

The solar cell temperature Tc can be found by the following equation below;

$$T_C = T_{amb} + \left(\frac{NOCT - 20}{800}\right) * G \quad (2.10)$$

Where: T_{amb}: ambient temperature in °C, G: solar radiation in W/m² and NOCT: Normal Operating Cell Temperature which is defined as the cell temperature

Solar radiation effect: The solar cell characteristics are affected by the variation of illumination. Increasing the solar radiation increases in the same proportion the short circuit current

The output power from the PV cell is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation.

$$P_{out\text{-}pv} = P_{r\text{-}pv} * (G/G_{ref}) * [\, 1 + K_T\, (T_c - T_{ref})\,] \quad (2.11)$$

$P_{out\text{-}pv}$: output power from the PV cell

$P_{r\text{-}pv}$: rated power at reference conditions

G: as defined before

G_{ref}: solar radiation at reference conditions (Gref =1000 W/ m²)

Tc: cell temperature, calculated using equation above

T_{ref}: cell temperature at reference conditions (Tref = 25 °C)

K_T: temperature coefficient of the maximum power

(K_T= - 3.7 $*10^{-3}$ °C for mono and poly crystalline Si)

2.2.10 Solar Terminologies

According to Taymur [21], the solar energy reached each year to the earth's surface is roughly 10k times the total energy consumed by human. As sunlight passes through the earth's atmosphere some of it absorbed, some is scattered and some passes through the molecules in the atmosphere. Solar energy that reaches the earth surface is solar radiation. Nuclear reactions occur in the sun as a result hydrogen is converted into helium with a process called fusion. This reaction caused for the release of large amount of radiation, where its temperature reaches about 15 million degree Celsius [21]. It is part of this energy that strikes the earth's surface. The magnitude of solar irradiance which strike on the surface of the earth depends on latitude, climatological location parameters like air pressure, cloudiness, etc. Some of the direct applications of solar energy are to heat, to pump, and to desalinate water. Solar energy can be converted in to electricity using different conversion technologies, among which photovoltaic and solar thermal are the basics.

Photovoltaic technologies convert the incoming solar insolation directly into electricity. Whereas, solar thermal technologies initially heats water then directs to mechanical systems such as steam turbines to generate electricity. This technology uses mirrors to concentrate the incoming solar energy, it captured in the form of heat. Taking an account for the PV systems and sunshine, it is necessary to take a note of the following important concepts.

Irradiance: It is the power density of the sun, measured in W/m2. At night and on sunrise times, irradiance is often zero and increases respectively then reaches at its highest value around noon. It again decreases from noon to sunset and dropping to zero at night.

Irradiation: it is the time integral of power density of the sun (irradiance), measured in kWh/m2.

Air mass: A parameter that influences the quantity of irradiance that is incident on the earth's atmosphere.

Solar constant: The amount of solar radiation incident on the earth's atmosphere at a vertical angle of air mass (AM=0), and its magnitude is about 1367 W/m2.

Global solar radiation: The total summation of the sunbeam and diffuse radiations. In case of horizontal laid surfaces, global solar radiation is the summation of vertical radiation and diffuse radiation. This is part of the constant solar radiation that hits the ground.

Beam radiation: It is the sunbeam that reaches the earth right from the sun disk.

Diffuse radiation: It is the solar insolation that reaches the ground from the sky where its direction is changed by the atmosphere. The diffuse radiations magnitude depends on solar height, and atmospheric transparency. The higher the cloud in the sky is the higher the dispersed radiation.

Albedo radiation: It is the reflected sunlight from the ground.

Extraterrestrial normal radiation: Is the quantity of solar insolation that arrives on a surface perpendicular to the atmosphere.

Extraterrestrial horizontal radiation: is the quantity of solar radiation reaching on a flat surface positioned on top of the atmosphere. If the entire direct solar radiation source is converted into usable form of energy in the earth, it would be more than enough to supply the energy requirement of the world.

Incident Radiation: The position of the sun, the slope and the orientation of the photovoltaic surface are the most important parameters for any solar system design. Photovoltaic power output affects by the amount of radiation reaching the surface area of the collector; however the irradiance that is incident is flat or horizontal. Thus the incident solar radiation in a tilted surface is inclined component of the radiation, which should be calculated from the global horizontal radiation. Figure-2.7 illustrates the orientation of photovoltaic system towards the sun. The angles involved in determining the amount of incident solar radiation on the surface of PV panel are described below.

Zenith angle (θz): Is the angle between the line drawn vertically and the line that connects to the sun from the vertical line. Usually this angle is 90º at sunrise and sunset times.

Solar altitude angle (αs): It is an angle included between the line that directs to the sun and the line drawn perpendicular to this line. Its value remained at 0º during sunrise and sunset times.

Solar azimuth angle (γs): It is an angle that draws from south direction to the line that indicates to the sun. Its value varies from 0º when sun is overhead, -90º at sunrise and 90º at sunset.

Angle of incidence (θ): It is the angle sandwiched between the line that draws normal to PV surface and the line that points to the sun. It is the critical angle in determining the incident radiation accordingly the photovoltaic power output. For the determination of this angle, it is basic to know the following angles too.

Hour angle (ω): is defined as the angular displacement of the sun, which is east or west, of the civil meridian time zone. The earth rotates 15º/ hour; furthermore this shows that at 11am and 1pm, hour angle is -15º and 15º respectively.

Surface azimuth angle (γ): is an angle that measures from south to the line that draws perpendicular to the PV panel surface. East and west orientations are negative and positive respectively. The azimuth specifies the direction towards which the panels slope. The direction into which the PV array faces is called azimuth. Zero degree azimuths depict south facing surface. So an azimuth of negative value results to a south-east facing surfaces, furthermore a surface oriented to an azimuth of 90° shows a surface facing to the west.

Collector slope (β): is the angle of inclination of a surface between the PV and the horizontal plane. A 0 and 90 slopes indicate the horizontal and vertical orientations of the PV array respectively. A slope roughly equal to the latitude will typically maximize the annual PV energy production.

Declination angle (δ): is the angle formed between the line from the sun directed from equator and the line that directs straight to the equator. It varies by plus or minus 23.45 degrees during the year.

Latitude (φ): is the angle measured from the line that draws to the center of the earth and the line directs to the equator.

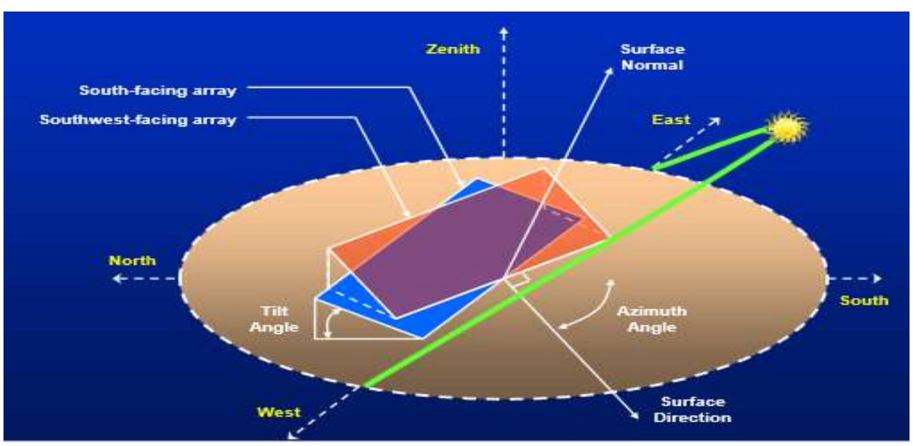

Figure 2.5: Geometry of solar collector and location of sun relative to earth

2.2.11 Methods of solar Radiation Estimation

The sun supplies energy in the form of radiation, without which life on earth could not exist. But it is not all of the energy from the sun that reaches the earth's surface. Ruther, it is only a tiny proportion (around two-millionths) of the sun's energy that could be available for use [21]. The intensity of solar radiation outside earth's atmosphere depends upon the distance between the sun and the earth. The earth's atmosphere also reduces the insolation through reflection, absorption and scattering. Sunlight on earth's surface comprises a direct portion (comes from the direction of the sun) and a diffuse portion (scattered from the dome of the sky and has no defined direction). The sum of the direct and diffuse radiation is known as global radiation. The global radiation varies greatly depending upon the geographical position of the region and the different seasons during a year.

Solar radiation reaching the earth surface is on average of 1000 W/m² although this depends on the following principal criteria:

- The latitude and altitude
- The angle of the surface and the direction faced, the time of year and the time of day
- The degree of pollution and shade and the thickness of the cloud layer

In any solar energy conversion system, the knowledge of global solar radiation is extremely important for the optimal design and the prediction of the system performance. The best way of knowing the amount of global solar radiation is to install pyranometers or photovoltaic sensors at as many locations as possible in the given region and look after their day-to-day maintenance and recording. But it is not affordable for most of the developing countries like Ethiopia. In such cases, indirect estimation can be a useful option.

Solar radiation estimation techniques can be broadly grouped in to two categories with one based on satellite observations while the other bases ground level measurements of sunshine hour and other meteorological parameters.

The study by NASA is the widely used estimate in most of solar designs in the country. Satellite-derived insolation estimates are not intended to replace ground measurement data but to fill gaps where ground measurements are missing and to complement ground measurements in other areas. The data quality may only be accurate enough for preliminary feasibility studies, but final planning of solar systems needs better radiation estimates or measured data.

The alternative approach is to correlate global solar radiation with meteorological parameters at the place where the data is collected. In this approach the mostly used meteorological parameters are sunshine duration, average air temperature and cloud cover. There have also been some trials to correlate the solar radiation of one location with other factors like altitude, latitude and longitude in order to have a better estimate of solar radiation.

A. Angstrom Model

The relation between solar radiation and sunshine duration was first proposed by Angstrom in 1924.The original Angstrom equation is given by below.

$$\frac{H}{Hc} = a + b\,\frac{n}{N} \qquad (2.12)$$

Where

H = monthly average daily global radiation (Wh/m^2/day), Hc = monthly average clear sky daily global radiation for the location, n = monthly average daily maximum bright sunshine duration in hours, N = actual sunshine duration in a day in hours, ‘a’ and ‘b’, are empirical coefficients. These coefficients are location specific.

A basic difficulty in this model is to determine clear sky radiation. To avoid this difficulty a modified model was presented by Prescott [14] in 1940.

B. Angstrom-Prescott Model (1940)

Popularly known Angstrom-Prescott model is given by;

$$\frac{H}{Ho} = a + b\,\frac{n}{N} \qquad (2.13)$$

Where, Ho= monthly average daily extraterrestrial radiation at the specific location.

The ratio of $\frac{H}{Ho}$ is called the clearness index and the ratio $\frac{n}{N}$ is referred to as the cloudness index.

- Monthly average daily extraterrestrial irradiation is calculated from the following equation

$$Ho = \frac{24}{\pi} Gsc * \left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\varphi\cos\delta\sin\omega s + \frac{\pi\omega s}{180}\sin\text{Ø}\sin\delta\right) \tag{2.14}$$

Where,

Gsc = global solar constant =1.367 Kw/m2

n= the day of a year (a number between 1 to 365, starting from first January)

Ø = the latitude in degree.

δ = the solar declination in degree and,   ωs = the sunset hour angle in degree

The average HO,avr for the month is calculated as follow; [20]

$$HO,avr = = \frac{\sum_{n=1}^{N} Ho}{N} \tag{2.15}$$

Where,   HO,avr = the average extraterrestrial horizontal radiation for the month in kwh/m2/day

The declination is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation (NREL, 2008),

$$\delta = 23.45\sin(360\frac{284+n}{365}) \tag{2.16}$$

The sunset hour angle is calculated using the following equation

$$\cos\omega s = -\tan\varphi\tan\delta \tag{2.17}$$

N= the number of month in year

The maximum possible sunshine duration N in hours for a horizontal surface is given by: [20]

$$N = \frac{2}{15}\omega s \tag{2.18}$$

2.2.11 Calculation of the global Irradiation on an Inclined Surface

Solar energy reach at photovoltaic panel through different ways as depicted in Figure 2.6. The most significant quantity of solar energy is provided by the direct radiation that came from the sun, especially on clear sky conditions. Due to various particles presented in earth atmosphere (such as air molecules, dust, fog or cloud elements, drops etc) occurs the diffuse radiation, which become significant in case of cloudy sky conditions. Also the ground surface, including buildings, water surface, vegetation etc, reflects solar radiation that can be collected by a tilted panel.

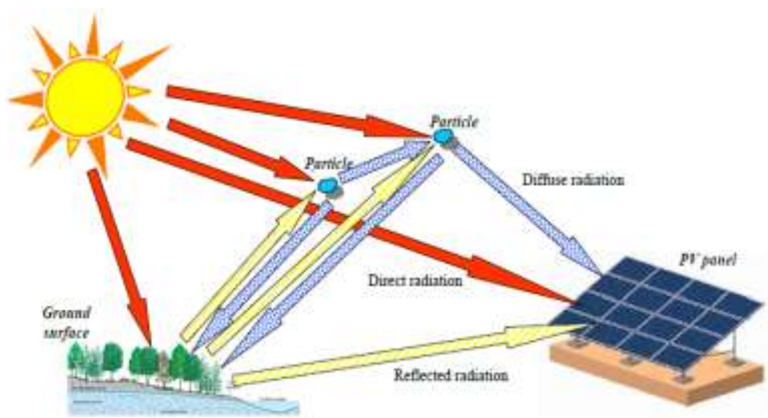

Figure-2.6 Solar radiations on the inclined solar panel

The solar radiation data are generally given in the form of global radiation on a horizontal surface. Global daily irradiation is denoted by H. If the PV panels are positioned with an angle on a horizontal surface the total global irradiation received by the PV will change.

The global (or total) solar irradiance incident with a tilted surface ‘H’ comprises three basic components, as shown in Fig. above: (i) direct (or beam) ‘B’, (ii) sky diffuse ‘D’, and (iii) reflected /albedo/’ R’ solar irradiance component.

The data ‘**H’,** for the site is used to determine the diffuse and beam contributions to the global irradiation by using ‘**Ho’** as a reference and ‘**KT’** is clearness index. The attenuation of the solar radiation through the atmosphere at a given area on the Earth can be described by **KT=H/Ho** in that month. Where ‘**Ho’** is calculated extraterrestrial irradiance on account of the eccentricity of the Earth’s orbit is considered. The diffuse irradiation can be obtained by using the diffuse fraction index **D/H** of the global irradiation. **D/H** is the universal function of clearness index **KT. B=H-D** gives the separate beam and diffuse radiation.

Finally, angular dependent of each component will give the diffuse and beam irradiation on an inclined surface. And also by using the reflectivity of surrounding area the total albedo is calculated. The total irradiation is found by adding albedo, beam and diffuse irradiation

The inputs for calculations are:

- Daily global irradiation H for a day,
- The middle of each month can be chosen to give the average monthly irradiation and
- The solar constant S, which is 1367w/m^2,
- The site's geographical latitude and
- The solar declination angle δ, for the day of the year.

Table-2.1: Typical Reflectivity **[21]**

GROUND COVER	REFLECTIVITY
Dry bare ground	0.2
Dry grassland	0.3
Desert sand	0.4
Snow	0.5-0.8

Since we have the daily irradiation data H, from KT=H/Ho, the clearness index can be found. Then, the diffuse irradiation' D' can be found from the formula below [21],

$$\frac{D}{H} = 1- 1.13KT \qquad (2.19)$$

The beam irradiation also can be found simply by subtracting D from G, i.e.

$$B=H-D \qquad (2.20)$$

- **For south-facing panel inclined at an angle β to the horizontal surface:**

After B is found for the horizontal surface, the beam irradiation B(β) on a south-facing panel inclined at an angle β to the horizontal surface is given, [Liu and Jordan – LJ model [37]]

$$B(\beta) = B\frac{(\cos(\emptyset-\beta)*\cos\delta*\sin\omega s'+\left(\frac{\pi}{180}\right)\omega s'\sin(\emptyset-\beta)*\sin\delta}{\cos\emptyset\cos\delta\sin\omega s+\left(\frac{\pi}{180}\right)\omega s*\sin\emptyset\sin\delta} \qquad (2.21)$$

Where, $\varpi s'$= the sunset hour angle adjusted for a tilted plane to allow for the effect of the sun rising and setting behind the panel, using the formula:

$$\varpi s' = - \cos{-1}[-\tan(\text{Ø}-\beta) * \tan\delta] \quad (2.22)$$

The numerator of Eq. (2.14) denotes amount of the extraterrestrial radiation on tilted surface and the denominator is that on horizontal surface. Each of these expressions is obtained by integration of incident angle of beam radiation over the appropriate time period, from the true sunrise to sunset on horizontal surface and from apparent sunrise to apparent sunset on the tilted surface.

In **L-J model [37],** the solar radiation on tilted surface is considered to be composed of three parts such as; beam, reflected from ground and diffuse fraction. It was assumed that the diffuse radiation is isotropic only; whereas, circumsolar and horizon brightening were taken as zero

Hence, $D(\beta) = \frac{1}{2} D^*(1+\cos\beta)$ (2.23)

And, the ground reflected radiation on tilted surface is composed of diffuse and beam reflectance from the ground (also called ground albedo) which is expressed as:

$$R(\beta) = \rho^*(Bbeam+Ddiffuse)\left(\frac{1-\cos\beta}{2}\right) \quad (2.24)$$

Where, ρ is reflectivity of ground cover

Then total global solar irradiation on inclined solar panel,

$$G(\beta) = B(\beta)+D(\beta)+R(\beta) \quad (2.25)$$

Table-2.2: lists the recommended tilt angles for a fixed system. (Source ref. 36)

Site Latitude	Fixed Tilt Angle
0° - 15°	15°
15° -25°	Same as Latitude
25° - 30°	Latitude + 5°
30° - 35°	Latitude + 10°
35° - 40°	Latitude + 15°
40°+	Latitude + 20°

2.3. Wind Energy system

2.3.1 Introduction

Winds are produced by uneven solar heating of the earth's land and sea surfaces. Thus, they are a form of "solar" energy. On average, the ratio of total wind power to incident solar power is on the order of two present, reflecting a balance between input and dissipation by turbulence and drag on the surface.

Wind is the movement of air caused by the irregular heating of the Earth's surface. It happens at all scales, from local breezes created by heating of land surfaces that lasts some minutes, to global winds caused from solar heating of the Earth. Wind power is the transformation of wind energy into more utile forms, typically electricity using wind turbines

The idea of creating something to capture the power from the wind is not a new idea. Wind turbines have been used for thousands of years for milling grain, pumping water, and other mechanical power applications. Today, there are over one million wind turbines in operation around the world. Most of them are used for water pumping and for generating electricity. Wind energy offers the potential to generate substantial amounts of electricity without the pollution problems of most conventional forms of electricity generation [33]

2.3.2 Wind Energy Converters and Regulation Mechanisms

A physical configuration which produces uneven force on the wind flow stream tends to rotate, oscillate and power could be harnessed from the wind flow. Wind turbines are machines that produce electricity by using power from wind to drive an electrical generator. The wind energy conversion machines extract the wind kinetic energy from the swept area of the turbine blades making pressure differences across the blade and initiate the electrical generator to generate electricity. The electrical generator produces electricity from the transformed mechanical energy. Wind turbines start to generate power when the wind speed flow passes the minimum wind speed (cut-in speed). The wind turbine power increases with the wind speed until it reaches the rated speed where it produces maximum power. The turbine does not produce power beyond the cut-off wind speed due to assembly of safety mechanisms that could stop turbine from producing power. There are two over speed or power control mechanisms needed to protect both load and turbine during high wind speed periods.

Pitch regulation: It has an electronic control system or active control mechanism which reduces the aerodynamic efficiency of the wind turbine. The principle how it works is that, the blades are to be turned along their axis of rotation with the help of pitch control mechanism as wind speed tries to cross rated speed. When wind velocity is greater than the rated wind speed the regulation mechanism automatically changes the blade pitch. The modification in the angle of attack would reduce the capability of the rotor. To avoid the operation of wind turbine blades out of the feasible range, the controlling mechanism should respond faster with wind speed variation. Pitch regulated turbines convert the wind speed more efficiently when wind flows in moderate range as blades set to its appropriate angle of attack. Referring in to figure 2.11 the power output of the turbine is increasing until the rated wind speed but beyond that it remains constant power.

