ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Feasibility Study of an Off-grid PV/Wind/Generator Hybrid System for Remote Mobile Base Station (Case Study: Hadnet Mobile Base Station)

A thesis submitted to Addis Ababa institute of technology, school of graduate studies, Addis Ababa University in partial fulfillment of the requirement for the degree of Master of Science in electrical and computer engineering (Electrical Power Engineering)

By

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Addis Ababa, Ethiopia

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been acknowledged.

All examiners' comments are incorporated.

Name: Abrehet Gaim Kahsay

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Date of submission: _________________

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

Dr. Getachew Bekele_ _______________________

Advisor's Name Signature

Dedication

To my beloved family

and

friends

... *for their incomparable support in all of my academic achievements!*

Acknowledgement

First of all, I would like to thank the Almighty GOD for his willingness without which this thesis work is impossible. In addition, I would like to thank AAiT (Addis Ababa Institute of Technology) for facilitating the thesis work.

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Abstract

There is a clear challenge to provide reliable cellular mobile service at remote locations where a reliable power supply is not available. So, the existing mobile towers or base transceiver station (BTSs) use a conventional diesel generator with backup battery banks. However, the current increase in diesel price and the negative effects of fossil fuels on the environment motivates to search for other alternative (preferably renewable) sources of energy. In this work, feasibility of PV/Wind/Generator hybrid system with battery storage as a backup is studied to provide a reliable electric power for a specific remote mobile base station located at Hadnet, Wukro, Tigray. The feasibility of this study is analyzed using HOMER (Hybrid Optimization Model for Electrical Renewable) software. The study utilized meteorological data obtained from National Meteorological Service Agency of Ethiopia and NASA to estimate the solar and wind energy potentials. The load consumption data for the base station is collected from network and operation center section of Ethio-telecom organization.

The best optimal system configurations namely PV/Wind/Generator/Battery and PV/Wind /Battery hybrid systems are compared with the conventional stand-alone diesel generator (DG) system. Findings indicated that PV/Wind/Generator/Battery hybrid system is the most economically viable option with a total cost of $168,137 for the whole system project life time, i.e. 20 years and for the diesel generator system the total cost is $653,602 for the whole system project life time. And the levelized cost of energy (COE) for both systems is $0.282/kWh and $0.729/kWh respectively. This implies the hybrid system saves $485,465 in terms of NPC and $0.447/kWh in terms of COE to the network operator. Also, simulation results show that the renewable energy source based hybrid energy system can decrease amount of air pollutants as compared to the conventional diesel generator only and so a reduction of 38,657kg/yr of CO_2, 95.38 kg/yr of CO, 10.532 kg/yr of UHC, 7.192 kg/yr of PM, 77.66 kg/yr of SO_2, and 851.3 kg/yr of NOx is observed and saves about 14,680 liters of fuel per annum to the network operator. The sensitivity analysis is also carried out to analyze the effects of probable variation in solar radiation, wind speed, diesel price and average annual energy usage of the system load in the optimal system configurations.

As a result, this study has verified that the hybrid system is superior to the diesel-only system for power generation at the BTS site from the perspective of economic, reliability and environmental analysis.

Keywords: Base Transceiver Station (BTSs); Hybrid system, Photovoltaic (PV), wind, Generator, HOMER

Table of Contents

List of figures

List of tables

Acronym

PV	Photo Voltaic
EIA	Energy Information Administration
NPC	Net present cost
GSM	Global System for Mobile Communication
UMTS	Universal mobile telecommunication system
CDMA	Code Division Multiple Access
PSTN	Public Switch Telephone Network
3G	Third Generations
4G (LTE)	Fourth generation or Long Term Evolution
BTS	Base transceiver station
AC	Alternating current
DC	Direct current
km	Kilo meter
kWh	Kilo watt hour
DG	Diesel generator
HOMER	Hybrid optimization model for electric renewable
O&M	Operation and maintenance costs
HAWT	Horizontal axis wind turbine
VAWT	Vertical axis wind turbine
ISA	International standard atmosphere
DOD	Depth of discharge
NMSA	National metrology service agency
NASA	National Aeronautics and Space Administration
COE	Cost of energy
$	Dollar
GHG	Greenhouse gas
Kg	Kilo gram
OPEX	operational expenditure

HRES	Hybrid Renewable Energy Systems

CHAPTER ONE
INTRODUCTION

1.1. Background

Telecommunication is one of the sectors where the continuous growth in demand for mobile services and the parallel technological development goes hand in hand with regards to energy consumption; it suffices to think that information and communications technology (ICT) is accountable for consumption of about 3% of the world's total electrical energy. By the end of 2030, it is expected that this figure will grow to 1,700 TWh [1].Telecommunication networks have changed the way people live, work and think. Since many people around the world are connected by telecommunication networks, the challenges to provide reliable and cost effective power solutions to these expanding networks is indispensable for telecom operators.