Stall regulation: In this power control mechanism the profile of the blade is designed to be aerodynamically adjusted along its longitudinal axis in order to increase the angle of attack and has no active control. The increment of the angle of attack causes air to stick on the upper side of the blade and these results in turbulence, thus this effect stops the lift force on the blades, leading to blade stall. Generally, the power output is controlled by the special design of the rotor blades to ensure that as the wind speed gets higher it produces turbulence on the side of the turbine blades as a result the aerodynamic efficiency of the turbine decreases. The power production, rotational speed, aerodynamic torque decreases with the raise of wind speed as illustrated in the above figure 2.11.

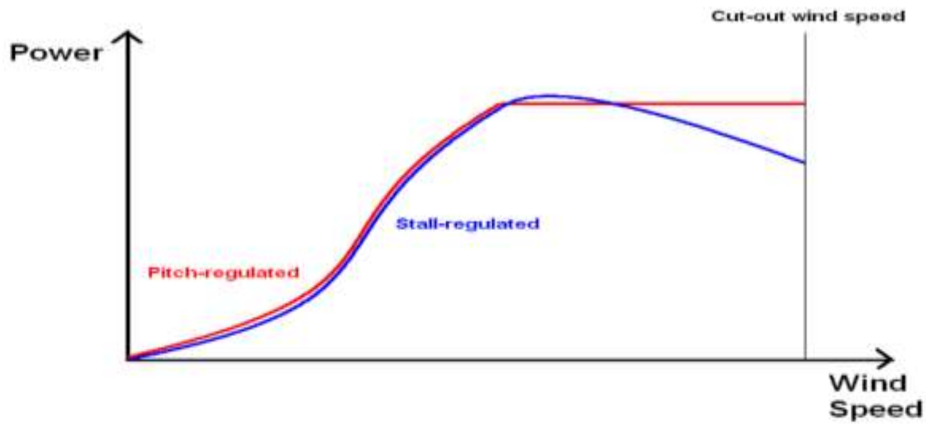

Figure-2.7: Wind Turbine Power Control Mechanisms

2.3.3 Wind Turbine types

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 [24].

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

The advantages with upwind turbines are that the tower does not act as an obstacle for the wind hitting the rotor. Despite this, the flow behind the passing blade is affected by the tower and causes a slight drop in power. When the blade passes the tower, it also decreases the drag on the construction which can cause an on / off bending process causing fatigue stress. This has of course been taking into account when designing the turbine. The upwind design needs a control system that helps the nacelle turn straight to the wind. In downwind turbines, the tower shades a rotor blade each time it passes by and causes greater power losses compared to the upwind design. An advantage with downwind turbines is that the nacelle is self-adjusting and is not in need of a control system. One drawback with this is the problem with untwisting the cable inside when the nacelle has turned same direction repeatedly. The VAWT´s are not as commercial and economically competitive as the HAWT´s. Some of the VAWT types suffer from low efficiency due to design difficulties as well as the problem with operation close to the ground. Parts of the vertical turbines will therefore receive low quality winds causing power losses. To keep the construction upright it also needs to be supported with guy cables attached to the ground. The vertical turbine is not in need of yaw control, which of course is an advantage and the wind always hits the turbine tangentially [33].

The modern wind turbine is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. The size of these turbines ranges from a few Watts (Small Wind Turbines) to several Million Watts (Large Wind Turbines). The modern trend in the wind industry is to go for bigger units of several MW capacities in places where the wind is favorable, as the system scaling up can reduce the unit cost of wind-generated electricity. Most of today's commercial machines are horizontal axis wind turbines (HAWT) with three bladed rotors. Figure 2.10 is the general architectures of the two well-known wind turbine types

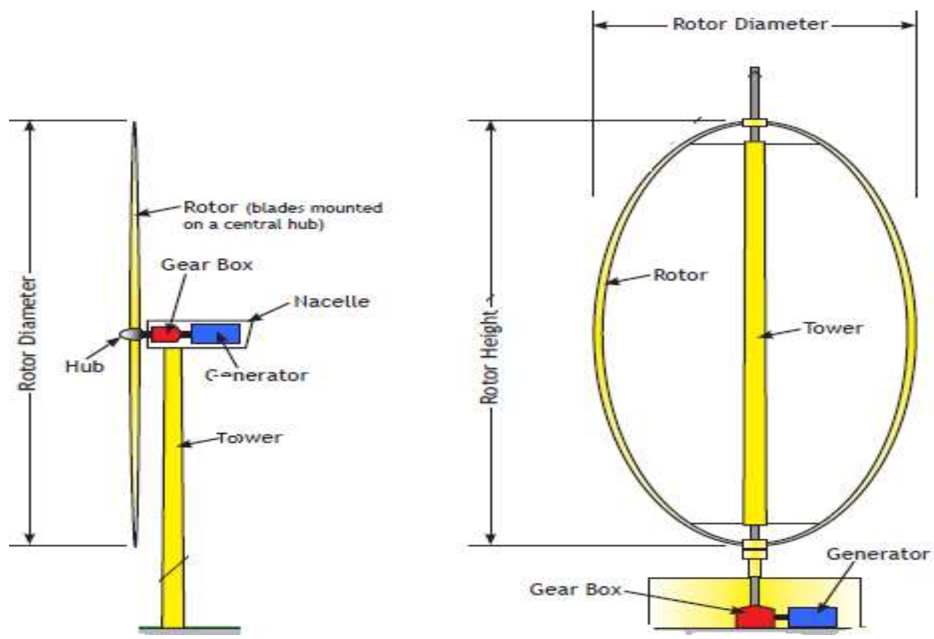

Figure-2.8: Horizontal and vertical wind turbine types

At their current size wind turbines accomplish significant economies of scale. According to Wizelius rising returns to scale the turbine is not an evident property as weight of the turbine might likely increase by third power of the turbine size, as the diameter of the turbine blades, swept area of turbine, would only rise by the square of the size. Nevertheless, increased hub height of the turbine and design optimization has enhanced turbine performance; as a result the bigger turbines are still cost effective (Wizelius, 2007).

2.3.4 Wind Turbines Components

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

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

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

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

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

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

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

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

High-speed shaft: Drives the generator.

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

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

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

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

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

Yaw motor: Powers the yaw drive.

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

2.3.5 Working Principle of Wind Turbines

Aerodynamic principle:

Air flow over a stationary airfoil produces two forces, a lift force perpendicular to the air flow and the drag force in the direction of air flow. The existence of lift force depends on a laminar flow over the airfoil, which means that the air flows smoothly over both sides of the airfoil. If turbulent flow exists rather than laminar flow, there will be a little or no lift force. The air flowing over the top of the air foil has to speed up because of the greater distance to travel; this increase in speed causes a slight decrease in pressure. This pressure difference across the air foil yields the lift force, which is perpendicular to the direction of air flow

The air moving over the air foil also produces a drag force in the direction of the air foil. This is a loss term and has to be minimized as much as possible in high performance wind turbines. Both the lift and drag are proportional to the air density, the area of the air foil, and the squire of the wind speed [34].

So how do wind turbines make electricity? Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

2.3.6 The Physics of Wind Energy

The power from the sun that comes to the earth's atmosphere reaches around 1.7*1014 kW [49]. This is the amount of radiation that heats the atmosphere air and the intensity of heating gets higher at the equator. The pressure gradient difference from the uneven heating of the earth's atmosphere (between the poles and equator) results in wind generation. Variation of wind velocity and direction above the ground level is necessary for energy conversion. A Wind turbine gets its power input from the wind flow that causes to develop a turning force of the rotor. Wind energy can be extracted from the wind using aerodynamic forces like lift & drag forces.

Lift force: It acts perpendicular to the wind flow direction and it is formulated due to unequal distribution of pressure across the surface of the blade profile. Lift driven devices have to be designed and are more efficient than drag driven devices. Turbine blades produces pressure difference in the top and bottom surfaces of the blade which resulted into lift force accordingly the kinetic energy of the wind is extracted. Figure 3-5 B1 represents the lift force based wind turbine.

Drag force: It acts parallel to the direction of wind flow. Savonius rotor is one of the wind turbine types that used drag force to rotate the turbine rotor and thus to generate power. It is simple to manufacture at any simple workshops. Referring into figure 2.14 B2 shows the savonius type turbine, where the drag force is higher in the convex or open shape of the cylinder than the concave surface.

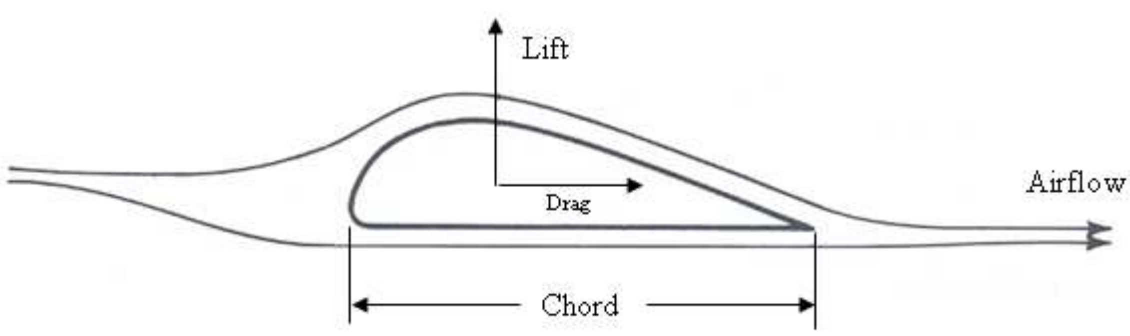

Figure -2.9 Lift and drag on a stationary airfoil

Wind speed: It is the most critical variable than the two parameters described above in determining the output power of the wind energy conversion machine. The figure 4-5 demonstrates how the wind flow varies before and after it hits the turbine rotor. The wind speed drops as it appeals the turbine, whereas the wind pressure increases in the upstream of the turbine and gets dropped below atmospheric pressure after the turbine. The increase in pressure at the rotor surface is due to the part of kinetic energy of the wind is changed into potential energy.

Cut-in Wind Speed: Speed Turbines start to generate power at wind speeds between 3-5m/sec. This wind speed is called the cut-in wind speed. Wind machines will not produce any more power below this wind speed.

Cut-off Wind Speed: It is the highest wind speed at which wind turbines not being produced power rather should stop to protect from damage. For most turbines the cut off speed is 25 m/s.

Nominal or Rated Wind Speed*:* The wind speed at which the maximum power is derived. This wind speed is the most important one which determines the power curve. Beyond this wind speed higher power generation is possible with special control to the power output to reduce rotor blade stress. Power curves having lower rated speed produce more energy because it will produce more energy between cut-in and rated wind speed. For most turbines the rated wind speed is between 11.5 to 15 m/sec [23, 32].

Survival Speed*:* Any wind turbine machine will not able to with stand wind speed beyond the cut out wind speed. It is not actually part of the power curve, but important to specify the design wind speed of the turbine. The range of survival speed is between 50 to 60 m/sec [32].

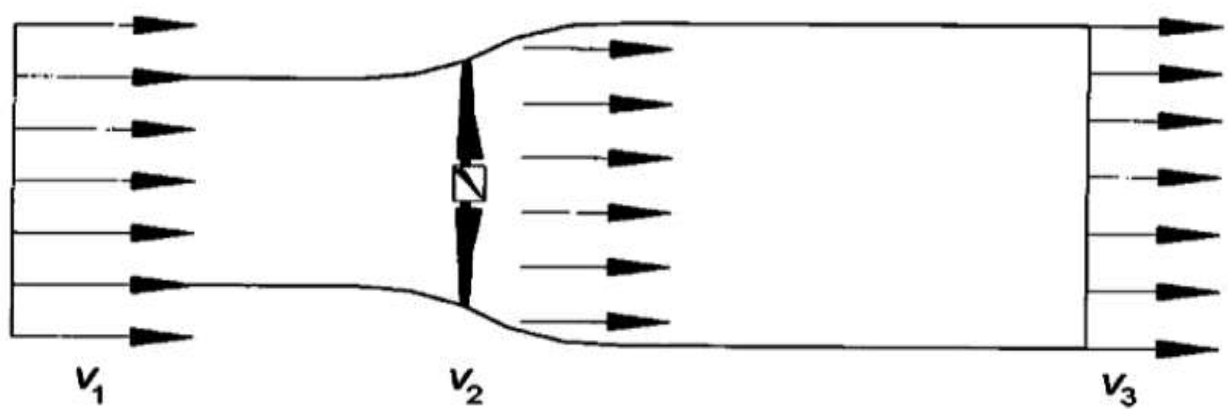

Figure-2.10: Air Flow across the Wind Rotor **[15]**

The general characteristic curve of a wind turbine, which exhibits wind turbine power output variation with wind speed, is as follows.

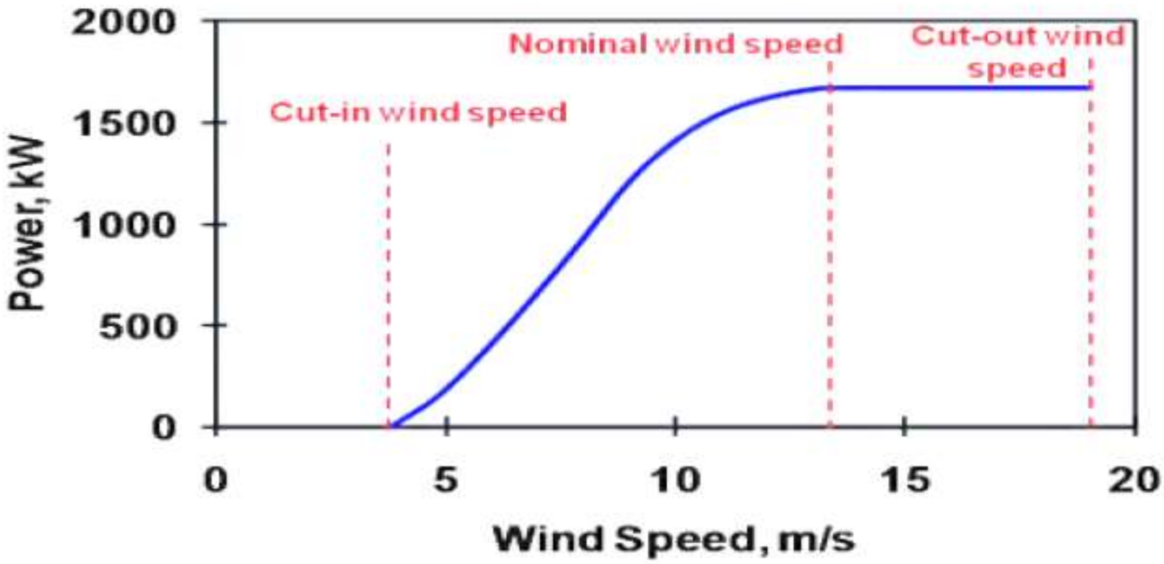

Figure-2.11: General characteristic curve of a wind turbine

2.3.7 Wind Shear

Apart from the availability of wind speed for an extended period of time, its distribution is an important factor in wind potential determination. The ground friction in relation to wind speed decreases with height from ground. Wind shear is the wind speed variations with height above ground level, thus it is also called wind speed profile. As wind turbine height increase length from ground the wind speed also increase and hence, power production also rises. This shows that the force acting on the turbine blade when it is in the top position is large. It is described by two methods, such as power law profile and logarithm profile. The wind speed at any height above ground level can be expressed either in exponential function or logarithmic function forms [22, 32]. The power law profile is given in equation below.

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad (2.26)$$

Where:

α: The power law exponent, which depends on the elevation, the time of the day, the season, the terrain, the wind speed and the temperature of the site.

V2: Wind speed estimated at hub height h2 [m/s]

V1: Wind speed at reference height h1 [m/s]

h1: Reference height above ground level [m]

h2: Hub height [m]

Table-2.3: The Power Law Exponent **[15]**

Terrain Type	Friction coefficient (α)
Lake, ocean, smooth hard ground	0.10
Foot-high grass on level ground	0.15
Tall crops and shrubs	0.20
country with many trees	0.25
Small town thru some trees and shrubs	0.30
City with tall buildings	0.40

Another method is the logarithmic function that is given below in equation 4.18. The logarithmic function adopts that the logarithmic height above ground surface is related to the wind speed.

$$\frac{V_2}{V_1} = \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \qquad (2.27)$$

Where

zo: Surface roughness length factor [m]; Surface roughness length describes the roughness of the surroundings terrain.

ln(…): Natural logarithm

Table: 2-4 Surface Roughness Lengths **[15]**

Terrain Description	z_o (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.010
Crops	0.05
Few trees	0.10
Many trees, few buildings	0.25
Forest and woodlands	0.5

The turbine efficiency varies with wind speed, due to this; performance of wind turbines is described using the power curve that specifies wind turbine output power in terms of wind speed moving towards the turbine. The cut-in, rated and cut out speeds are among the several crucial features of the power curve of a wind turbine it has. The lowest wind speed where the wind turbine can generate power is known as cut-in speed. The rated speed is the minimum speed that the wind turbine has to produce at rated output. Since the wind speed increases starting from the cut-in speed to the rated speed, the output power from the turbine rises steadily to the rated output. The output power from the turbine is limited to the rated output above the rated speed (Gipe, 2009; Wizelius, 2007). It is unlikely to exploit the extra power in the wind above the rated speed. The turbine stops above the cut-out speed for safety reasons and no power production at extremely high wind speeds. Wind turbines also have a survival wind speed that is the maximum wind speed the turbine can withstand from damage. Wind turbine power curve is illustrated in figure 2.12 below.

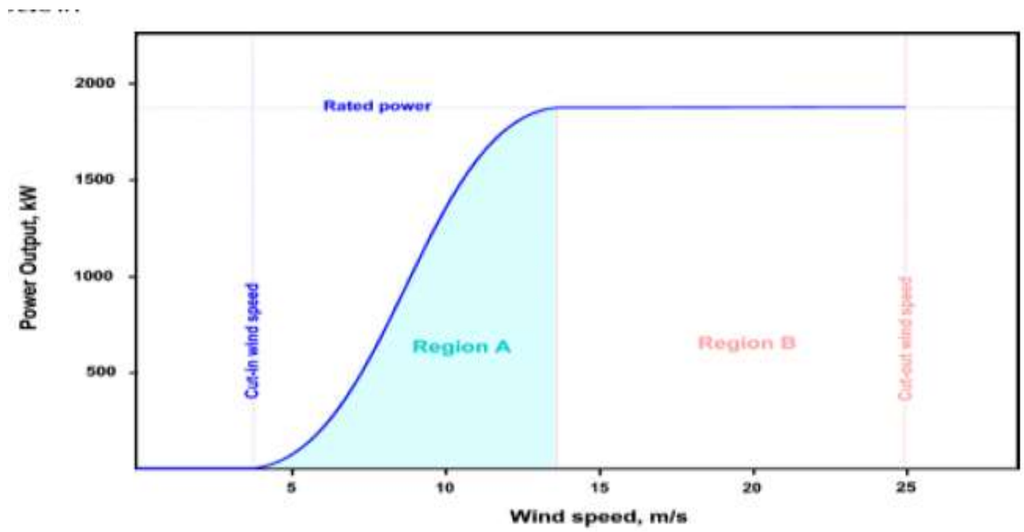

Figure 2.12: Power curve of wind turbine with wind speed Vs power output

2.3.8 Wind Turbine efficiency

All the kinetic energy existing in the wind cannot be extracted with a wind turbine, as this would need reducing the wind speed to zero. According to Betz law the maximum amount of energy which can be harvested by the turbine at its nominal wind speed is about 59.3%, this is called as performance of the turbine, i.e. the turbine's efficiency which is below the limit placed by Betz limit. Turbines which commercially exist today operate at their highest coefficient of performance (Cp) value up to 45% (Wizelius, 2007). Figure 2.13 illustrates efficiency of a turbine at a series of wind speeds. A turbine's power coefficient depends on many factors like the profile of the turbines' rotor blades, blade arrangement and setting etc.

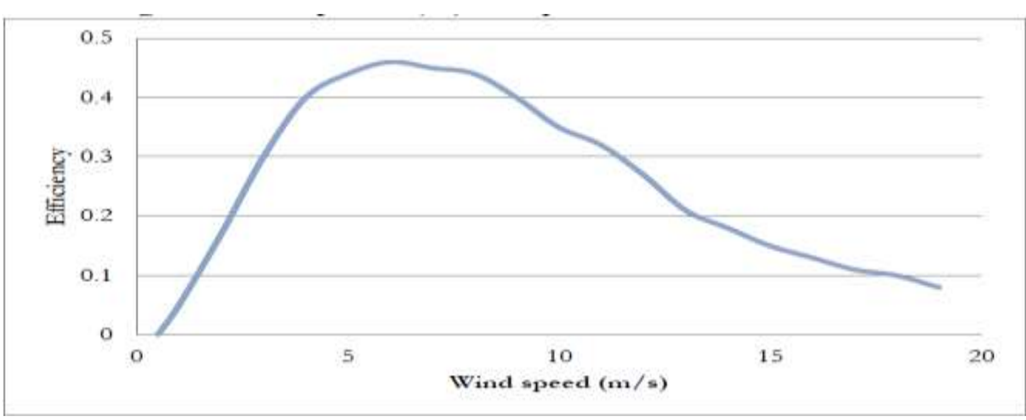

Figure 2.13 efficiency of a turbine at a series of wind speeds

2.3.9 Weibull Distribution

Beyond the strength of wind in a time period, the wind speed distribution is also a decisive factor in the wind potential determination. Weibull value is a measure of the annual distribution of wind speeds. Weibul distribution parameters help to attribute wind regimes. For two wind turbines installed at two different sites but having the same wind speed may result in different power outputs as a result of wind speed distribution. According to [33 and 34,] wind speed distribution at any site of interest is best described by the Weibull probability distribution function (PDF) or cumulative distribution function (CDF). The probability of the wind speed being V at any instant time is expressed as in equation below.

$$h(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} e\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{2.28}$$

Where:

h: probability distribution function

k: shape factor, describing the dispersion of the wind speed.

c: scale parameter in [m/s] and V: wind speed in [m/s]

The lesser value of the shape factor represents large distribution of wind speed; whereas the larger value shows the minimum distribution of the wind speed value. The wind weibull distribution with k=2 is called Rayleigh distribution. The cumulative distribution function of wind speed is given by the following expression:

$$F(V) = 1 - e^{\left[-\left(\frac{V}{c}\right)^{k}\right]} \tag{2.29}$$

Based on the Rayleigh distribution, the PDF can be expressed mathematically as below.

$$h(V) = \frac{2V}{c^2}\, e\left[-\left(\frac{V}{c}\right)^{2}\right] \tag{2.30}$$

The scale factor (c) is given by equation (2.36) below and this equation relates the weibul parameters

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \qquad (2.31)$$

Where: Γ: Gamma function

Most wind sites have values of shape factor k varying from 1.5 to 3 and the scale parameter c from 5 to 10 m/s anemometer high and altitude [31].

2.3.10 Power extracted from wind turbine

The potential of power density or specific power for a specific site is expressed in terms of air density and wind speed as follows [22, 23, 26, and 28].

$$\frac{P}{A} = \frac{1}{2}\rho V^3 \qquad (2.32)$$

Where:

P/A: Power density [W/m2]

The power density expressed in equation 4.7, is the power in the upstream of the wind turbine rotor. However, the power extracted by the rotor blade is less than the calculated one using the equation above**.** Betz equation suggested that the wind turbine rotor cannot extract all of the wind energy provided and it deals with the wind speeds of V1 & V3 in the upstream and downstream of the turbine rotor respectively. Referring into figure 2.15, the wind flow decreases at the face of the rotor and the mechanical power obtained can be expressed mathematically as below.

$$P_0 = \frac{1}{2} m_a\left({V_1}^2 - {V_3}^2\right) \qquad (2.33)$$

Where:

Po: Mechanical power extracted by the wind turbine machine [W]

V1: Wind flow speed in the upside of rotor [m/s]

V3: Wind flow speed in the downside of rotor [m/s] ma: The mass flow rate of air [kg/s]

The mass flow rate of air can be determined by using equation 4.9 considering both wind speeds in the upper stream and downstream of the rotor.

$$m_a = \rho A\left(\frac{V_1+V_3}{2}\right) \tag{2.34}$$

The power extracted by the wind turbine is given as in equation 2.27.

$$P_0 = \frac{1}{2}\rho A V_2{}^2(V_1 - V_3) = 2\rho A V_2{}^2(V_1 - V_3) \tag{2.35}$$

The maximum power of wind turbines is extracted when the wind speed at the surface of the rotor is given as in equation 2.20.

$$V_2 = \frac{2}{3}V_1 \tag{2.36}$$

This shows that wind speed down of the wind turbine is:

$$V_3 = \frac{1}{3}V_1 \tag{2.37}$$

Where:

V1: The wind speed at the face of the wind turbine rotor
V3: Wind speed in the downstream after power extraction by the wind turbine rotor
V2: Wind speed in the upstream before power is extracted by the wind turbine machine

Performance coefficient is the measure of the wind turbine efficiency in producing energy from the wind stream, however the Betz limit equation concerns with the two wind speeds as stated above. The fraction of wind power extracted by the wind rotor or it is also called efficiency of the rotor is given as follows:

$$C_p = \frac{\text{maximum power extracted}}{\text{power availabl in the wind}} = \frac{\rho A V_1{}^3\left(\frac{8}{27}\right)}{\frac{1}{2}\rho A V_1{}^3} = \frac{16}{27} \tag{2.38}$$

The rotor efficiency has a theoretical maximum value of 0.593, as depicted in figure and it is called the Betz limit. In real cases due to lose the maximum value of Cp is 0.4 and 0.5 for two blade rotors and between 0.2 and 0.4 for more blade as well as low speed turbines [26].

A wind turbine converts kinetic energy of air i.e. wind power into mechanical power i.e. rotating motion of the turbine that can be used directly to run the machine or generator. Power captured by wind turbine blade is a concomitant of the blade shape, the pitch angle, speed of rotation, radius of the rotor [33]. The equation for the power generated is shown below.

$$P_M = \frac{1}{2}\pi\rho C_P(\lambda, \beta)R^2V^3 \tag{2.39}$$

PM– Power captured by wind turbine

ρ – Air density, β– Pitch angle (in degrees)

R– Blade radius (in meters), V– Wind speed (in m/s)

The term λ-is the tip-speed ratio, given by the equation

$$\lambda = \frac{\omega R}{V} \tag{2.40}$$

Because wind energy has become the least expensive source of new renewable energy that is also compatible with environment preservation programs, many countries promote wind power technology by means of national

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator.

The theoretical power available in the wind can be expressed mathematically as follows.

$$P = \frac{1}{2}\rho A V^3 \tag{2.41}$$

Where:

P: Power available in the wind [W]

V: Wind speed [m/s] , A: Rotor swept area [m2] and ρ: Air density [kg/m3]

This theoretical power that is available in the wind could not be realized at all due to the decrease of kinetic energy of the wind which would not be dropped to zero level.

The fundamental equations governing the mechanical power capture of the wind turbine rotor blades, which drive the electrical generator, are given by;

Mechanical power available for the load machine is obtained by the multiplying with the efficiency of the drive train (gearbox)

$$P_m = \frac{1}{2}\rho A V^3 C_p \, \eta_m \qquad (2.42)$$

.

Electrical power of the wind turbine is expressed mathematically as;

$$P_{el} = \frac{1}{2}\rho A V^3 C_p \, \eta_g \eta_m \qquad (2.43)$$

Where:

P_{el}: wind turbine electrical power [kW] , P_m: wind turbine mechanical power [kW]

η_m: The mechanical (gear box) [%] , η_g: Electrical generator efficiencies [%]

The rotor swept area is expressed mathematically.

$$A = \frac{\pi D^2}{4} \qquad (2.44)$$

Where:

A: The rotor area [m2] and D: The rotor diameter [m]

Air density: The heavier the air, more energy harnessed by the turbine. Density is mass per volume and kinetic energy is a function of the two air flow parameters. It also affects by the variation of air temperature and pressure of the location.

$$\rho = \frac{P}{RT} \qquad (2.45)$$

Where:

: Air flow density [kg/m3], P: Air pressure [pascal]

R: Gas constant [287 J/kg˚k] , T: Absolute temperature of air [k]

2.4 Hybrid power system

Hybrid energy system is a configuration of two or more renewable and even non-renewable energy as main sources of energy generation so that the capacity shortage of power from one source will substitute by other available sources to cater sustainable power. It is appropriate means to provide electricity from locally available energy sources for areas where grid extension is capital intensive, geographically isolated places for which electricity transmission from centralized utility is difficult. Naturally gifted renewable sources can be harnessed to generate electricity in a sustainable way to provide power and make comfortable the living standard of people. There are different merits and drawbacks of using only renewable sources for electricity generation in rural villages, merits like fuel cost incline, fuel transport cost is high, issues of global warming and climate change in large. The drawbacks of using renewable sources as off-grid/standalone power systems, it has intermittence nature that makes difficult to regulate the power output to manage with the load sought. To make sure for the reliability and affordability of the supply, combining conventional diesel generator with nonconventional energy generators can solve the problem visible while operating individually.

Some of the advantages combining the two sources of energy production are stated as follows.

- Diesel generator fuel usage and greenhouse gas reduction
- Resourceful use of locally available resources
- Deducts/avoids power shortfalls, increase sustainability power supply
- It provides electricity access in short periods than waiting for grid extension and ease to scale-up at any time
- Reduce the dependency from oil price fluctuations.
- Reduce the transportation costs of fuels.

- **System components**

The hybrid power system, described here, basically includes the following main elements:

- ✓ Renewable energy sources: PV-system, Wind generator.
- ✓ . Energy storage bank: Battery bank.
- ✓ Backup energy source: Diesel generator set.
- ✓ AC-loads.
- ✓ Power electronic devices.

2.4.1 Battery Storage system

In recent years much of the focus on the development of electric storage technology has been on batter storage which is the main emphasis of this paper. In a chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the system. The first commercially available battery was the flooded lead-acid battery which was used for fixed, centralized applications. The valve-regulated lead-acid (VRLA) battery is the latest commercially available option. The VRLA battery is low-maintenance, spill- and leak-proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not yet reached the commercial market. Other lithium-based batteries are under development. Batteries are manufactured in a wide variety of capacities ranging from less than 100 watts to modular configurations of several megawatts. As a result, batteries can be used for various utility applications in the areas of generation, transmission and distribution and customer service. Batteries currently have the widest range of applications as compared to other energy storage technologies. The type and the number of battery storage applications are constantly expanding mainly in the areas of electric and electric hybrid vehicles, electric utility energy storage, portable electronics, and storage of electric energy produced by renewable resources such as wind and solar generators

From the energy storage devices, the selected and most common one is lead-acid battery which is applicable for standalone systems due to its moderate cost, maturity, high performance over cost ratio. It is available in different capacities like 6V, 12V and 24V terminal voltages. A battery life is affected with how much of their energy storage capacity is consumed at a time known as depth of discharge. During unfavorable climatic conditions, the demand has to meet by the batteries; moreover, if the battery is discharging deeper, the diesel generator caters the energy demand, and at the same time charges the battery if the power controls mechanism could be cycle charging. Deep cycle batteries can discharge from 15-20% of their capacity, which means that it shows a discharge of 85-80%.

Some of the Factors that affect the sizing of battery system are the following.

- Daily energy demand
- Days of autonomy
- Maximum depth of discharge

- Temperature correction
- Rated battery capacity and battery life
- Cost and warranty:
- Accessibility of location:

To use part of the total stored energy of the battery it should be sized large enough and this is determined using the DOD. Energy generated from renewable energy conversion technologies has energy outages when there is no sun or wind blow, to avoid such shortfalls a battery bank should maintain days or hours of autonomy. It is described mathematically by the following formulas [42, 43].

Total capacity of the battery capable to supply the full load demand can be determined using the following mathematical expression.

$$C_B = \frac{E_L S_D}{V_B (DOD)_{max} T_{cf}\, \eta_B} \tag{2.46}$$

Where:

CB: Capacity of battery [Ah]

EL: The electrical load [Wh]

SD: Battery autonomy [days]

VB: Storage battery voltage [V]

(DOD)max: Maximum depth of discharge of battery

Tcf: Temperature correction factor

ηB: efficiency of battery [%]

Batteries are the basic component of an energy storage system. A battery consists of one or more electrochemical cells that are electrically connected. The basic components of an electrolytic cell like a lead-acid cell are a positive electrode, a negative electrode, a porous separator and an electrolyte. During cell operation, ions are created and consumed at the two electrode/electrolyte interface by oxidation/reduction reactions. The electrolytes which can either be a solid or liquid chemical, has high conductivity for ions but not for electrons, because if the electrolyte conducts electrons then the battery will self-discharge

The model of the lead acid battery, the equivalent circuit of the battery storage system can be represented as in below,

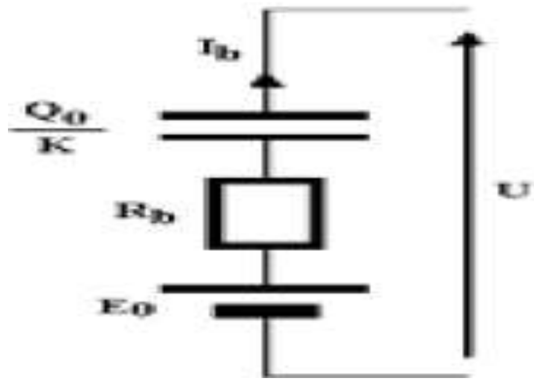

Figure: 2.14 Electrical equivalent model of the battery

The mathematical model given by Eq. (3.14) that best describes the physical phenomenon of the charge and discharge is given below:

$$U = E_0 - K.\frac{\int I_b.dt}{Q_0} - R_b.I_b \tag{2.47}$$

Where

U is the voltage across the battery; $\mathbf{E_0}$ is the open circuit voltage of the charged battery, a constant **K** which depends on the battery, the internal resistance $\mathbf{R_b}$ of the battery, the discharging current $\mathbf{I_b}$, Q_0 is the ability of the battery (Ah), the integration,

$\frac{\int I_b.dt}{Q_0}$ shows the discharge state of battery.

2.4.2 Backup Diesel Generator

Backup generator is part of the hybrid system contemplated in this thesis. A power generator is a machine used to generate electricity by changing/transforming the kinetic energy of motion of the combustion engines into electricity using different energy sources. Combustion engines are the simplest means of electricity generators with the use of oil due to their low initial capital investment. Backup generator is used to optimize renewable power output, to improve frequent shortfall of energy when power interruption is happened from renewable sources and the battery is unable to provide the required energy. The running cost of generators is high as compared to the running cost of renewable sources. When considered the incorporation of combustion engine into the hybrid system, the fuel availability and engine efficiency are the significant factors to consider. Backup generators allow designing power systems with minimum or without storage batteries. Based on the explanation given in [61] generator operates efficiently at full load, and thus it's better to run only after the energy storage (batteries) have fallen 20% of their full charge. DC generators and AC generators are the two basic types of generators. Referring into [41] AC machines also categorized as asynchronous and synchronous generators/motors.

Synchronous generators: They are machines that convert mechanical power into AC electricity. They provide precise control of voltage, frequency. Runs at synchronous speed, moreover, provide the alternating current needed. They provide the electric energy required by the society. It can be used for both grid and off the grid power providing systems [52]. Synchronous generator drives through a constant speed engine that corresponds to the required generator output voltage frequency. Here below is described the mathematical expressions for the generator fuel curve and efficiency curves.

Fuel curve: It shows the fuel quantity the generator consumes to generate electricity. The mathematical expression below is to give the generators fuel consumption in units per hour [31].

$$F = F_o . Y_{gen} + F_1 . P_{gen} \tag{2.48}$$

Where:

Fo: The fuel curve intercept coefficient [units/hr/kW]

Ygen: Fuel curve slope [units/hr/kW]

F1: Rated capacity in [kW]

Pgen: Electric output in [kW]

Efficiency curve: the efficiency is the ratio of the electrical energy generated to the chemical energy of the fuel consumed by the generator [41]

$$\eta_{gen} = \frac{3.6 * P_{gen}}{\dot{m}_{fuel} * LHV_{fuel}} \tag{2.49}$$

where:

η_{gen}: Generator efficiency

m_{fuel}: The mass flow rate of fuel [kg/hr], L_{HVfuel}: The lower heating value [MJ/kg]

P_{gen}: The electrical output [kW], 1 kWh = 3.6 MJ

The fuel consumption and the mass flow rate relate as follows, however the relation depends on fuel units. When the fuel unit is in kg, then mass flow rate is equal to consumption.

$$\dot{m}_{fuel} = F = F_o . F_{gen} + F_1 . P_{gen} \tag{2.50}$$

When liter is the unit of the fuel, the mass flow rate and fuel consumption relation depends on density. Thus the equation for mass flow is given as below.

$$\dot{m}_{fuel} = \rho_{fuel}\left(\frac{F}{1000}\right) = \rho_{fuel}\frac{\left(F_{0}.Y_{gen} + F_1.P_{gen}\right)}{1000} \tag{2.51}$$

Where:

ρ_{fuel}: Fuel density [kg/m3]

2.4.3 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 in to 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 direct current output voltage. In this paper 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 & PV, moreover to change the AC voltage from the wind or diesel generator into direct current 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 paper case since power is provided from both diesel generator and 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. Direct current electricity generated from PV and wind is converted in to AC electricity by using an inverter, and hence, this electricity is the one connected to individual household's appliances.

2.4.5 Technical configurations for hybrid power systems

The hybrid system can be designed following different configurations to effectively use the locally available renewable energy sources and to serve all power appliances.

For the hybrid power system whose demand is to be supplied from wind turbine, PV system, a diesel generator and a battery, in general, there are three accepted categories hybrid system technological configurations according to the voltage they are coupled with each other and the load. These are:

i. AC-coupled hybrid power systems
ii. DC-coupled hybrid power systems.
iii. Mixed-coupled hybrid power systems

For hybrid power system whose demand is to be supplied from wind turbine, PV system, and a battery are connected to a DC main bus before being connected to the load. Connection with the AC loads is done through a main inverter. the AC producing power components like wind turbine and diesel generator can provide part of the load directly to consumers. It has somehow complex design, but it has advantage as compared with series arrangement, optimal power generation can be met, maximized diesel efficiency, possible decrease in capacity of fuel and battery.

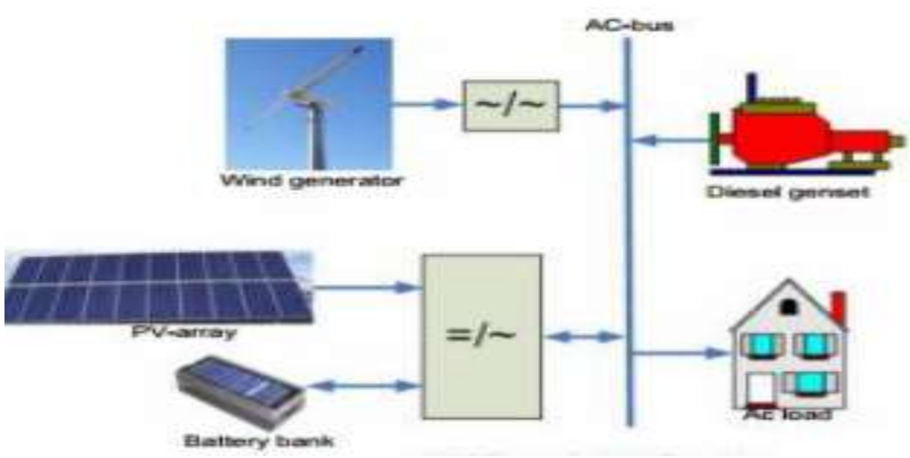

Figure-2.15: Centralized AC-coupled HPSs.

- **Total hybrid power generated at any time t,**

$$P(t) = \sum_{PV=1}^{NPV} PV + \sum_{WE=1}^{NW} PWE + \sum_{DG=1}^{NDG} PDG \quad (2.52)$$

Where, N_{PV}, N_W, N_{DG} are number of units of PV cells, wind generator and diesel generator units respectively.

This generated power will feed to the loads. The diesel generator has the constraint to always operate between 80 and 100% of their kW rating. 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 occur to meet the load. The charged quantity of the battery bank has the constraint $SOC_{MIN} \leq SOC(t) \leq SOC_{MAX}$.