There are various renewable energy sources such as solar energy, wind energy, fuel cells, biodiesel and so on for telecommunication applications. The implementation of renewable energy technologies, such as a stand-alone wind, PV, or wind-solar hybrid systems, to meet energy demands is on a steady increase since resources are naturally available, free, inexhaustible and pollution free. However, the reliability of these renewable sources of power supply poses a challenge since resources availability is seasonal. Hence, hybrid energy systems, improved stand-alone and grid-connected systems in some cases are being developed; incorporating advanced energy storage in order to increase power generation rates, improve reliability and consistency of power supply and to provide secure power supply to the end user. The grid, sometimes, is either not available or its extension can be extremely costly in remote area coupled with the losses experienced during transmission.

According to the U.S. Energy Information Administration, EIA (2009) [2], an average of 6.5% losses is experienced during transmission and distribution, hence, the stand-alone systems are recommended especially for off-grid locations. Wind and solar energy sources are the cheapest available natural resources for renewable energy and they best complement each other seasonal alternations and with incorporated energy storage system (such as a battery storage system) to supply energy in case of shortfall by the wind/solar hybrid system as a result of fluctuating weather conditions.

Ethio telecom is an integrated telecommunication solutions provider operating in Ethiopia. It provides various telecommunication services as Global System for Mobile Communication (GSM), Code Division Multiple Access (CDMA) and Public Switch Telephone Network (PSTN) services. Recently, it deployed Third Generation (3G), Evolution Data Optimized (EVDO), 4G (Long Term Evolution), Next Generation Network (NGN) and Optical Network Unit (ONU) based network services. All these telecommunication stations at different location required efficient design and reliable power network. The electric power infrastructure is playing a negative role in the growth of mobile telecommunications in terms of network coverage and great impact on the operation cost of running the system due to non-availability of grid power supply. Due to this there is very limited or no coverage of mobile network for the rural population.

Conventional diesel generators with backup battery are used for powering these mobile tower sites (BTS). These off-grid systems, usually located in areas with difficult accessibilities require regular maintenance and are characterized by their high fuel consumption and high transportation and operational cost [3,4]. Also, due to the increasing demand of clean energy technology to reduce the greenhouse gas emission pressure telecom companies for alternative solutions for powering these sites is needed. Therefore, in order to meet the continuous typical load demand of a mobile base station during varying atmospheric conditions, different energy sources need to be integrated for extended usage of alternative energy. This will create a large demand for off-grid power supply in rural areas which renewable energy is best suited to realize Ethio-telecom tower site with renewable energy technologies. Solar and wind are available freely and thus appears to be a promising technology to provide reliable power supplies in the remote areas and telecom industry of Ethiopia. The thesis aims to design an off-grid hybrid renewable energy system for Base Transceiver Station (BTS), so that can generate and provide cost effective electric power to meet the BTS electric load requirement.

1.1.1 An overview of cellular base station

A cellular base station is a wireless system and makes use of microwave radio communication technology. The base station acts as an interface between either two mobile phones or between a mobile phone and a fixed phone. Generally, these base stations are made up of several antennas mounted on a metallic tower and a house of electronics at the base of the tower. The antennas are connected to the base with cables. The base station antennas are used for transmitting as well as receiving the radio signals to and from mobile phones. Generally, these antennas are mounted on the top of the tower so that obstacles such as trees, high rise buildings, hills, etc. should not obstruct the radio signals.

Usually, three antennas are mounted on the top of the tower to cover the specified region. Among three antennas, two are used for receiving and one is for transmitting. Though these antennas operate at different frequencies they are well separated from each other to avoid interference of emitted power from each other. At the bottom of the tower a small house of electronic circuits comprising of power amplifiers, used to generate strong signals and these power amplifiers are connected to mounted antennas with long cables. The base station also has supporting components such as base station controllers using computers and AC/DC rectifiers to convert AC power to DC power.