- **Total Cost optimization**

The approach involves the minimization of a cost function subject to a set of equality and inequality constraints. The total capital cost C_C for the proposed combination of PV-Wind-diesel generator hybrid system is given by,

$$CC = \sum_{PV=1}^{NPV} CPV + \sum_{WE=1}^{NW} CPWE + \sum_{DG=1}^{NDG} CPDG + \sum_{B=1}^{NB} CBat + CF \quad (2.53)$$

Where CF= Fixed cost including cost of inverter and other installation costs

The annual operating cost **Co** computed based on the operating costs of all the installed units for the interval t in a day as shown below.

$$Co = \sum_{t=1}^{365} \{\sum_{t=1}^{24} Copv\ (t) + Copwe(t) + Copdg(t) + Cobat(t) + CoF(t)\} \quad (2.54)$$

Total annualized life cycle cost of the system comprises both capital and operating cost,

$$C_{Annual} = (C_C * CRF + C_O) \quad (2.55)$$

Where, C_{Annual} =total annualized life cycle cost of the system, C_C = total capital cost, CRF=capital recovery factor for the system with expected discount rate and C_O= annual operating cost

Unit cost of electricity (C_{OE}) by hybrid energy system is,

$$C_{OE} = \frac{CAnnual}{ET}, \text{ where } E_T\text{- is total load served in Kwh/year} \quad (2.56)$$

CHAPTER THREE
SITE INSPECTION AND DATA COLLECTION

3.1 Assessment of Solar Resource Potential

Solar radiation that reaches the earth's surface in a in a straight line is called direct, while sunlight scattered by could, dust, humidity and pollution is called diffused. The sum of the direct and diffuse sunlight is called global-horizontal insolation. Concentrating solar technologies, which use mirrors and lenses to concentrate sunlight, rely on direct radiation, while PV cells and other solar technologies can function with diffused radiation. Photovoltaic cells not only use the direct component of the light, but also produce electricity when the sky is overcast to the average total solar energy received over the year, rather than to refer to instantaneous irradiance

Studies indicate that for Ethiopia as a whole, the yearly average daily radiation reaching the ground is 5.26kWh/m^2. This varies significantly during the year, ranging from a minimum of 4.55kWh/m^2 in July to a maximum of 5.55kWh/m^2 in February and March. On regional basis, the yearly average radiation ranges from values as low as 4.25 kWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to values as high as 6.25 kWh/m^2 around Adigrat in the Tigray regional state (northern Ethiopia) and in Afar and Somali Region of Eastern Ethiopia

Current uses of solar energy are for Off-grid rural applications in homes, rural telecoms and in the social sectors (water pumping, health services, schools). Solar energy is also becoming an important alternative to water heating in the major cities. The current total installed photovoltaic power in Ethiopia is about 3.5MW, three-quarters installed in telecom stations (mostly in mobile towers but also in other stations). Solar water-heating installations are in a thousand or so units in Addis Ababa and the major cities [14].

3.1.1 Solar potential of study village

The assessment of the potential for solar radiation of the selected area was done by taking data from different sources. These were National Metrological Service Agency of Ethiopia (NMSA), NASA, and other literatures. There is no metrological station that can measure neither sunshine hour nor radiation data at the Addis Boder village.

The nearby station found is Tarcha town about 60 kilometer distance with latitude of 7.10 North and longitude 37.09.East. It is common not to get the direct measurement of solar radiation in many developing countries. The same is true for many stations in Ethiopia. At the first approach, the data taken from the National Metrological Service Agency was analyzed using mathematical approach based on the sunshine duration collected on the past five consecutive years starting from 2011 to 2015. The sunshine duration data was taken from the National Metrological Agency of Ethiopia Hawassa branch. In order to determine the solar radiation from the measured sunshine hour, among different model describing solar radiation and sunshine hour, here Angstrom- Prescott model was selected which is an improvement on angstrom model by avoiding clear sky radiation (Hc) as it is difficult to get from measurement and calculation [20], was converted into solar radiation using Angstrom Radiation-Sunshine Relation [20]. Therefore, for calculating the radiation in KWh/m^2 from the sunshine duration, the values for the regression coefficients ɑ and b were firstly calculated [16] and, finally this result was compared with the data taken from NASA.

❖ Irradiation calculations of the village from collected sunshine hours:

Geographical parameters

Station	Latitude	Longitude	Elevation
Tarcha	7^0 10'16''	37^0 09'16''	1844m

I. Declination angle

$\delta = 23.45 \sin(360 \frac{284+n}{365})$, Where, n= the day of a year (a number between 1 to 365, starting from first January

Then; $\delta 1$=23.45(-0.7583) = -17.7823 $\delta 7$=23.45(0.7749) = 18.171

$\delta 2$=23.45(-0.369725) = -8.67 $\delta 8$=23.45(0.345612) = 8.1046

$\delta 3$=23.45(0.15431) = -3.61854 $\delta 9$=23.45(-0.1628) = 3.8178

$\delta 4$=23.45(0.6221) = 14.587 $\delta 10$=23.45(-0.64205) = -15.0562

$\delta 5$=23.45(0.93384) = 21.8985 $\delta 11$=23.45(-0.9369) = -21.9699

$\delta 6$=23.45(0.98867) = 23.185 $\delta 12$=23.45(-0.98447) = -23.0859

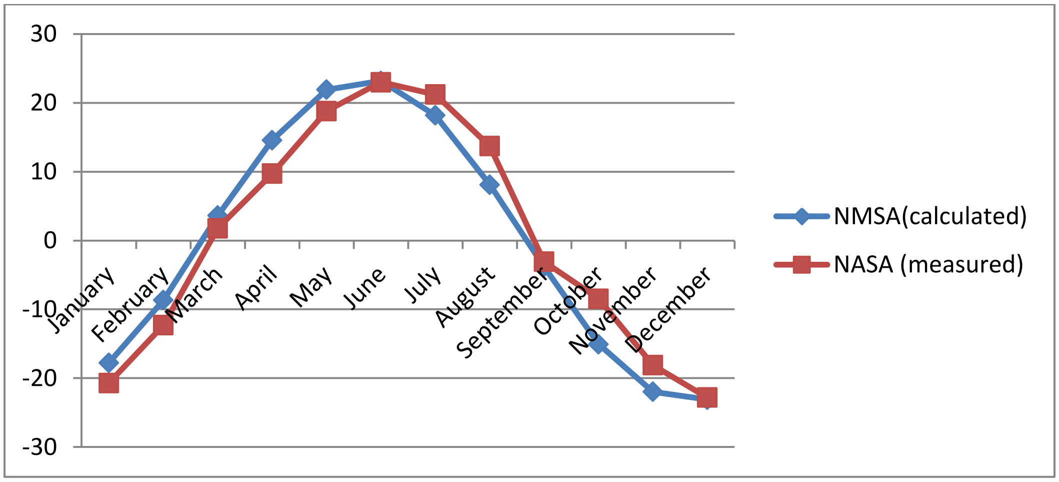

Figure 3.1- Calculated and NASA measured declination angle

II. Solar Hour Angle and Sunset Hour Angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon.

The sunset hour angle is the solar hour angle corresponding to the time when the sun sets and it is given by ωs from equation 2.17;

$cos\omega s = -tan\emptyset tan\delta$, Where ωs sunrise hour is angle and – ωs is sunset hour angle for the day of the year.

$$\omega s = \cos^{-1}[-tan\varphi tan\delta), \text{ where } \emptyset = \text{latitude angle} = 7.1^0$$

$$cos\omega s1 = -tan\varphi tan\delta 1 = -\tan 7.1 \tan(-17.7823) = (-(0.1245566)(-0.3207) = 0.039948$$

$$\omega s1 = 87.71$$

Similarly substituting the corresponding values and calculating;

$\omega s2$ =88.91 $\omega s8$ =91.02

$\omega s3$ =90.45 $\omega s9$ =89.52

$\omega s4$ =91.86 $\omega s10$ =88.08

$\omega s5$ =92.87 $\omega s11$ =87.12

$\omega s6$ =93.06 $\omega s12$ =86.95

$\omega s7$ =93.34

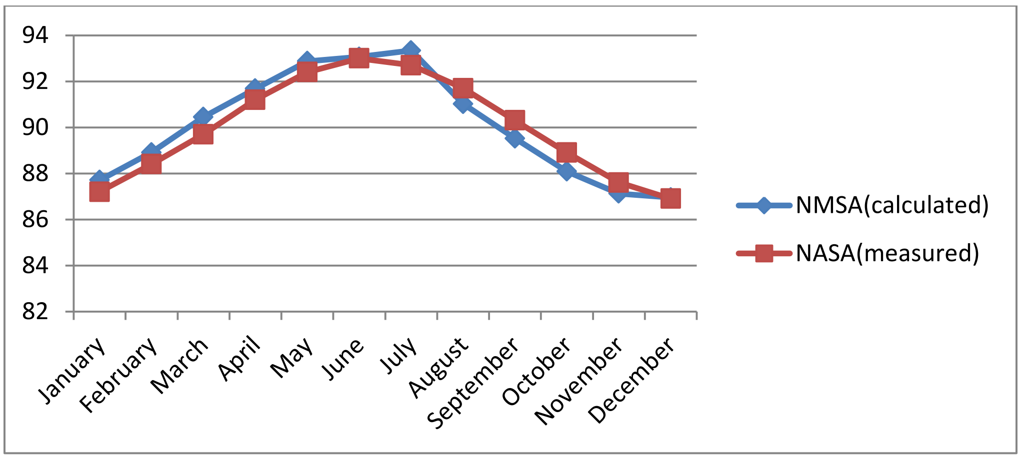

Figure-3.2- Calculated and NASA measured sunset angle

III. Extraterrestrial Radiation (Ho) calculation

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Monthly average daily extraterrestrial irradiation is calculated from the above equation 2.14:

$Ho = \frac{24}{\pi} Gsc * \left(1 + 0.033\cos\frac{360n}{365}\right)(\cos\varphi\cos\delta\sin\omega s + \frac{\pi\omega s}{180}\sin\varphi\sin\delta)$ and Average Ho,avr for the month is calculated as follow. [20]

$Ho,avr = \frac{\sum_{n=1}^{N} Ho}{N}$, Where, Gsc = global solar constant =1.367 Kw/m2 , Then;

$$Ho_1 = \frac{24}{\pi} Gsc * \left(1 + 0.033\cos(\frac{360n}{365})\right)(\cos\varphi\cos\delta 1\sin\omega s1 + \frac{\pi\omega s}{180}\sin\varphi\sin\delta 1)$$

$$= \frac{24}{\pi} 1.367\left(1 + 0.033\cos\frac{360*15}{365}\right)(\cos 7.1\cos(-17.7823)\sin 87.71 + \frac{\pi 87.71}{180}\sin 7.1\sin(-17.7823)$$

Ho_1=10.4431*1.0319 [(0.9923 *0.9522*0.9992) + (1.531*0.12360*(-0.151))] = 9.55

Similarly, by substituting the corresponding values of δ and ωs, the values of remaining monthly average daily extraterrestrial irradiation is as follows:

Ho_2 =10.16 Ho_8 =10.29

Ho_3 =10.30 Ho_9 =10.37

Ho_4 =10.46 Ho_{10} =9.56

Ho_5 =10.16 Ho_{11}=9.07

Ho_6 =10.01 Ho_{12} =9.03

Ho_7 =10.15

$$Ho,avr = \frac{\sum_{n=1}^{12} Hon}{12} = \frac{119.11}{12} = \mathbf{9.92\ kwh/m2/day}$$

IV. Calculation of Monthly Average Daily Horizontal Global Radiation (H)

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index.

- The maximum possible sunshine duration N in hours for a horizontal surface is given by above equation 2.18 as;

$$N=\frac{2}{15}\omega s$$

Substituting ωs values from above calculations, we have, N values as;

$N1 = \frac{2}{15}(\omega s1) = N1 = \frac{2}{15}(87.71) = 11.69,$

$N2 = \frac{2}{15}(88.91) = 11.85,$ $N3 = \frac{2}{15}(90.45) = 12.06$, $N4 = \frac{2}{15}(91.86) = 12.25$

$N5 = \frac{2}{15}(92.87) = 12.38,$ $N6 = \frac{2}{15}(93.06) = 12.41,$ $N7 = \frac{2}{15}(93.34) = 12.45$,

$N8 = \frac{2}{15}(91.02) = 12.14$, $N9 = \frac{2}{15}(89.52) = 11.94,$ $N10 = \frac{2}{15}(88.08) = 11.74$

$N11 = \frac{2}{15}(87.12) = 11.62$, $N12 = \frac{2}{15}(86.95) = 11.59$

Then, Horizontal radiation can be calculated by using the modified quadratic Angstrom regression equation from equation 2.13 above.

$\frac{H}{Ho} = a + b\frac{n}{N}$, where, $\frac{H}{Ho}$ is clearness index

$\frac{n}{N}$ is cloudiness index

Whereas, 'a' and 'b' are constants for the locations and their values is calculated from the equations, [Alfa Hailemariam A. et al [38]]

$$a = -0.309 + 0.539\cos\text{Ø} - 0.0693Eo + 0.290(\frac{n}{N}) \quad (3.1)$$

$$b = 1.527 - 1.027\cos\text{Ø} + 0.0926Eo - 0.359(\frac{n}{N}) \quad (3.2)$$

Where, Ø = the latitude in degree, which is equals to 7.10, n- is the monthly average of bright sunshine hours per day , N- is the average of the maximum daily hours of sunshine and Eo is altitude/elevation/ of site in kilometers.

From above calculations, monthly average of n = 7.24 and N=12.01, and site elevation is 1844m/1.844km/, then inserting the values of Ø, n, N and Eo, we have;

$$a = -0.309 + 0.539\cos 7.1 - 0.0693*1.844 + 0.290(\frac{7.24}{12.01}) = 0.272$$

$$b = 1.527 - 1.027\cos 7.1 + 0.0926*1.844 - 0.359(\frac{7.24}{12.o1}) = 0.462$$

Then, $\frac{H}{Ho} = a + b\frac{n}{N} \rightarrow H = Ho\,[a + b\frac{n}{N}]$, From above calculations,

$H_1 = Ho_1\,[a + b\frac{n1}{N1}] = 9.55[0.272+0.462(0.0.746) = 5.89$

Similarly, by substituting the corresponding values, the results of remaining monthly average radiation are as follows:

$H_2 = 6.20$	$H_8 = 5.03$
$H_3 = 6.02$	$H_9 = 5.65$

$H_4 = 6.04$ $H_{10} = 5.87$

$H_5 = 5.29$ $H_{11} = 5.44$

$H_6 = 4.32$ $H_{12} = 5.01$

$H_7 = 4.81$

The average value of H, $H, avr = \frac{\sum_{n=1}^{12} Hn}{12} = \frac{65.57}{12} = 5.46 Kwh/m2/day$

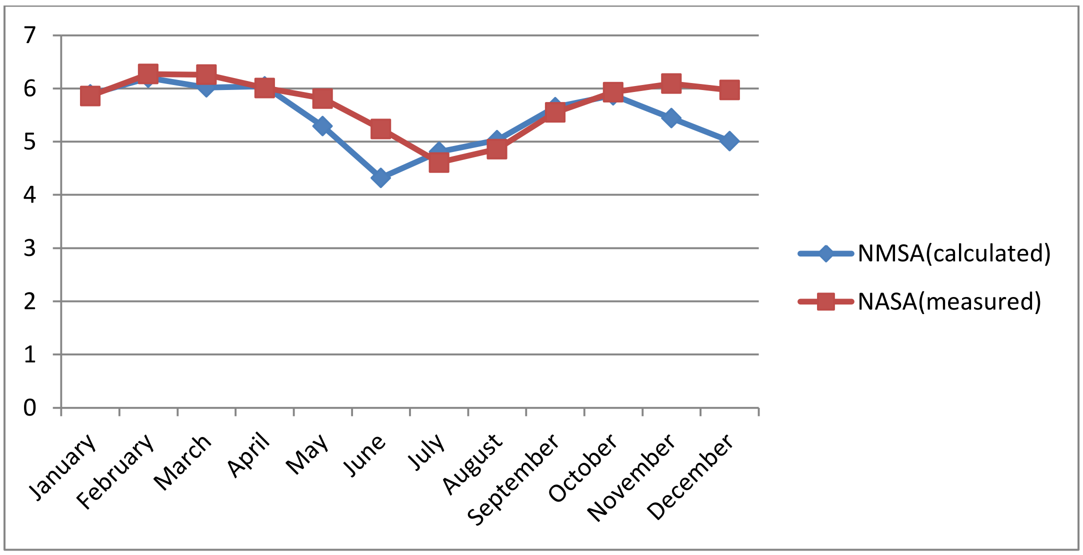

Figure 3.3- Calculated and NASA, monthly average daily horizontal global radiation

Table-3.1 summary of calculated and measured value of solar data for the village

Mon.	**Ho Aver.**	**Max. Monthly average Sunshine duration. 'N'**	**Declination angle ,'δ'**	**Sunset hour angle, 'ωs'**	**Monthly average sunshine duration, 'n'**	**Calculated monthly average irradiation, $H_{calcu.}$**	**Measured monthly average irradiation, $H_{meas.(NASA)}$**
Jan.	9.55	11.69	-17.78	87.71	8.74	5.59	5.86
Feb.	10.16	11.85	-8.67	88.91	8.68	6.20	6.27
Mar.	10.30	12.06	-3.62	90.45	8.15	6.02	6.26

Apr.	10.46	12.25	14.59	91.86	8.10	6.04	6.01
May.	10.16	12.38	21.89	92.87	6.68	5.29	5.81
June.	10.01	12.41	23.18	93.06	4.29	4.32	5.24
July.	10.15	12.45	18.17	93.34	5.44	4.81	4.61
Aug.	10.29	12.14	8.11	91.02	5.75	5.03	4.86
Sep.	10.34	11.94	3.82	89.52	7.78	5.56	5.55
Oct.	9.56	11.74	-15.06	88.08	8.70	5.87	5.93
Nov.	9.07	11.62	-21.97	87.12	8.25	5.44	6.09
Dec.	9.03	11.59	-23.09	86.95	7.07	5.01	5.97
Aver.	**9.92**	**12.01**			**7.25**	**5.46**	**5.70**

V. Calculation of Global Beam and Diffuse irradiance on a horizontal surface

The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index (KT) is described as;

$KT = \frac{H}{Ho}$, so that, from above calculations, $KT1 = \frac{H1}{Ho1} = \frac{5.89}{9.55} = 0.617$, similarly,

$KT_2 = 0.610$ $KT_4 = 0.578$ $KT_6 = 0.431$ $KT_8 = 0.488$ $KT_{10} = 0.614$ $KT_{12} = 0.554$

$KT_3 = 0.584$ $KT_5 = 0.521$ $KT_7 = 0.474$ $KT_9 = 0.544$ $KT_{11} = 0.599$

Therefore, the monthly diffuse irradiation' D' can be found from the formula above in equation 2.19,

$$\frac{D}{H} = 1 - 1.13KT \rightarrow D = H[1 - 1.13KT]$$

From this, $D_1 = H1[1-1.13KT1] = 5.89[1-1.13(0.617)] = 1.78$, similarly,

$D_2 = 1.93$ $D_4 = 2.09$ $D_6 = 2.22$ $D_8 = 2.25$ $D_{10} = 1.79$ $D_{12} = 1.87$

$D_3 = 2.05$ $D_5 = 2.17$ $D_7 = 2.23$ $D_9 = 2.18$ $D_{11} = 1.75$

The **monthly beam irradiation 'B'** also can be found simply by subtracting D from G, equation (2.20), i.e.

B = H-D → B_1 = H1-D1 = 5.89 – 1.78 = 4.11, similarly,

B_2 = 4.27 B_4= 3.95 B_6=2.10 B_8= 2.78 B_{10}= 4.08 B_{12}= 3.14

B_3= 3.97 B_5 = 3.12 B_7= 2.58 B_9= 3.47 B_{11}= 3.69

Note that; it is assumed that no albedo radiation reaches the horizontal surface, as would be expected from consideration of the physical situation.

Table-3.2 Calculated Global Beam and Diffuse irradiance on a horizontal surface

Month	Jan.	Fen.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Beam/Direct 'B'	4.11	4.27	3.97	3.95	3.12	2.10	2.58	2.78	3.47	4.08	3.69	3.14
Diffused 'D'	1.78	1.93	2.05	2.09	2.17	2.22	2.23	2.25	2.18	1.79	1.75	1.87

I. Calculation of the Global Irradiation on inclined solar panel (Tilted at an angle of 15^0, (From table-2.1))

For a panel facing due north in the southern hemisphere, or due south in the northern hemisphere, and tilted at an angle '**β**' to the horizontal, the calculations for beam irradiation '*B*', diffuse irradiation '*D*' and albedo radiation '*R*' are in equation above (2.21, 2.22, 2.23, 2.24 and 2.25) as follows:

$$B(\beta) = B\,\frac{(\cos(\text{Ø}-\beta)*\cos\delta*\sin\omega s' + \left(\frac{\pi}{180}\right)\omega s' \sin(\text{Ø}-\beta)*\sin\delta}{\cos\text{Ø}\, \cos\delta \sin\omega s + \left(\frac{\pi}{180}\right)\omega s*\sin\text{Ø}\sin\delta}$$

→ $\omega s' = -\cos^{-1}[-\tan(\text{Ø}-\beta) * \tan\delta]$

Then, monthly average values by substituting corresponding values, we have, (values are in Kwh/m2)

$$B_1(\beta) = B1\,\frac{(\cos(7.1-15)*\cos\delta1*\sin\omega s1' + \left(\frac{\pi}{180}\right)\omega s1' \sin(7.1-15)*\sin\delta1}{\cos 7.1\cos\delta1\sin\omega s1 + \left(\frac{\pi}{180}\right)\omega s1*\sin 7.1\sin\delta1} = 4.66$$

Similarly,

$B_2(\beta) = 4.27$ $B_4(\beta) = 3.54$ $B_6(\beta) = 1.92$ $B_8(\beta) = 2.61$ $B_{10}(\beta) = 4.55$ $B_{12}(\beta) = 3.74$

$B_3(\beta) = 4.53$ $B_5(\beta) = 2.63$ $B_7(\beta) = 2.25$ $B_9(\beta) = 3.38$ $B_{11}(\beta) = 3.62$

Then, the monthly average diffuse irradiation on tilted panel will be, from equation (2.15) above,

$$D(\beta) = \frac{1}{2} D*(1+\cos\beta) ,$$

$\rightarrow D1(\beta) = \frac{1}{2} D1*(1+\cos150) = \frac{1}{2} 1.78*(1+\cos150) = 1.75$, similarly,

$D2(\beta) = 1.59$ $D4(\beta) = 2.05$ $D6(\beta) = 2.18$ $D8(\beta) = 2.21$ $D10(\beta) = 1.76$ $D12(\beta) = 1.84$

$D3(\beta) = 2.01$ $D5(\beta) = 2.13$ $D7(\beta) = 2.19$ $D9(\beta) = 2.14$ $D11(\beta) = 1.72$

And, the monthly average albedo/ reflected/ irradiation is calculated as equation (2.16). i.e

$$R(\beta) = \rho*(Bbeam+Ddiffuse)\left(\frac{1-\cos\beta}{2}\right)$$

Where, ρ is reflectivity of ground cover and its value is 0.3, which is the typical value for grassland from table-2.1. And the term [1-cosβ/2] is the ratio of the incident irradiation on the tilted surface of the radiation reflected by the soil.

$\rightarrow R_1(\beta) = \frac{1}{2}(B1+D1)*\rho*[1-\cos150] = \frac{1}{2}(4.11+1.78)*0.3*[1-\cos150] = 0.03$,

Similarly,

$R_2(\beta) = 0.032$ $R_4(\beta) = 0.030$ $R_6(\beta) = 0.022$ $R_8(\beta) = 0.026$ $R_{10}(\beta) = 0.030$ $R_{12}(\beta) = 0.025$

$R_3(\beta) = 0.030$ $R_5(\beta) = 0.027$ $R_7(\beta) = 0.025$ $R_9(\beta) = 0.028$ $R_{11}(\beta) = 0.028$

Then monthly total global irradiation received by a tilted plane is then found by summing the calculated values of the beam, diffuse and albedo irradiations. i.e. $G(\beta) = B(\beta)+D(\beta)+R(\beta)$, therefore calculating for each month,

$G_1(\beta) = B_1(\beta)+D_1(\beta)+R_1(\beta) = 6.44$, similarly,

$G_2(\beta) = 6.15$ $G_4(\beta) = 5.62$ $G_6(\beta) = 4.12$ $G_8(\beta) = 4.85$ $G_{10}(\beta) = 6.34$ $G_{12}(\beta) = 5.61$

$G_3(\beta) = 6.11$ $G_5(\beta) = 4.79$ $G_7(\beta) = 4.46$ $G_9(\beta) = 5.55$ $G_{11}(\beta) = 5.67$, Then, monthly average value will be: G, avr = $\frac{\sum_{n=1}^{12} Gn}{12} = \frac{65.714}{12}$ **= <u>5.48Kwh/m^2</u>**

Table-3.3 Global irradiation on inclined plane

Mon.	**Beam /Dirrect/ 'B'**	**Diffused 'D'**	**Reflected (Albedo), 'R'**	**Total Global irradiation 'G'**
Jan.	4.66	1.75	0.030	6.44
Feb.	4.27	1.59	0.032	6.15
Mar.	4.53	2.01	0.030	6.11
Apr.	3.54	2.05	0.030	5.62
May.	2.63	2.13	0.027	4.79
June.	1.92	2.18	0.022	4.12
July.	2.25	2.19	0.025	4.46
Aug.	2.61	2.21	0.026	4.85
Sep.	3.38	2.14	0.028	5.55
Oct.	4.55	1.76	0.030	6.34
Nov.	3.62	1.72	0.028	5.67
Dec.	3.74	1.84	0.025	5.61
Avr.	**3.47**	**1.96**	**0.028**	**5.48**

3.2 Assessment of Wind Resource potential

In Ethiopia, there are few places with sufficiently high wind speed suitable for power generation. In most part of the country, the average wind speed is in the range of 3.5 to 5.5 m/s. This is not a sufficiently high potential for commercial power production

Ethiopia has exploitable reserve of 100 GW wind energy with an average speed of 3.5 – 5.5 m/s, flowing for 6 hours/day. There are two basic zones with homogenous periodicity separated by the rift valley. In the first of these, covering most of the highland plateaus, there are two well-defined wind speed maximal occurring, respectively, between March and May and between September and November. In the second zone, covering most of the Ogaden and the eastern lowlands, average wind velocity reaches maximum values between May and August [23 and 30]. Currently two projects are constructed, one Ashegoda wind park (near Mekele) of 120MW and the other Adama Wind Park of nearly 51MW.

3.2.1 Wind potential assessment of study village

In order to estimate the expected power output of the wind turbines in a hybrid system, data pertaining to the wind resource available at the location was required. The annual average wind speeds in the village was collected from National Metrological Service Agency at an anemometer height and it is estimated by using the logarithmic function given in equation (2.34) that adopts the logarithmic height above ground surface is related to the wind speed.

The monthly average wind speed data for the site was collected and averaged over a 5-years period from 2011-2015 at an anemometer height of 2m given in table below.

Tabe3.4 NMSA wind speed at 2m

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.
Ave. Wind speed (at 2m)	1.87	1.76	1.91	1.31	1.16	1.25	1.36	1.16	1.06	1.04	1.34	1.32

The wind power output was determined using wind speeds at the hub height, which is the distance from the turbine platform to the rotor of an installed wind turbine.

Therefore, the wind speed at the hub height is predicted in terms of the measured speed at the anemometer height using Equation from above equation 2.27 as follows:

$$\frac{V2}{V1} = \frac{\ln(\frac{h2}{Zo})}{\ln(\frac{h1}{Zo})} \rightarrow V2 = V1\ (\ \frac{\ln(\frac{h2}{Zo})}{\ln(\frac{h1}{Zo})}\ )$$

Where,

V_2: Wind speed estimated at hub height h2 [m/s], V_1: Wind speed at reference height h1 [m/s]

h_1: Reference height above ground level [m], h_2: Hub height [m]

Z_0: Surface roughness length factor [m];

Surface roughness length describes the roughness of the surroundings terrain and its value will be 0.25 (from table-2.3), because the area is with many trees and few buildings.

Therefore, by substituting corresponding values of parameters, we have the corresponding calculated average wind speed values provided in table below.

Table-3.5 monthly average NMSA calculated and NASA measured wind speed

Month	**Monthly Average Wind Speed (m/s)**			
	NMSA (at 2m)	Calculated (at 25m)	Calculated (at 50m)	NASA (at 50m)
January	1.87	4.14	4.76	4.49
February	1.76	3.89	4.48	4.03
March	1.91	4.23	4.87	3.81
April	1.31	2.90	3.34	3.96
May	1.16	2.57	2.95	3.64
June	1.05	2.33	2.67	3.50
July	1.15	2.55	2.93	2.94
August	1.16	2.57	2.95	2.69
September	1.05	2.32	2.67	2.87
October	1.04	2.31	2.65	3.64
November	1.34	2.97	3.41	4.17
December	1.32	2.92	3.36	4.46
Average	**1.34**	**2.97**	**3.42**	**3.68**

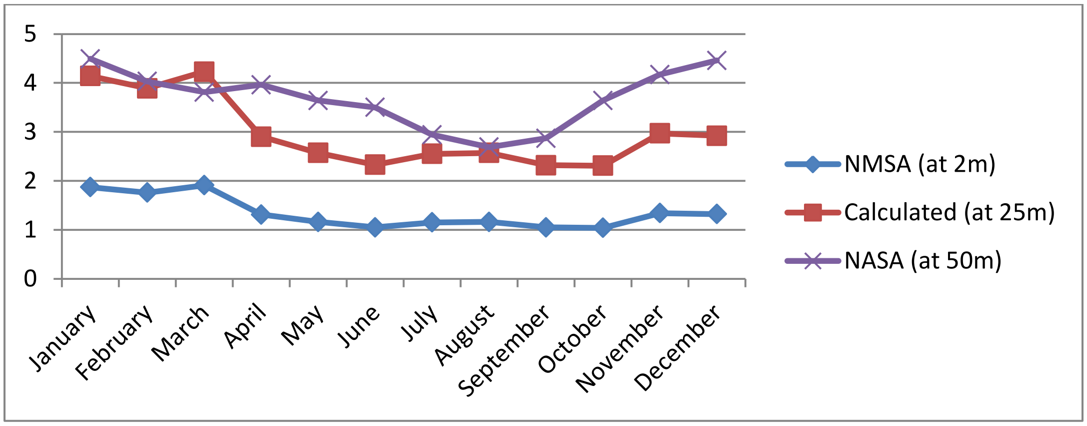

Figure: 3.4 Monthly Average NMSA calculated and NASA measured wind speed

3.3 Electricity Load Estimation of the Village

In this paper the electric load demand of the village community is divided in to the following four major categories like; household/domestic sector which includes of (lighting, TV, Radio, and cooking appliances); Commercial loads (flour milling machine); Community load which consists of (elementary school lighting, desktop computer, printer), health clinic which includes (vaccine refrigerator, communication radio, television, microscope, computer and printer) and deferrable load (water supply and irrigation systems). The total electric load estimated for the listed appliances above were summed up to get the required load to be supplied by the system. It is very obvious that the load factor in a rural community is lower than urban areas; therefore, it is necessary to keep the load factor from being poor when designing an energy system with balancing the cost of energy per kilowatt hour.

Load estimation was approached based on the electric appliances to be used by each sector, with no attention given for their efficiency. Renewable sources power production systems cannot generate the exact amount sought to meet the load demand, either they produce excess electricity or below the demand. Thus instead of calculating the estimated load of the community by the efficiency factor of each appliances it is better to allow excess electricity production from the system. The initial point to know in calculating the load is deciding which appliance has to be used by the rural family households accounting the current and future situation of the local community as well as the countries energy system framework.

3.3.1 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, fax, simple laboratory equipment's and others. The study village has the population size of 2021 (from Administrative woreda). In this population it was estimated that, one house hold averagely contains five members, hence it was assumed as the village contains approximately 400 households in total. From this I have assumed as one third of people in community were settled as small town (village) and two third were dispersed in different locations of area. Thus load determination was performed for one third (approximately 130 households) households. 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.

i. Domestic Load

In an individual household the electricity demand was suggested to apply for low energy compact fluorescent lumps (CFL), radio or cassette recorder and TV. The individual households was assumed to use 3 units of 13W compact fluorescent lamps, 2 units for residential rooms lighting and 1 unit for external lighting which is to be operational for 4:00 hours, on average from 18:00-22:00 hour. A radio of 5W which will operate for 3 hours from 18:00 to 21:00 is suggested. 21 inch television of 65W is to be functioned in each household on average basis starting from 12:00-14:00 and from 18:00-24:00 hours. In Ethiopia, the weekends are recognized as religious holidays and at these days there are no practical activities done particularly in the agricultural fields. The peak load demands in the households are normally happened in the weekends and holidays because TV and radio can be turned on for an extended period of time.

During this time television would function for 14:00 hours from 8:00-22:00 hour and radio will be enjoying for 6:00 hours from 6:00-12:00 hour.

Table-3.6: Single Household Electricity Consumption Features

Appliances	Quantity	Capacity (w)	Run time (hrs/day)	Peak load (Kw)	Energy usage (Kwh/day)
Lightings	3	13	4	0.039	0.156
Television	1	65	6	0.065	0.39
Radio	1	5	3	0.005	0.015
Total		**83**		**0.109**	**0.561**

Projecting this to 130 households

Peak load (Kw)	Energy usage (Kwh/day)
14.17	**72.93**

ii. Commercial Load

Although, currently diesel driven flour milling machines are popular but the running cost is high and so is the price per kilogram of the milled flour. Thus, one flour milling machine was proposed to be installed in the village community. This machine will not actually serve only the local community but also the nearby communities that do not have electricity access will also get the service, and thus it will help for the owners to increase their income. The machine has power rating of 12.5kW that will operate for 5:00 hours a day from 9:00-12:00 hours and from 14:00-16:00 hours only during the working days. The total daily electricity demand by the flour milling machine is shown below in table 6-2.

Table-3.7: Electric Load Consumption Characteristics of Flour milling Machine

Equipment	Quantity	Capacity (Kw)	Run-time (hrs/day)	Energy usage (Kwh/day)
Flour milling	1	12.5	5	62.5

iii. School Load

Primary school consists of three blocks with 4 classrooms and each classroom would be installed with four 15W CFLs (compact fluorescent lamps) and a 5W radio receiver. Additional 3 CFLs (of 30W) for external lighting and six11W lamp for a toilet are also considered.

Electric lighting for the school in the evenings (18:00-21:00) for those who wish to pursue basic education is suggested. Moreover, 2 administration offices with 1 unit of 60W desktop computer, 1 unit of 50W printer and with 2 unit of 13W CFL for each is required. The school has 2 toilet room for staffs and 4 toilet rooms for students with 11W CFL for each**.** As noticed above during the day time no need of electricity for the class rooms since the sunlight can brighten the classes through the glass windows. Thus, most of the electricity will be utilized by the computers and printer at day times which is very small. The largest load of the school will be recorded on the evening times when evening classes would be accompanying**.** The desktop computer is to be functioned for 8:00 hours from 8:00-12:00 and from 13:00-17:00 and printer 50W is to be run for average of 1 hour from 15:00-16:00, following all typing will be completed. But the number of evening students would expect not to be more than three classes.

During the weekends evening classes would be conducted in the day time from 8:00 to 12:00 and at the same time students can have tutorial classes. The annual break of the academic year for schools is during July and August and the semester break is in January. The total daily electricity consumed by the school except for January, July and August is shown below in table.

Table-3.8: School Electricity Load Consumption

Appliances	Quantity	Capacity (w)	Run time (hrs/day)	Peak load (Kw)	Energy usage (Kwh/day)
Class room light	12x4= (48)	15	3	0.720	2.160
Admn. Office	2	13	2	0.026	0.052
External light	3	30	6	0.090	0.540
Toilet room light	6	11	3	0.066	0.198
Radio receiver	1	5	4	0.005	0.020
Computer	1	60	8	0.060	0.480
Printer	1	50	2	0.050	0.100
Total		**186**		**1.017**	**3.550**

iv. Health Clinic Load

The health center work as health clinic, which serves stocking medicine, follow up of health condition of the residents including pregnant day to day health condition. The critical ailments that requires special treating will not be served in this health center rather will be referred to the nearby well equipped clinics or hospitals. The main possible appliances that draw electric power in this clinic are low energy light bulbs, Communication radio, television, computer, printer, laboratory microscope, and vaccine freezer. The health center has 8 rooms including reception and toilet rooms lighted with 13W fluorescent lump which would work for 6 hours from 18:00-24:00 and 2 units of 30W lumps for external lighting from 18:00-6:00 hours. It is also equipped with 1 unit of 20W microscope to work for 5:00 hours per day from 8:00-12:00 on top of this from 13:00-14:00, communication apparatus radio 5W assumed to work for 8:00 hours of a day from 08:00-12:00 and from 13:00-17:00, 1 unit of 65W 21'' television which is expected to work for 12:00 hours per day from 08:00-20:00 hours, 1 unit of 60W vaccine freezer operating for 24:00 hours, 1 unit 60W desktop computer working for 6:00 hours from 8:00-12:00 and 14:00-16:00 hour, 1 unit 50W printer working for 1:00 hour per day from 14:00-15:00.

Table-3.9: Health Clinic Electricity Consumption

Appliances	Quantity	Capacity (w)	Run time (hrs/day)	Peak load (Kw)	Energy usage (Kwh/day)
Room lighting	8	13	8	0.104	0.832
External lighting	2	30	12	0.060	0.720
Commn. Radio	1	5	8	0.005	0.040
Television	1	65	12	0.065	0.780
Lab. Microscope	1	20	5	0.020	0.100
Vaccine freezer	1	60	24	0.060	1.440
Computer	1	60	8	0.060	0.480
Printer	1	50	1	0.050	0.050
Total		**303**		**0.424**	**4.442**

3.3.2 Estimation of Deferrable Load

Deferrable load is the load that should be fulfilled after the primary load demand is supplied except in especial cases such as when water tank left empty below the required level, regardless of the time. It is also called as secondary load, as it is not constrained with time to deliver. Some of the activities performed by the deferrable are water pumping, irrigation system and for recreation. Loads are actually considered as deferrable due to the nature of the load they are associated with storage mechanisms. The deferrable load is prioritized after the fully satisfaction of the primary load. The storage capacity (kWh) of the pump is the electricity demanded to fill up the water storage tank because the electricity will be supplied for other activities during the time of no pump operation.

i. Water Supply Load

The supply of clean water is among the basic needs for human beings day to day activity. In this thesis the supply of water was considered into a common central area to all households, meaning there will no water pipe distribution to each household. The aim is to cater water to the community water distribution midpoint, health clinic and school. In the paper it was stated that the minimum water requirement per household per day is $0.1m^3$. The quantity of water for both the health clinic and primary school is being $2.4m^3$ per day. To satisfy the quantity of water for the health center, school and households, size of pumps would be selected based on their power capacity and discharge rate. 2 units of pumps that draw electrical power of 150W with a discharge capacity of 10 liter/min operating for 4:00 hours per day would be installed to provide water for the community service centers (school and health centers). The total power drawn by the pumps is about 0.3 kW. Community services was suggested for 3 days water storage capacity and electricity consumption drained by the pumps to fill the reservoir for three days is about 3.6 kWh.

Water provision to the central distribution reservoir for household's usage would be pumped thru 6 units of pumps with rating capacity of 550W that delivers 45litter/min of water. Pumps could run for an average of 7:00 hours per day. For this case water storage capacity for 3 days is also recommended.

As the energy demand and power generation from renewable resources of the village can vary from time to time. 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 10% reduction is being suggested.

Table-3.10: Pump Power Consumption Characteristics for Household's Water Supply

No. of pumps	Capacity (w)	Running hrs	Peak deferrable (Kw)	Energy consumption (Kwh/day)
2	150	4	0.3	2*150*4hr/day*3day = **3.6**
6	550	7	3.3	6*550*7hr/day*3day = **69.3**
Total			**3.6**	**72.9**

Irrigation System Load

The electrical load required for this purpose is used to drive electrical water pumping to pump water to the farm land or reservoir for later use of watering. For the irrigation purpose 2 units of 550W pumps having discharge capacity of 45 liter/min which delivers 43.2m^3 per day was considered. These pumps runs daily for 4:00 hours and the electrical energy consumption would be 8.8kWh per day; except for July, August and September. During the rainy seasons the deferrable load decreases, especially the irrigation pumps will be out of operation at all.

Exceptions:

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

CHAPTER FOUR

DESIGN AND SIZING OF THE SYSTEM

4.1 Photovoltaic subsystem

Main electrical generator of the proposed system is photovoltaic panel which converts solar irradiation directly into Electricity. Since the solar radiation varies daily, hourly and seasonally the electricity produced by the PV array vary accordingly. Since the selected site has very good solar irradiation throughout the year and battery storage and diesel generator are incorporated in the system to handle this variability, the system can supply grid quality electricity for 24 hours.

4.1.1 PV Panel Selection and Array Sizing

The items needed to be addressed when sizing a photovoltaic array are module selection, number of modules and orientation.

Module Selection: Module selection is made based on the specifications provided by the manufacturer. The panel's electrical performance is normally described by its characteristics delivered under maximum sunlight: i.e. its Peak power, Voltage at peak power, Current at peak power, Short circuit current, open circuit voltage. The module efficiency and the cost are the basic criteria used for the selection.