Many base stations have a DC power back up system in the form of batteries connected either in series or parallel and these batteries supply power to the base station during blackout or power failure. The area covered by base station signals is called cell [5]**.** Based on the amount of area covered the base stations can be classified as a Macro cell base station, Micro cell base station, Pico cell station and Femto cell base station. Femto cells cover the smallest area and they are deployed in a room. Pico cells are deployed in offices or shopping malls and they cover more area than Femto cells. Micro cells can cover blocks of buildings in an urban locality and cover area more than pique cells. Macro cells cover the largest area among all the cells and generally they are deployed in rural areas or on highways.

Regarding the typology, the characteristics of different BSs are indicated below [1]:

Shelter: cabins made of aluminum and polyurethane foam containing the transmission equipment (housed in special boxes), air conditioning system and all that is needed for the correct functioning of the BS.

- ✓ **Room**: buildings containing the same equipment as a shelter.
- ✓ **Outdoor**: box containing the transmission equipment. Neither any kind of coverage, nor air conditioning systems are present. The cooling of indoor air is required in the room and shelter because of the high temperatures of the indoor environment; this is due to the

large amount of heat dissipated by the transmission systems and to the factor of solar radiations falling on the cabin (the latter is obviously also present in the case of outdoor BSs, though they are not provided with air-conditioning systems).

The methodologies usually used to decrease the temperature inside the shelter can be identified as:

- ✓ **Free cooling:** cooling system that utilizes an atmospheric air temperature to lower the temperature inside the structure: the air enters the room from the outside through a vent.
- ✓ **Air conditioner:** In the case study, for both types of BS (shelter, room), the free cooling system and the air conditioner are located on the same machine and are ON / OFF type. When free cooling is turned on, an extractor is activated, which stops the enclosure from over pressuring. The on/off of the air conditioner and free cooling is controlled by a PLC (Programmable Logic Controller), with preset "ON" thresholds and associated hysteresis values. The latter represents the temperature drop needed (after reaching the "ON" threshold) so that the cooling machine turns itself off.

1.1.2 Power requirements of Cellular Base Stations

The power needed for the radio base station depends on the number of calls at that time. For different region's traffic is different. During night time signal traffic is low when compared to day time. So it is difficult to find an actual power needed for the base station. The power needed for the radio base station varies between 800W to 3200W [6]. The average power for the whole year is 1400W for a Macro base station. The equivalent average power in MWh per year for a macro base station can be computed as 12.3 MWh.

If the site container contains more than one cabinet, then the power needed may be more. As in RBS (radio base station) there are air conditioner and heat exchanger, electronics also present. So the power is used by all the components. The highest amount of power needed for the by macro RBS IS 3200W.Micro base station needs 110W. If mini link is there the power is 150W. RBS and electrical exchanges are connected by mini link [6].

1.1.3 System voltage of telecom base station

Although other voltages are possible, most radio transceiver loads used in telecom base stations run on a -48V DC bus. This practice originated in the early days of telephony, when 48V DC was found to be suitably high for long telephone lines, but low enough to prevent serious injury from touching the telephone wires. Consequently, most electrical safety regulations consider DC voltage lower than 50V to be a safe low-voltage circuit. It is also practical, because this voltage is easily supplied from the standard valve regulated lead acid (VRLA) batteries by connecting four 12V batteries (like those used in cars) in series, making it a simple system. The positive grounded or -48V system is another survivor from earlier industry practice. The negative voltage on the line was found to be superior to positive voltage in preventing electrochemical reactions from destroying copper cables if they happen to get wet. Negative voltage also protects against Sulphation on battery terminals. Sulphation, the buildup of crystals of lead sulfate, is the leading cause of early battery failure [7].

1.2 Statement of the problem

One of the main obstacles for telecom companies (Ethio telecom) not to expand its services (especially in remote areas) is the power problem, i e. Diesel generator (DGs) and Battery are typically used for powering at off-grid remote BS sites because extending the grid connection to power off-grid BS sites is not economically attractive (is costly due to the losses experienced during transmission) or existing grid electricity is not available because of geographical limitations. But, the idea of using diesel generators as a primary power supply has become less favorable because of the challenges linked to their operational and maintenance (O&M) cost, replacement costs and significant environmental impacts. As a result, this study aims to provide a sustainable power supply solution for an off-grid base station at Hadnet based on the characteristics of its average solar radiation exposure and wind speed. Figure 1 shows the mobile base station in the study area. The mobile base station is located in Hadnet which is found 45.4kms far from wukro town, Fig 4.