Proper selection of solar panels is fundamental to the successful long term return on investment for any project. However it should be noted that having a low price per item cannot grant a lower total cost. This is because using the low cost and low efficiency panels requires more number of panels than the more efficient ones.

Number of Modules: modules in a PV system are usually connected in serious and parallel strings in order to achieve the design current and voltage.

The chosen PV panel has the following characteristics

Module: Samsung solar panel	**Model :LPC250S**
Performance at standard test condition (STC): at, Irradiance 1000W/m^2, A.M 1.5, Cell Temp. 25^0C	
Pmax(Wp)	250
Vmp(V)	30.5
Imp(A)	8.20
Voc(V)	37.6
Isc(A)	8.66
Module efficiency	15.62

- **Effect of temperature on module parameters**
  - **Correct P_m, V_m, i_m for the field values of the parameter, T_c,**

Let's take a PV-panel whose environmental temperature is equal to 46^0C. Then, the operating temperature, T_c, of the PV-panels is determined as follows: From above equation 2.10,

$$\mathrm{Tc} = Tamb + \frac{(\mathrm{NOCT}-\mathbf{20})}{800} * G$$

Where: T_{amb}: ambient temperature in °C, G: solar radiation in W/m² and NOCT: Normal Operating Cell Temperature which is defined as the cell temperature

$$\mathrm{Tc} = Tamb + \frac{(46-\mathbf{20})}{800} * 1000\mathrm{W/m^2} = \mathrm{Ta} + 32.5^0\mathrm{C}$$

The ambient temperature of the study village design month, is 20.65^0C

Then, Tc = 17.8^0C +32.5^0C=50.3^0C

For this temperature we evaluate **I_{sc}**, **V_{oc}**, **FF** and from these new conditions, we get:

- Isc =8.66,is assumed to be independent of temperature, because the increase in Isc for change in temperature is very small
- Voc = Voc-rated(1- βΔT) = 37.6(1-0.005V/^{0}C*(50.3-25) ^{0}C =32.84V,

  Where β =0.005 per ^{0}C for crystal silcon [42]

  Fill factor, FF =Pm/ (ImxVoc) =250/(8.20x37.6) = 0.811

Notice: it is assumed that FF does not change substantially with Tc, Then,

- Pm (at 1000W/m^2, Tc=53.150C) =IscxVocxFF = 8.66x32.84x0.811= 230.6W

The first step toward sizing the PV array is to determine the daily energy requirement from the array. The required energy obtained is then divided by the average solar radiation per day for the site to obtain the peak power. The peak power is then divided by the selected system Dc voltage to obtain the total Dc current. Finally, the number of series and parallel modules can then be determined to give the array size. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current as desired.

The total system load demand is supplied by the hybrid system is based on the resource available and capacity of energy extracted from each sources .The wind resource in the location is low and this results low power extraction form the wind energy subsystem, so that higher percent (85%) of the load is supplied from solar system and lower (15%) is from wind system.

From above load estimation:

System	Peak power (Kw)	Daily energy demand (Kwh/day)
Total system capacity	31.71	172.22
PV-subsystem (85%)	26.95	146.38
WT-subsystem (15%)	4.755	25.83

Determining System Voltage

System voltages are generally 12, 24 or 48 Volts and the actual voltage is determined by the requirements of the system. In larger systems 120V or 240V DC could be used, but these are not the typical household systems.

As a general rule, the recommended system voltage increases as the total load increases. For small daily loads, a 12V system voltage can be used. For intermediate daily loads, 24V is used and for larger loads 48V is used.

Table-4.1 Selecting System Voltage

AC power demand (Watts)	Inverter Input Voltage (Volts DC)
<1,500	12
1,500 – 5,000	24 – 48
>5,000	48 – 120

The selected system having,

- ✓ System Voltage (**Vdc**) = 48 V
- ✓ Average solar Radiation for the site (Ra) = 5.48KWh/m2/day [for inclined panel from above table
- ✓ Daily Average Demand (**Ed**) for PV-subsystem, from above Table, Ed =113.66Kwh/day
- ✓ Battery Efficiency selected as (**ηb**) = 0.85
- ✓ Inverter Efficiency selected as (**ηi**) = 0.95
- ✓ Charge Controller Efficiency selected as (**ηc**) = 0.90

Sizing the array begins by determining the daily energy demand required (Erd) from PV array to supply load through inverter, by ηi =0.95,

$$\mathrm{Erd} = \frac{Ed}{\eta \mathrm{i}} = \frac{146.38Kwh/day}{0.95} = 154.08\text{Kwh/day, and} \tag{4.1}$$

$$\text{Required PV-Avr-Amp-hrs per day} = \frac{Erd}{\mathrm{Vsytem}} = \frac{154.08Kwh/day}{48} = 3.21\mathrm{KAhrs} \tag{4.2}$$

$$\text{Then, PV-array-peak-amp} = \frac{Av.\!-\!Amp.hrs\ per\ day}{\eta c{*}\eta b{*}\mathrm{Ra}} = \frac{3.21KAhrs}{0.90{*}0.85{*}5.48} = 765.71\mathrm{A} \tag{4.3}$$

Next, we obtain the number of parallel module strings (Npm), by dividing the total dc current of the system by the rated current of one module (Im) as;

$$Npm = \frac{\text{PV.array.peak.amp}}{\text{Im}} = \frac{765.71A}{8.20} \approx 94 \text{ , and} \tag{4.4}$$

The number of modules in series (Nsm) is then obtained by dividing the system dc voltage by the rated voltage of each module (Vm);

$$Nsm = \frac{\text{Vdc system}}{\text{Vm}} = \frac{48V}{30.5V} = 1.57 \approx 2 \tag{4.5}$$

Then, total number of modules (Ntm) that form the array is then finally determined by multiplying the number of modules in series by the number of parallel modules, thus giving the required array size,

$$Ntm=Nsm*Npm=2*94=188 \quad (4.6)$$

4.1.2 Controller Selection and Sizing

The primary function of a charge controller in a stand-alone PV system is to maintain the battery at highest possible state of charge while protecting it from overcharge by the array and from over-discharge by the loads. It can also provide load control functions like automatically connecting and disconnecting an electrical load at a specified time.

There are two basic types of controllers used for small PV systems. A shunt controller redirects or shunts the charging current away from the battery. These controllers require a large heat sink to dissipate the excess current. Most shunt controllers are designed for smaller systems producing 30 amperes or less [41]. A series controller interrupts the charging current by open-circuiting the PV array. There are many variations of both types.

One design type is Pulse Width Modulation (PWM). By electronically controlling a high speed switching or regulation element, the PWM controller breaks the array current into pulses at some constant frequency, and varies the width and time of the pulses to regulate the amount of charge flowing into the battery. Maximum power Point tracking (MPPT) controllers are special type of these controllers which employ pulse-width modulation techniques to switch from one dc voltage level to another dc voltage at a different level, similar to a switching dc power supply. The MPPT employs a feedback loop to sense the output power and change the output voltage accordingly until the output power is maximized.

The selection and sizing of charge controllers and system controls in PV systems involves the consideration of several factors, depending on the complexity and control options required. Charge controllers are sized according to the voltages and currents expected during operation of the PV system. The controller must not only be able to handle typical or rated voltages and currents, but must also be sized to handle expected peak or surge conditions from the PV array or required by the electrical loads that may be connected to the controller.

The size of a controller is determined by multiplying the peak rated current from an array times an enhancement safety factor which is taken to be 1.25 to allow for a reasonable system expansion.

Thus, the required charge controller current (Ircc) is:

$$Ircc = IscxNpmxFsafe = 8.66Ax94x1.25 = 1{,}017.55A = 1.01755KA \approx 1KA \quad (4.7)$$

Therefore the required Charge controller current is 1KA and this charge controller must be able to withstand the array current as well as the total load current of the system.

4.1.3 Battery Bank selection and sizing

Battery bank voltage selection is often dictated by load voltage requirements, most often 12 or 24 volts for small remote stand-alone PV systems. For larger loads requiring a larger PV array, it is sometimes prudent to go to higher voltages if possible to lower currents. Lower system current minimizes the sizes and costs of conductors, fuses disconnects and other current handling components in the PV system.

Sizing the battery begins by first determining the estimated energy storage (Eest) required which is equal to the product of the daily average energy demand and the number of autonomy days (D_{aut}) as in equation below.

The selected battery for the system is:

Deep cycle lead Acid battery, Nominal voltage (Vb) =24V, Rated capacity (Cb) =280Ah

Maximum allowable Depth of Discharge=80%, Days of autonomy (Daut) =3days

Then, Estimated Energy storage,

$$E_{est}=E_d x D_{au\,t} = Eest=146.38KWh/day*3days=439.14KWh \quad (4.8)$$

A safe energy storage (Esafe) is then computed by dividing the obtained estimated energy storage by maximum allowable depth of discharge (Ddisch);

$$\text{Esafe} = \frac{Eest}{Ddisch} = \frac{439.14Wh}{0.8} = 548.92\ KWh \quad (4.9)$$

Then, the total capacity of the battery bank in ampere-hours (Ctb) is then determined by dividing the safe energy storage by the rated dc voltage of one battery (Vb);

$$\text{Ctb} = \frac{Esafe}{Vb} = \frac{548.92KWh}{24V} = 22.87\ KAh \quad (4.10)$$

The total number of batteries (Nb) can then be obtained by dividing the total capacity of the battery bank in ampere-hours by the capacity of one of the selected batteries in ampere-hours (Cb) as given by equation (3.10).

$$\text{Ntb} = \frac{Ctb}{Cb} = \frac{22.87KAh}{280Ah} = 81.68 \approx 8 \quad (4.1)$$

The number of batteries in series (Nsb) can now be determined by dividing the system dc voltage by the rated dc voltage of one battery as in equation below.

$$\text{Nsb} = \frac{Vdc}{Vb} = \frac{48V}{24V} = 2 \quad (4.12)$$

Then, determine the number of parallel battery strings (Npb) by dividing the total number of batteries by the number of batteries in series as in equation below

$$\text{Npb} = \frac{Ntb}{Nsb} = \frac{82}{2} = 41 \quad (4.13)$$

Finally, since the number of batteries in series (Nsb) and the number of parallel battery strings (Npb) are known, then the size of the battery bank consists of $\text{Nsb}x\text{Npb}$ batteries.

4.1.4 Inverter Sizing and Selection

An inverter is required to change the 12/24/48-volt battery or array power to 110/220 V at 50/60 Hz AC power. Inverters are often categorized according to the type of waveform produced as square wave, modified sine wave, and sine wave. Square wave inverters are relatively inexpensive, have efficiencies above 90%, high harmonic frequency content, and little output voltage regulation. They are suitable for resistive loads and incandescent lamps.

Modified sine wave inverters offer improved voltage regulation by varying the duration of the pulse width in their output. Sine wave inverters produce an AC waveform as good as that from most electric utilities.

As it is advisable to use pure sine wave inverters where possible, the inverters in all systems under the case studies are opted to be of this type. But the actual inverter out of the available pure sine wave inverters is selected based on the price tagged by the manufacturer or the distributer..

The basic criterion in sizing an inverter is whether it can be capable of supplying the maximum anticipated AC load or not. This is always taken to be the combined maximum load for all AC appliances running at the same time. The inverter should also allow loads that have a surge rating. The only appliance considered in this paper with a significant surge watt requirement is the vaccine refrigerator used in the health clinic.

Typically, capacity of the inverter is taken to be the sum of all the loads running simultaneously and 3times the total power of the inductive loads to take care of surge protection. Thus the power of all non-inductive appliances (Pnia) is first determined, then the power of all inductive appliances scaled by a factor of three (3Pia) is computed. From load profile given in above table-, inductive loads are Refrigerator (60W) and Vaccine freezer (60W) from health clinic and peak deferrable loads (3.6KW)

Then, the total inverter power is now simply the sum of all continuously running powers demand the building and furthermore, the obtained value is then multiplied by a factor of 1.25 to make it 25% larger in capacity in order to allow for a reasonable system expansion.

Thus, the inverter power is determined using equation as follows:

$$P_{inv}=1.25(P_{nia}+3P_{ia}) \quad (4.14)$$

Where P_{inv} = Power of the inverter

P_{sum}= Power of all loads running simultaneously

Then from the above table the sum of power of all appliances from primary loads and sum of power of inductive appliances from commercial and deferrable loads.

Hence, Pinv= 1.25[13.27KW + (3x13.68KW)] = 67.90KW

But this conversion is not 100% efficient. So, efficiency ($\eta_{inv,}$) of inverter is an important parameter which has to be taken care of continuous AC power load, which is the total power needed when all the appliances are running at steady state condition.

From the above, selected inverter efficiency, η_{inv} =90%=0.9, Therefore, the inverter power rate will be,

$$\text{Pinv} = \frac{1.25(\text{Pnia}+3\text{Pia})}{\eta\text{inv}} = \frac{67.90W}{0.9} = 75.45KW \approx 80KW \quad (4.15)$$

4.2 Wind power subsystem

Wind power as a renewable energy alternative is by far the most successful technology in the many places in the world. Wind turbines these days are readily available in different sizes from a few watts to 100 kW in the small turbine category and extend to about 2 MW for larger commercial farm types.

4.2.1 Wind Turbine selection

In turbine selection, the tower height of the turbine was considered as one parameter in the selection of the wind turbines as the turbines is going to be install at a height of 24m above the ground to overcome the obstruction and turbulence created by the buildings and other objects at nearby. Hence, a turbine with this tower height is needed and this tower must be a tube and free standing tower as there is no enough area for guyed towers.

The low cut-in speed is considered as one factor in the identification and this is due the fact that wind speed in urban areas are so low, to overcome this low wind speeds small wind turbine technologies with low starting wind speeds and accordingly can produce power at low wind speeds are required. As the wind speed at ETD is classified in between low and moderate.

Proven WT 15000 was selected in this 15 kW rating category as it has a bigger swept area, less expensive, and turns out to be equally as roust and requires low maintenance.

Proven Energy is a UK based family owned business located in Stewarton in South West Scotland. It is into the manufacture of wind turbines, solar photovoltaic panels and hydro energy systems. It manufactures a range of small wind turbines up to 15 kW. These proven turbines have the ability to produce power even in extreme weather conditions including hurricanes. Its recently developed 15 kW turbine (WT 15000) is ideal for light industrial, light commercial and agricultural use and presently the most highly sort after of all its models.

The selected wind turbine technical specification

Proven Energy WT 15000	
Rotor Diameter (m)	9
Cut in Wind Speed (m/s)	2.5
Rated Wind Speed (m/s)	12
Cut – out Wind Speed (m/s)	None
Survival Wind Speed (m/s)	65
Rotor Weight (kg)	1100
Rated Output (kW)	15
Annual Output (kWh) in an average 5m/s wind speed	29,000
Number of blades	3

4.2.2 Wind power calculation

As discussed in above chapters, wind velocity increases with height and that contributes increase in power harnessed. The number of hours for which the wind blows at a given speed is then multiplied by the instantaneous power output at that speed to obtain the energy captured at that speed. The total number of turbines required to meet the monthly electricity demand for site could then be estimated by dividing the electricity demand by the electricity generated per turbine.

Electrical power of the wind turbine is expressed mathematically as, (from above equation 2.43)

$$P_{el} = \frac{1}{2}\rho A V^3 C_p \, \eta_g \eta_m$$

Where:

P_{el}: wind turbine electrical power [kW] ,

η_m: The mechanical (gear box) [%] , η_g: Electrical generator efficiencies [%]

The rotor swept area is expressed mathematically, from above equation 2.44,

$$A = \frac{\pi D^2}{4}$$

Where:

A: The rotor area [m^2] and D: The rotor diameter [m]

According to this equations and selected turbine specifications,

From above given, Rotor diameter = 9m,

Then swept area, $A = \frac{\pi D * D}{4} = \frac{\pi * 81}{4} =63.62m^2$,

Then selecting $\eta_{m\ =85\%}$, , ,η_g=90% , air density ρ=1.225, Cp= 0.45,

We have, average electrical power extracted from wind turbine of average V=3.42m/s

Pel= 0.5* ρ*Cp*A*V^3* η_g*η_m=0.5*1.225*63.62*$(3.42)^3$*0.85%*0.90 =1,192.44W

Thus average power extracted from single turbine is 1,192.44W or 1.19244KW

Then total number of turbines required to meet the monthly electricity demand for site could then be estimated by dividing the electricity demand by the electricity generated per turbine.

i.e. Total number of turbines required =electricity demand/power extracted from single turbine (from above power distribution, the load demand met by wind power subsystem is 4.755KW)

Therefore total number of turbines required= 4.755KW/1.19244KW=3.98 ≈ 4,

Hence 4-turbines are needed to supply the demand.

Table-4.2: Monthly Average Wind Speed and power extracted from selected single turbine

Month	**Calculated wind speed (m/s) (at 50m)**	**Power extracted (KW)**
January	4.76	3.215
February	4.48	2.680
March	4.87	3.443
April	3.34	1.111
May	2.95	0.752
June	2.67	0.567
July	2.93	0.750
August	2.95	0.765
September	2.67	0.567
October	2.65	0.555
November	3.41	1.182
December	3.36	1.130
Average	**3.42**	**1.192**

Then the power curve of turbine for above calculated values:

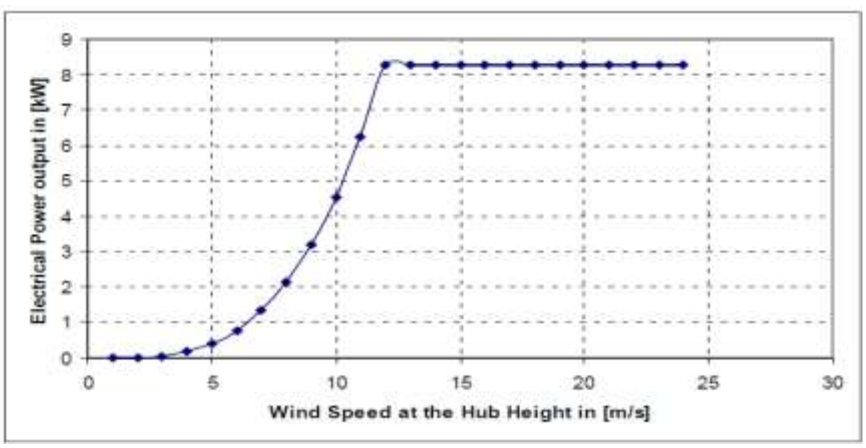

Figure-4.1 Electrical power output vs. wind speed at hub height

4.2.3 Generator selection for Turbines

Small turbine manufacturers mostly turn to use permanent magnet generators. With permanent magnet generators, there is no need for field windings or supply of current to the field as the generators themselves provide the needed magnetic field.

Some small turbine manufacturers like some Company and World Power have their generators designed such that the permanent magnets are attached to the casing (magnet can) which rotates outside the stator (which is the stationary part of the generator). This makes it possible for the rotor blades to be bolted directly to the case.

The shaft power output is not normally used directly, but it is usually coupled to a load through a transmission however, for small turbines the shaft power is directly coupled with the load. To generate electricity the load is the electrical generator and the basic system of electric generation using wind turbine is as shown in figure below. The generator losses may be considered in three categories: hysteresis and eddy current losses (functions of the operating voltage and frequency), windage and bearing friction losses (varies with rotational speed), and copper losses (vary as the square of the load or output current) [37].

The advantages of PMSGs include the elimination of commutator, slip rings and brushes so that the machines are rugged, reliable and simple. The use of PMs removes the field winding (and its associated power losses) but makes the field control impossible and the cost of PMs can be prohibitively high for large machines.

4.3 Cost analysis

The monthly energy cost which hast to be beard by the user is calculated from the annual cost of the investment and annual operating cost which is mainly maintenance cost. Similarly, the unit energy cost can be calculated by dividing the total annual cost by the energy generated per annum.(37)

$$C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m \qquad (4.16)$$

Where:-
C_A= Annual payment, C_I = Capital cost, C_m = maintenance cost, n = life span , i = interest rate
The unit energy cost (price) is determined by dividing the total annual cost by the total of electrical energy generated per year.

The energy produced to supply the whole village load demand optimally is given below table.

Production	Kwh/year
PV array	59,704
Wind turbines	245
Diesel Generator	21,092
Total	**81,041**

[From above table 3.6 and HOMER output]

The system component cost and total cost

Component	Capital cost ($)	O&M cost ($)
PV	80,000	0
wind	19,600	5,113
Generator	3,600	10,570
Battery	3,332	7767
Converter	14,000	0
Total System cost	**120, 532**	**16,451**

[From table-5.1 and HOMER output]

Then, annual payment, form above equation 4.16,

Considering life span 25 years and 10% interest rate,

$$\text{CA} = \frac{120532}{[(1+0.1)^{25}/\ 0.1([(1+0.1)^{25}} + 16451 = \$28{,}504.98$$

Then monthly payment of the system = Annual payment/12 = $2,375.415

The unit energy cost, CoE = $\frac{Annual\ Payment}{Yearly\ energy\ production} = \frac{28{,}504.98}{81{,}041} = 0.352$

CHAPTER FIVE

HYBRID SYSTEM OPTIMIZATION AND HOMER SIMULATION

5.1 Optimization of Inputs

The hybrid energy system should meet the load demand of the community of proposed households. The main renewable sources of energy considered in this thesis are solar and wind. Diesel generator as backup and battery bank as energy storage systems are employed in the energy system due to the intermittent nature of the renewable sources. The wind turbine and diesel generator produces AC type voltage as they are alternating in nature, whereas the PV panels output is DC type. Bidirectional converter is fitted in this configuration which is basically used to charge the battery by changing the alternating current type load into DC, moreover supplies alternating current type electricity back from battery to AC load consumers. All loads required by consumers are AC type. Some of the input values into the software are expressed in size and in quantity. Wind turbines, batteries are the power system components which vary in quantity, and solar PV, diesel generator and converter are other components that vary in size. Figure 7-1 presents the schematic representation of HOMER simulation model of the hybrid system architecture considered in this thesis.

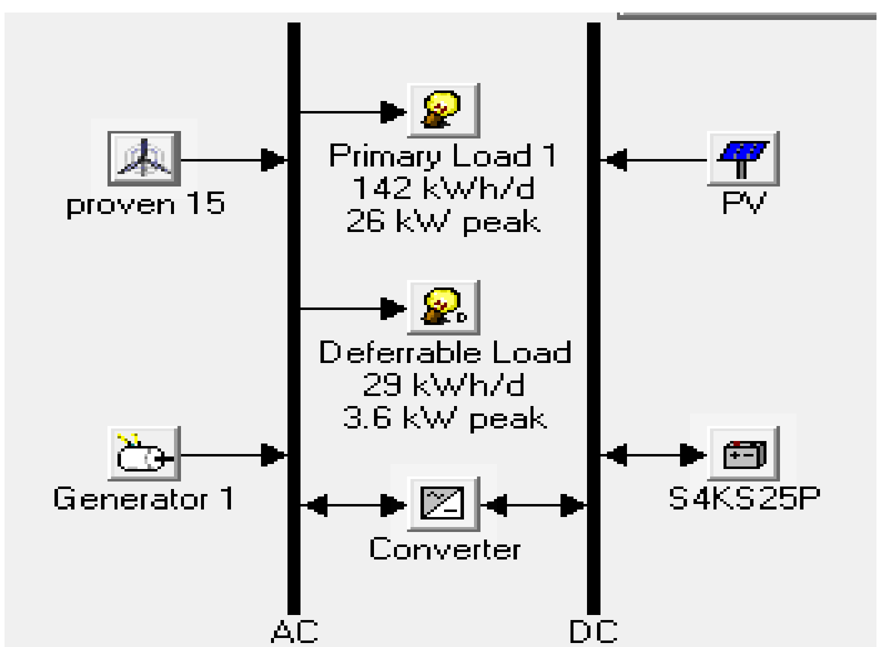

Figure-5-1: Architecture of the Hybrid System Produced by HOMER

5.2 Electricity Load Input

Next to the selection of the components technology from the library of HOMER software, the electricity load is the first to be entered in to the modeling tool. The primary load input, which was determined in section 3.2 above, has entered on hourly basis (24 hours data) and thereafter the software modeled the peak load. Moreover it also synthesized the monthly load from the 24 hour input data and the deferrable loads described as average monthly basis. The diurnal variation of the primary load profile of the community is depicted in figure below generated by HOMER after inserting the 24 hour load data. Most of the appliances employed in residential and service areas operate with alternating current voltages and hence AC loads were suggested in the load estimation in chapter 3. The 24 hour primary and deferrable load profiles are given in figures (a) and (b) respectively.

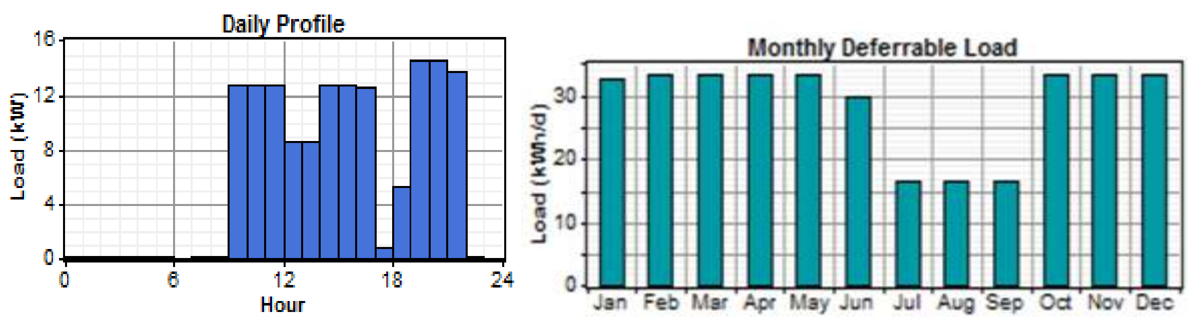

Figure 5.2 (a) Daily Primary load profiles; (b) Monthly average deferrable load profiles

5.3 Resource input

The nature of the available renewable resources affects the behavior and economics of renewable power systems, since the resource determines the quantity and the timing of renewable power production. The careful modeling of the renewable resources is therefore an essential element of system modeling.

5.3.1 Solar resource

To model a system containing a PV array, the solar resource data for the location of interest has been provided. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes

Earth's surface in a typical year. The data fed to HOMER is monthly average global solar radiation on the inclined solar panel (kWh/m2/day).

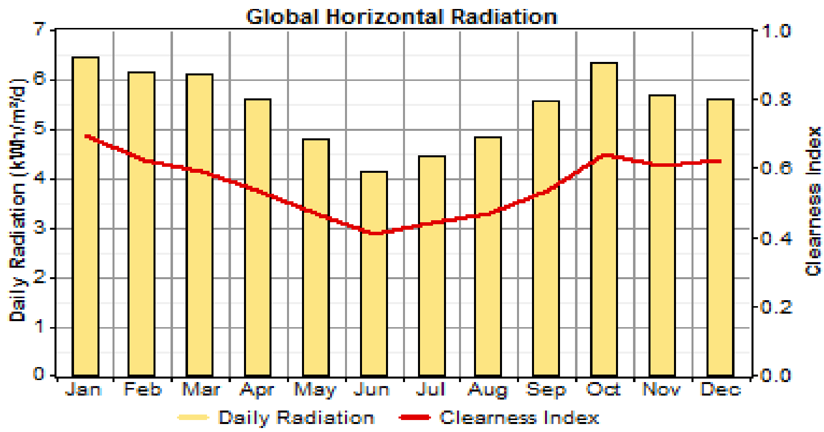

Figure-5.3. Average Monthly solar radiation of the site

5.3.2 Wind Energy Resource:

To model a system comprising one or more wind turbines, the wind resource data indicating the wind speeds the turbines would experience in a typical year has been provided. The Weibull shape factor is a measure of the distribution of wind speeds over the year. The autocorrelation factor is a measure of how strongly the wind speed in one hour tends to depend on the wind speed in the preceding hour. For complex topography the autocorrelation factor is (0.70 - 0.80) while for a uniform topography the range is higher, (0.90 - 0.97). A typical range for the autocorrelation factor is 0.8 – 0.95 [41]. An average value of 0.85 is used here because the selected areas are of averagely uniform topography. The diurnal pattern strength is a measure of how strongly the wind speed tends to depend on the time of day [41]. Typical values for diurnal pattern strength range from 0 to 0.4. A value of 0.25 has been selected for calculations.

The monthly average wind speed for site, together with other related data, such as values of Weibull parameter k, diurnal pattern, autocorrelation, etc, was fed into HOMER and the result is as shown figures below.

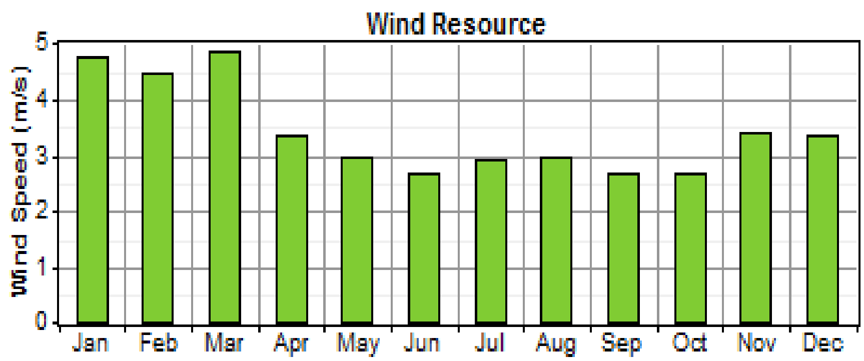

Figure 5.4: Monthly average wind speed at 50 m

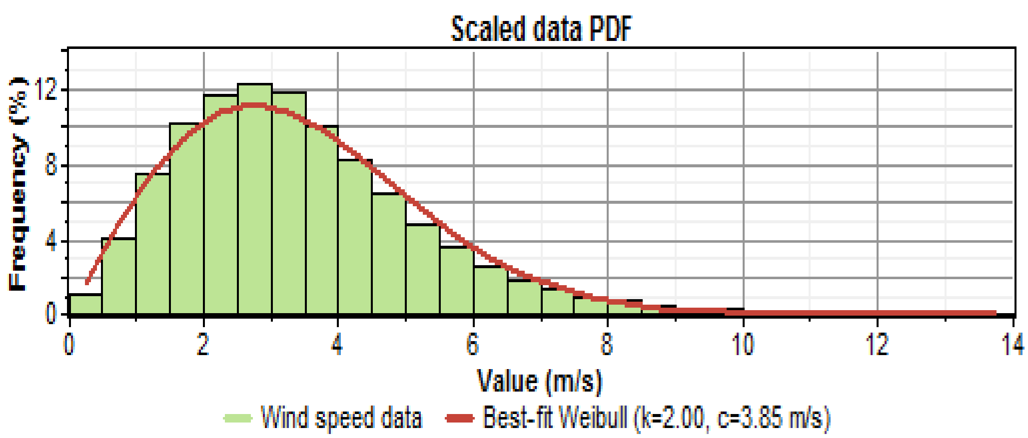

Figure-5.5 Weibul frequency distribution of wind speed

5.4 Cost Data and Size Specifications of Each Component

The basic criterion related to the selection of the power system components is the cost of components, as the main purpose of the work are searching the optimum power system configuration that would meet the demand with minimum NPC and COE. The estimation of the components cost was made based on the current cost available on market.

Initial capital cost of components: It is the total installed cost deployed to purchase and install the component at the commencement of the project.

O&M cost: It is the cost accounted for maintenance and operation of the system. The entire scheme components considered in this paper has different operation and maintenance costs.

Miscellaneous O&M costs considered by HOMER are like emission penalties, capacity shortage penalty and fixed operation and maintenance costs.

Replacement cost: This is the cost required to replace wear out components at the end of its life cycle. This cost is different from initial cost of the component, due to the following reasons. At the end of its lifecycle not all of the spares of the component need to replace, Costs from donors may eliminate or can reduce initial cost, however replacement cost may not account travel costs but initial costs do.

The cost and size inputs into the software, such as the range of sizes for the PV, wind turbines, biogas generator and the converter and the number of batteries, are given in Table below so as to give flexibility to the software and optimize the output results.

Table-5.1 Cost and size inputs to the HOMER software

	PV module	Wind turbine	Gen-set	Battery	Converter
Size(KW)	1	5	20	1,156Ah	1
Capital ($)	2000	4900	18000	833	700
Replacement cost ($)	2000	3327	18000	833	700
O$M cost ($/year)	0	100	0.103/hr	15	0
Sizes considered (KW)	0,5,10,15, 20,30	____	0, 10.20, 40, 80, 100,	____	0,20,30,50 ,80,100
Quantities considered	____	0,5,10,15	____	0,10,20,30 ,50,70,80	____
Life time	20 yrs	20 yrs	2500hrs	12 yrs	15 yrs

5.5 Other Inputs that Affect Power System Optimization

5.5.1 Economic Inputs

HOMER is provided also with economic inputs window, thus to get the NPC of the system. Economic input parameters include like project lifetime, annual real interest rate, capacity shortage penalty, fixed capital cost, and system fixed O&M cost. System fixed capital cost is the cost that engaged at the beginning of the project implementation. Despite of the size and scheme architecture, the system fixed capital cost and O&M cost are considered as fixed values. Though these values have an effect on the NPC of each system however it affects them all at the same rate, thus they have no effect on the power system ranking

Real interest rate is the difference between inflation rate and nominal interest rate. HOMER discounted the capital cost of each components of the power system in to annual cost by amortizing the lifelong time of the components using real interest rate. It does not consider inflation; rather it assumes prices will rise at the same rate during the life long period of the power system. To compare the economics of the power system configuration with renewable and non-renewable sources of energy, the modeling tool would consider the following additional inputs. The lifetime of the off-grid power system is designed to end for 25 years long with generating capacity to meet the demand and the annual real interest rate is taken as 7% that is used to calculate the NPC of the project.

5.5.2 Constraint Inputs

Constraint is a condition set by the power system designer in which the power providing scheme should satisfy to be feasible. An infeasible power system is a system that does not meet the constraints set by the modeler. It should be noted that capacity shortage is a power shortfall made between the needed operating capacity and system actual operating capacity of the scheme at certain time period. The needed operating capacity includes the surplus demand and operating reserve loads. The operating reserve is safety margin for excess electrical energy generating capability that ensures reliable provision of electricity, despite of the load, solar and wind fluctuations. HOMER is smart enough to calculate the capacity shortage of any power system architecture per annum. Excess electricity is produced due to either excess generation of power from renewable sources above load demand beside to this when battery bank is fully charged so unable to store the produced energy [13]. For this thesis case the following constraint inputs are considered and no thermal load is accounted for this site of interest. Maximum annual capacity shortage of 10%, minimum renewable fraction 40%, operating reserve, as percentage of hourly load 10% and annual peak load of 0%, operating reserve, as percent of renewable output, solar power output: 25% and wind power output of 50%.

5.5.3 Emission and System Control Parameters

In Ethiopia, there is no framework that leads to penalizing rules for emission. Although emission penalty is already applied in the developed world, however as the African continent is considered as unindustrialized continent emission penalty is not adopted yet. In this thesis no emission penalty is considered at all for the system. The power flow control mechanism is an important input parameter for the power system. The control strategy is simple when the hybrid system includes PV, wind and battery components, however it becomes complex when generator is included in the hybrid system, as it is important to know how to charge batteries and how to supply the power either from the batteries or from generator.

Cycle charging: batteries are to be charged to the set point state of charge when the system starts to charge with no interruption until it will reach the set point state of charge. It helps to reduce the generator number of start cycles, charge and discharge cycles of the battery bank and also the time the battery waste at minimum state of charge.

Load following (zero charging strategy): this means batteries do not get charged by the diesel generator, it gets maximum charging time when renewable sources gets higher, meaning when generated power is greater than the load demand.

Set-point state of charge (SOC) 80%: This would help to minimize the operation cost of the power system however during the load following strategy this percentage would be zero.

5.5.4 Sensitivity Inputs

The modeling tool permits to take an account for future dynamic changes, meaning increasing or decreasing demands, renewable and non-renewable resources fluctuations. Sensitivity parameters chosen by the modeler would tell how sensitive the power system is for each change of the input variables. The benefit of putting sensitivity analysis is to define the uncertainty pertaining with the power system, when the modeler is not quite sure about the values of the components considered choosing several parameters to ensure the likely range and see how the system changes. When considering large number of sensitivity variables, it should be noted that the computational time of HOMER takes too much to complete the simulation which is very challenging to the software. The computational time depends on the quantity and sizes of the power system components and the sensitivity number of variables. Thus, this all combinations prolongs the running time, which is the limitation of the software. Although the accuracy of simulation result increase with the increase of the number of sensitivity variables, computational time is long and it requires larger memory computer. Taking the limitations into account in this thesis work the sensitivity cases are given maximum capacity shortage (%) 0, 5, 8, 10; minimum renewable fraction (%) 40, 60 and diesel price ($/liter) 0.8, 0.9,1 and 1.24.

CHAPTER SIX
RESULT AND DISCUSSION

6.1 Homer optimization results

After entering the necessary inputs, to find the optimum solutions, HOMER run repeatedly by varying parameters that have a controlling effect over the output. The output of the simulation was a list of feasible combinations of PV, wind-turbine, generator, converter, and battery hybrid system set-up. Optimization results are displayed in the form of overall and categorized showing the most feasible power systems architecture which meets the load and the inputs constraints made by the modeler. The feasible solutions were presented in an increasing order of the net present cost from top to down. The categorized table presented the least cost effective combinations from among all components setup, whereas, the overall optimization results displayed all of the affordable system combinations based on their NPC. Power systems were selected after simulation based on primarily minimum net present cost. On top of these parameters less cost of energy, high renewable fraction, low capacity shortage, low excess electricity generation, and less diesel fuel consumption could be used for comparison of power generating schemes in order to check their technical feasibility. Table 6.1 shows a list of the possible combinations of system components in an overall form from top-ranked system.

Although HOMER simulated different configurations of energy system components, however it only displays the feasible power schemes scenarios for extra detailed analysis. The complexity and computation time are affected by the number of parameters and total number of potential values involved in the design.

Table 6.1 list of the possible combinations of system components in an overall form

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

PV (kW)	Pro15	Label (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
40		10	4	20	LF	$ 100,932	11,274	$ 245,047	0.334	0.74	0.10	8,572	4,066	12.0
40		10	4	30	LF	$ 107,932	11,439	$ 254,156	0.346	0.74	0.10	8,555	4,055	12.0
50		10	4	20	LF	$ 120,932	10,598	$ 256,404	0.347	0.79	0.09	7,815	3,680	12.0
40		20	4	20	CC	$ 104,532	12,500	$ 264,329	0.335	0.69	0.00	9,916	2,083	12.0
50		10	4	30	LF	$ 127,932	10,728	$ 265,078	0.359	0.79	0.09	7,770	3,651	12.0
30		20	4	20	CC	$ 84,532	14,305	$ 267,392	0.339	0.60	0.00	11,622	2,521	12.0
40	4	10	4	20	LF	$ 120,532	11,710	$ 270,220	0.368	0.74	0.10	8,484	4,014	12.0
40		10	4	10	LF	$ 93,932	13,917	$ 271,839	0.369	0.69	0.10	10,945	5,353	12.0
50		20	4	20	CC	$ 124,532	11,554	$ 272,233	0.345	0.76	0.00	8,931	1,822	12.0
40		20	4	30	CC	$ 111,532	12,603	$ 272,639	0.345	0.69	0.00	9,848	2,061	12.0
40		10	4	50	LF	$ 121,932	11,811	$ 272,910	0.372	0.74	0.10	8,555	4,055	12.0
30		20	4	30	CC	$ 91,532	14,468	$ 276,484	0.350	0.60	0.00	11,604	2,515	12.0
40	5	10	4	20	LF	$ 125,432	11,841	$ 276,797	0.377	0.74	0.10	8,480	4,013	12.0
40		20	2	20	CC	$ 102,866	13,625	$ 277,042	0.351	0.69	0.00	10,841	2,501	12.0
40	4	10	4	30	LF	$ 127,532	11,874	$ 279,328	0.380	0.74	0.10	8,467	4,003	12.0
50		20	4	30	CC	$ 131,532	11,594	$ 279,739	0.354	0.76	0.00	8,811	1,783	12.0
50	4	10	4	20	LF	$ 140,532	11,026	$ 281,486	0.381	0.80	0.09	7,721	3,623	12.0
30		20	2	20	CC	$ 82,866	15,542	$ 281,539	0.357	0.59	0.00	12,636	2,993	12.0
20		20	4	20	CC	$ 64,532	17,063	$ 282,648	0.358	0.45	0.00	14,197	3,097	12.0
50		20	2	20	CC	$ 122,866	12,536	$ 283,118	0.359	0.75	0.00	9,754	2,196	12.0
50		10	4	50	LF	$ 141,932	11,100	$ 283,832	0.385	0.79	0.09	7,770	3,651	12.0
40	5	10	4	30	LF	$ 132,432	12,006	$ 285,905	0.389	0.74	0.10	8,463	4,002	12.0
40		20	2	30	CC	$ 109,866	13,773	$ 285,932	0.362	0.69	0.00	10,810	2,491	12.0
50	5	10	4	20	LF	$ 145,432	11,163	$ 288,133	0.390	0.80	0.09	7,722	3,624	12.0
40	4	20	4	20	CC	$ 124,132	12,989	$ 290,180	0.367	0.70	0.00	9,871	2,071	12.0
50	4	10	4	30	LF	$ 147,532	11,159	$ 290,184	0.393	0.80	0.09	7,678	3,595	12.0

Table 6.2 categorized form where only the least-cost system configuration is considered

Sensitivity Results | Optimization Results

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

PV (kW)	Pro15	Label (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
40		10	4	20	LF	$ 100,932	11,274	$ 245,047	0.334	0.74	0.10	8,572	4,066	12.0
40	4	10	4	20	LF	$ 120,532	11,710	$ 270,220	0.368	0.74	0.10	8,484	4,014	12.0
40		20		20	LF	$ 101,200	26,702	$ 442,536	0.561	0.56	0.00	21,469	6,125	
40	4	20		20	LF	$ 120,800	27,128	$ 467,586	0.593	0.56	0.00	21,373	6,097	

6.2 Optimization Analysis of the Selected Schemes

The most cost effective system, i.e. the system with the lowest net present cost, is the PV-wind - generator-battery-converter set-up with the generator operating under a load following (LF) strategy (a dispatch strategy whereby the generator operates to produce just enough power to meet the primary load; lower-priority objectives, such as charging the battery bank or serving the deferrable load, is left to the renewable power sources). For this set-up, the total net present cost (NPC) is $245,047, the cost of energy (COE) is 0.332 $/kWh, contribution from renewable resources is 74%, the amount of diesel oil used annually is 8,572 liters and the generator operates for 4,066 hours per year.

In this set-up, there is an excess electricity generation of 23.2%, unmet electric load is 7.0% and capacity shortage is 9.8%. Table 6.2 above gives some of the main information about the system. Figure 6.1 shows the monthly average electrical production of this system.

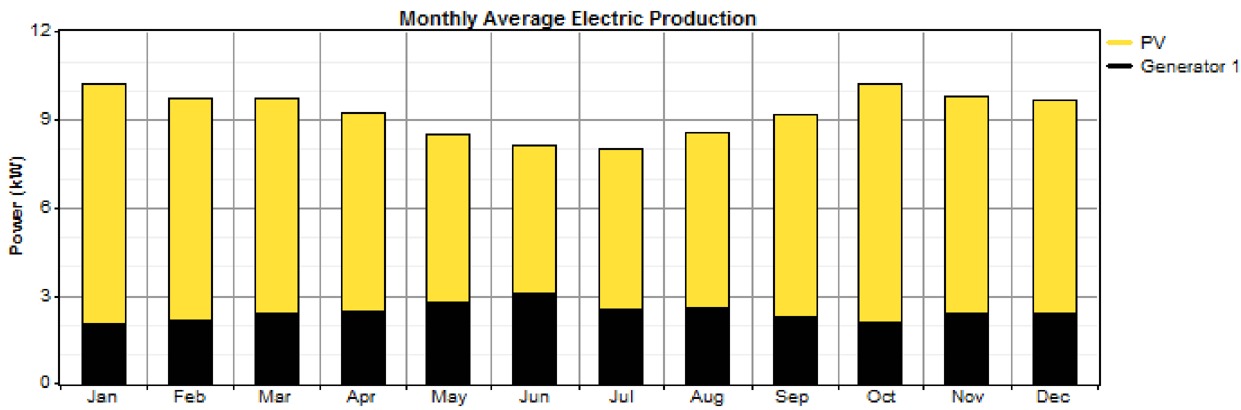

Figure 6.1 the monthly average electrical production of first cost effective system.

The second cost effective set-up is PV-wind-generator-battery having lowest net present cost with the generator operating under load following (LF) strategy. This is the set-up in which my title was concerned and analytical sizing calculation used as designing procedures in above sections. For this set-up the total net present cost (NPC) is $270,220, the cost of energy (COE) is 0.368 $/kWh, contribution from renewable resources is 74%, the amount of diesel oil used annually is 8,484 liters and the generator operates for 4,014 hours per year which is lower than the first set up and reduces annual oil consumption and operating hours.

The monthly average energy production of the hybrid scheme is presented in figure 6.2. The architecture of this power system contributed 79% of renewable fraction. The trend of electricity production from wind turbine has shown an increase of 6% from the first ranked cost effective configuration.

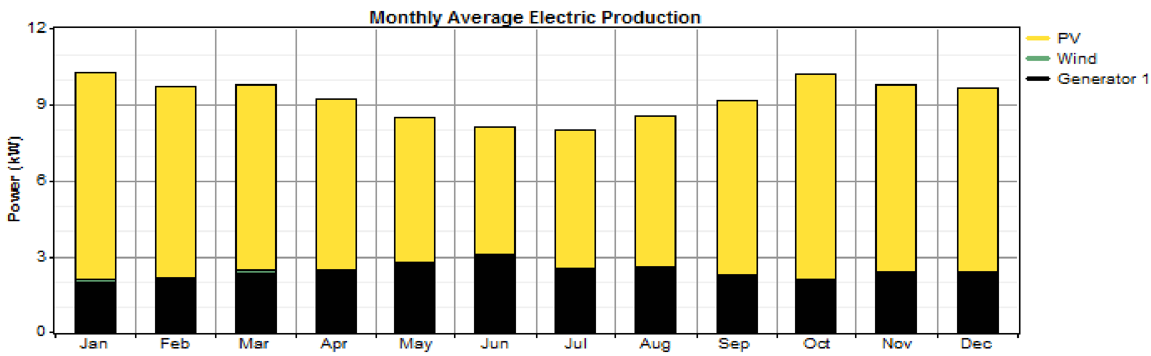

Figure 6.2 the monthly average electrical production of the second cost effective system.

The magnitudes associated to the generation of electricity by individual components showed that this power system setup has annual electricity production of 81,041Wh/year. The power generation offered from solar PV is the largest as presented in the above graph which is about 74%, followed by generator power. The AC served load is accounted for 47531kWh/year in which 83% of primary load served.

Excess electricity obtained from this scheme is about 18,794KWh/year, which is accounted for 23.2% of the total energy produced; it is presented in figure-6.3. Essentially this power system architecture indicates that it would enable to supply the demand growth of the community in the future, however it is the excess electricity produced in account of the operating reserve and the capacity shortage of introduced into the system. This excess electricity can provide to neighboring villages, furthermore can supply to grid or introduce small businesses to increase the load factor of the power system; consequently the cost of electricity will decrease also. This scheme has capacity shortage of 9.8% and the unmet load happened in this system is about 7.0%.

CHAPTER SEVEN

CONCLUSION, RECOMMENDATION AND FUTURE WORKS

7.1 CONCLUSSION

This thesis work has been devoted to the resource assessment and optimal design of an off-grid renewable hybrid power system for a rural village of Addis Boder Dawuro. The result from empirical formula for calculation of solar radiation showed that the site has huge exploitable solar energy potentials for the provision of electricity. When the result was compared with the data collected from NASA, it was found to be nearly the same. The result also clearly displayed that global irradiation on inclined panel has a significant difference from horizontal irradiation. Consequently, for this study the calculated solar radiation on inclined panel was used for modeling the hybrid system, in which maximum power is extracted.

The solar radiation has to be understood for PV modules to get the maximum irradiation in optimum inclination angle. The technical details of the array configuration and component sizing in PV systems are also very important for efficient power generation, because the factors affecting the PV output are related these components, the PV array configuration, and losses. In technical design, all the losses are considered and alternative ways are recommended to reduce the losses.

The five years mean wind speed data were collected from NMSA at 2m anemometer height was extrapolated to 30m and 50m height by logarithmic exponential law, but the result showed that the area has low wind energy resource and consequently power extracted from wind turbine is very low. In the above wind speed calculation, the maximum wind speed at 50m was 4.87m/s, which is still lower value. Thus larger percentages of load demand were supplied by solar PV system. Hence for this hybrid system the location of turbine site should be change to place of hill area/hill top where significant wind speed is available. Because when altitude increases wind speed also proportionally increases. Unless using wind energy system with lower power system is simply enhancing the system cost rather than meeting load demand.

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During the design of the off-grid system different set-ups were done an HOMER software tool optimization process based on the electricity load, climatic data sources, and economics of the power components in which the NPC has to be minimized to select an economic feasible power system. The simulation result displayed the most economical feasible system sorted by NPC from top to down.

The results obtained from the software give numerous alternatives feasible hybrid systems with different levels of renewable resources penetration which their choice is restricted by changing the net present cost of each set up Power schemes (scenarios) with less NPC, less COE, higher renewable fraction, less capacity shortage, smaller excess electricity and minimum fuel consumption would be suggested as optimum system.

The proposed wind/solar hybrid system seeks to optimize and maximize the exploitation of wind energy and solar energy while experiencing the shortcomings that arise from the dynamic nature of wind and the uncertainty of the sun. The proposed design comes with a relatively high cost but with the output of the system, the benefits are immeasurable considering environment friendly generation of electricity that supplied to the proposed community.

Besides electricity provisions, the role of a standalone hybrid system in protecting the environment from degradation, the improvement of life of people living in rural area, development of clean energy, and the future situation regarding fossil fuel sources should be taken in to account. Taking these issues into account the free solar and wind energy of the country should be utilized to improve the quality of life of the communities living in rural areas.

7.2 RECOMMENDATION

Across different corners of the country there are renewable energy resources which varies from site to site, thus can be used for electricity generation either in grid or off-grid system. Electricity generation using off-grid systems form local renewables alleviates the country's electricity shortage. However, there are and will continue to face different challenges to implement such systems like; finance of the community, infrastructures, absence of awareness how to use renewable resources and risk taking decisions by investors and other related issues.

As far as the environmental aspects are concerned, this kind of hybrid energy systems have to be wide spread in order to cover the energy demands of rural communities, and in that support Ethiopian Government Green Economic Police as well way to help reduce the greenhouse gases emission and the deforestation of the environment in general

To improve the energy deficiency at national and state level, grid and off-grid renewable energy technology systems has to be promoted using different mechanisms including aid. Empowering the rural communities' income to grow renewable generated electricity purchasing power is also fundamental. If due attention is given for land degradation, environmental pollution and poor living standard of the rural community renewable sources hybrid should be implemented, however the current electrification trend of Ethiopia's government is by constructing large hydropower dams and somehow wind power farms. Furthermore in a rare case PV standalone system for individual homes is also introducing but this system is not reliable and sustainable. Thus hybridizing of wind and solar should be given due merit and could provide a 24 hour quality electricity.

Such hybrid systems should be undertaken in the area due to various factors including:

- The favorable conditions available in the country to run such a project i.e. 12 hours of sunshine throughout the year due to its geographical location along the equator.
- The need for water distribution in most of rural village and also to increase the water capacity available in the country thus tackling the problem of water shortages in the urban areas.

7.3 SUGGESTION FOR FUTURE WORKS

- The study only focused on one selected village of south region in Ethiopia and it does not cover all villages around region. So, the future researchers should expand this research work in other sites of the region and make the rural people beneficiary with renewable energy resource.
- As far as environmental issues are concerned, these kinds of hybrid systems have to be wide spread in order to reduce greenhouse effects and pollution of the environment and in that support Ethiopian Government Green Economic Police as well way to help reduce the greenhouse gases emission and the deforestation of the environment in general
- By using tracking system and different types of reflector PV-wind Hybrid system can be designed to achieved more energy.
- On a technical level, this thesis has looked at HRE systems consisting of PV panels, wind turbines and lead acid batteries. There are many other types of energy generation which could be included in a system such as micro-hydro generation, biogas and other methods of energy generation.

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APPEDIXES:

A. Daily Sunshine hours data from NMSA

Stn. Name Tercha — Daily Sunshine Duration per Hour

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Mon.Av.
Jan	9.5	9.6	9.7	8	8.3	7	9.5	9.6	9.3	9.9	7.6	9.1	7.4	7.5	9.8	8.8	8.6	7.7	4.8	7	6.6	8.8	8.8	9.1	9.6	9.7	10	9.9	10.2	9.1	10.3	8.7355
Feb	10.4	10.3	9.9	10.2	10.2	10	10.2	9.9	8	9.5	8.3	9.4	10.2	9.2	1.6	7.8	3.8	8.9	7.8	8.7	10.3	9.1	9.1	7.2	7.7	8.2	9.4	7.8				8.6821
Mar	9.6	9.8	9.9	10.1	10	9.9	10	9.7	9.1	9.9	9.8	4	8.4	8.9	9.6	9.7	10.2	8.8	6.2	4.4	5.8	9	5.5	0	5.1	4.3	10.3	9.8	9.1	7.5	8.2	8.1484
Apr	10	10.3	5.3	3.7	9.1	9.3	8.4	10	8.4	10.3	9.7	8.6	5.1	5.5	6.9	7.5	8.2	9.2	8.4	8.6	10.2	4.3	10	7.4	9	4.8	6.5	10.4	9.8	10		8.1
May	7.3	9.5	4.4	10	1.9	5	3.1	4.5	6.2	3.6	4.8	10.5	6.4	9.3	10	5.9	9.1	5.6	6.8	7.6	8.2	6.6	7.5	7.6	1.2	8.1	9	10.5	1.4	6	9.5	6.6806
Jun	2.9	4.4	10.3	8.8	8.4	10	5.1	8	6	5.6	1.9	3.3	7.6	3.8	2	2.7	3.5	1.2	6.1	6.3	2.2	3	0	0.9	4	0.5	4.6	0.1	3.9	1.6		4.29
Jul	4.8	3.1	8.9	2.4	9.2	9.3	10.3	7.8	6.1	8	5.5	6.4	0.1	0	8	4	6.9	6.1	2.6	6.3	3.4	2.8	4.4	6.1	7.5	7.3	5.9	7.4	3.9	2.3	1.9	5.4419
Aug	3.7	3.4	3.3	4.6	4.3	7.4	0.8	6	7.1	9.3	7.5	6.7	6.6	6.3	7.9	2.8	6.3	0.4	7.9	9	7.5	4.9	7.6	7.7	6.9	2.2	10.4	8.9	5.1	4.6	1.1	5.7484
Sep	4.5	7.9	7.4	7.9	4	7.1	8.2	6.7	5.7	10	9.5	9.3	4.2	5.5	9.3	10.2	6.9	1.5	5	7.7	5.2	8.9	6.4	9	8.9	7.9	6.7	8.4	5.1	7.1		7.07
Oct	9.8	9.9	9.7	8.9	9.7	9.5	6.9	9.8	10.3	9.9	9.2	5.6	8.8	9.8	9.3	9.8	10.4	8.5	4.4	10.2	7.4	1.7	7.4	10.6	9.6	9.4	9.8	8.6	8.8	7.7	8.8	8.7
Nov	8	9	9.1	5.7	6.2	5	4.9	5.2	9.3	7.7	6.9	9.3	1.1	8.2	9.8	9.6	9.5	9.5	9.6	9.6	8.6	10	10	9.8	8.8	9.1	9.3	9.3	9.6	9.9		8.2533
Dec	1.1	9.3	8.5	9.6	10	8.5	8.8	7.6	4.6	0	4.3	1.7	2	0.1	2.5	6.8	9.2	10	9.8	9.2	9.3	9.8	9.9	10.1	5.2	7.8	8.8	9.9	9.6	6.2	9	7.071
																																7.2448

B. Daily wind speed at 2m height anemometer from NMSA

Stn. Name Tercha — Daily Windspeed in m/s

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Mon. Ave.
Jan	2.83	2.72	0.84	0.83	1.05	1.39	2.12	3.01	0.83	0.63	1.36	2.14	2.69	1.84	1.47	1.58	1.13	0.84	1.04	1.38	2.04	1.62	1.65	1.64	2.08	2.30	1.59	2.18	3.06	4.21	3.78	1.87
Feb	3.63	2.84	2.45	2.69	2.36	2.77	2.65	1.27	1.15	1.26	1.09	2.08	1.57	0.90	1.41	1.11	1.15	1.57	1.19	1.19	1.47	1.24	1.33	1.38	1.22	2.72	2.65	2.64	0.00			1.76
Mar	2.39	3.78	4.16	2.86	1.57	2.38	3.19	4.20	3.10	2.26	1.48	1.34	1.60	1.69	1.37	1.37	1.61	1.87	2.04	1.74	1.35	1.14	1.24	0.78	1.08	1.44	1.37	0.92	1.26	1.21	1.27	1.91
Apr	1.17	1.30	1.38	0.90	1.82	1.16	1.23	1.32	1.13	1.19	1.10	1.20	1.18	1.40	1.30	1.57	1.95	1.34	1.09	1.33	1.54	1.27	1.33	0.97	1.22	1.12	1.26	1.44	1.46	1.54		1.31
May	1.34	1.67	1.45	0.97	1.32	1.05	0.89	0.87	1.10	1.00	0.81	1.12	1.04	0.89	1.36	1.32	0.96	1.35	1.11	1.44	1.29	1.41	0.79	1.36	1.14	1.29	1.19	0.97	0.95	1.32	1.07	1.16
Jun	1.14	0.65	0.97	0.93	1.16	1.09	0.96	0.97	1.09	1.41	0.79	1.14	0.93	0.97	0.89	1.49	1.05	1.38	0.87	1.30	1.26	1.06	0.82	0.61	0.98	1.38	0.81	0.83	1.19	1.52		1.05
Jul	1.02	1.10	1.53	1.44	1.38	1.10	1.21	1.26	1.55	1.22	1.05	1.31	1.00	0.87	1.32	0.93	1.16	1.23	1.44	1.28	0.87	0.90	0.66	1.18	0.98	0.81	1.24	1.12	1.26	1.25	0.92	1.15
Aug	0.92	0.81	1.47	1.72	1.10	0.83	1.10	1.29	1.00	1.02	1.22	1.18	1.06	1.02	1.25	1.58	0.78	1.15	1.36	1.02	1.29	1.30	1.22	1.20	1.31	1.19	1.00	1.32	1.29	0.88	1.13	1.16
Sep	0.99	1.02	0.98	1.15	1.13	0.77	1.01	0.84	1.01	1.24	1.22	0.81	1.10	1.23	1.33	0.96	0.90	0.88	1.11	1.37	1.10	1.12	0.90	1.12	1.30	1.21	1.23	0.79	0.82	0.92		1.05
Oct	1.29	1.64	1.51	1.20	0.50	0.87	0.88	1.09	1.13	1.15	1.11	0.65	1.16	1.10	1.05	0.94	1.13	1.11	1.50	0.38	1.01	0.93	1.18	0.96	0.90	0.78	0.75	0.98	1.14	0.78	1.55	1.04
Nov	0.74	1.70	2.38	0.98	1.23	0.96	1.52	1.08	1.10	1.16	0.63	0.57	0.86	0.63	1.25	1.42	1.28	1.32	2.10	2.03	1.54	2.21	1.50	1.51	1.45	1.43	1.77	2.46	1.23	0.67	0.73	1.34
Dec	0.74	1.70	2.38	0.98	1.23	0.96	1.52	1.08	1.10	1.16	0.63	0.57	0.86	0.63	1.25	1.42	1.28	1.32	2.10	2.03	1.54	2.21	1.50	1.51	1.45	1.43	1.77	2.46	1.23	0.67	0.73	1.34
																																1.34

C. Hourly primary load input to HOMER

Hour (h)	Hourly primary load (KW)
00:00-01:00	0.120
01:00-02:00	0.120
02:00-03:00	0.120
03:00-04:00	0.120
04:00-05:00	0.120
05:00-06:00	0.120
06:00-07:00	0.060
07:00-08:00	0.130
08:00-09:00	0.220
09:00-10:00	12.670
10:00-11:00	12.670
11:00-12:00	12.640
11:00-12:00	8.510
12:00-13:00	8.510
13:00-14:00	12.670
14:00-15:00	12.670
15:00-16:00	12.510
16:00-17:00	0.890
17:00-18:00	5.330
18:00-19:00	14.550
19:00-20:00	14.550
20:00-21:00	13.760
21:00-22:00	0.220
23:00-00:00	0.220

D. Monthly Deferrable load input to HOMER

Month	Deferrable (KW)
January	32.500
February	33.100
March	33.100
April	33.100
May	33.100
June	29.790
July	16.590
August	16.590
September	16.590
October	33.100
November	33.100
December	33.100
January	32.500