Figure 1: Mobile base station in the study area

Figure 2: Generator plus fuel tank used in the site

Figure 3: Battery bank used in the site

Figure 4: Google map picture of the place where the base station is located with its distance from wukro town

1.3 Objective

1.3.1 Main Objective

The main objective of this thesis is to study the feasibility of a hybrid off-grid PV/Wind/Generator power system for remote mobile base station under a case study of Hadnet mobile base station.

1.3.2 Specific Objectives

The specific objectives include;

- To study the solar and wind energy potential of the study area.
- To study the energy demand of the telecom base station in Hadnet.
- To select appropriate solar modules, wind turbines and batteries, depending on the energy demand.
- To model hybrid renewable energy system for the base station in Hadnet.
- To compare the feasibility of hybrid PV/Wind/Generator system with respect to a conventional DG and Battery powered solution in terms of the;
  - ✓ operational expenditure (savings to maintain profitability for cellular network operators)

- ✓ Greenhouse gas emissions that have a bad effect on the environment.
- ✓ Reliability

1.4 Significance of the study

This thesis has a significant importance on how to overcome the clear challenge to provide reliable cellular mobile service at remote locations of the country where a reliable power supply is not available.

1.5 Methodology

The methodology followed in the study consists of Site identification, Data collection and Survey, as well as Data analysis and feasibility study.

1.5.1 Site Identification

The selected base station is a mobile station located in Hadnet, found 45.4km apart from wukro town. Figure 1.4 above shows the location of the base station on the map. It is located in latitude13^0 39’53’’and longitude 39^0 40’00’’with an average elevation of 2,240 meters. Generally, the selected off-grid remote BS for this thesis is the BTS located in Hadnet, Wukro district Tigray region.

1.5.2 Data Collection

As it is mentioned in the introduction section, this research is mainly concerned with looking into better option of energy sources to electrify remote base stations which are isolated from the national grid by comparing against the existed ones i.e. diesel generator and battery. The main concern is the assessment of resource potential and modeling of the hybrid system by analyzing the data taken from different sources. Relevant data are collected from two main sources. The first is from organizations and agencies like the National Meteorological service Agency and Ethio telecom organization. Sunshine hour and energy consumption of the base station are collected from these offices and agencies. The second one is from different websites, especially related to cost of PV modules, wind turbines, diesel generator, converter and battery and also the wind potential of the study area since no data is available in NMSA.

Related literatures on remote cellular base stations electrification are surveyed. These include papers and books related to remote cellular base station load estimation, potential assessment techniques of wind, solar resources, and storage system for optimization of hybrid system components.

1.5.3 Data Analysis and Feasibility Study

The energy demand of the telecom base station in the study area which includes the daily average load variation for the base station is collected from the Ethio telecom organization. The wind speed is taken from NASA and solar radiation of the study area is collected from NASA and is compared with data from NMSA. Finally, the hybrid system will be modeled and simulated using HOMER, based on the data collected to get the optimum power system configuration that would meet the demand with minimum NPC and COE.

1.6 Related Works

Following the emerging concept of green telecommunication networks, the realization of powering BS sites using sustainable solutions has started to receive significant attention. Therefore, various studies and developments have been done to help telecom operator's shift away from using diesel generators as their primary power supply solution for BSs. It is being realized that by moving away from diesel generators, the unreliability factors and the high O&M costs usually associated with this solution can be avoided. Some of the studies and methodologies implied by various researches are briefly summarized below:

Acharya D. [8] presents a solution utilizing a hybrid of solar and wind power systems with a portable generator to provide reliable power for a mobile base station located behind the Himalayas in south Asia. The design is based on the local mobile subscribers with 350 capacities with 51mE per subscriber traffic and the peak load capacity of 750 W. The meteorological data, including solar sunshine hours and hourly wind speed are taken from a site in Mustang district at 3444 m altitude. The power consumption pattern of a mobile base station depends upon the traffic pattern of the mobile users. The cost of the hybrid system is also estimated as $81,512.04 Canadian dollars. The proposed system ensures the reliability of power supply to run the 24/7 cellular mobile services at an extremely remote site of Nepal.

Paudel et al. [9] highlighted that conducting a feasibility assessment is essential when designing renewable energy systems. This is to mitigate any poorly designed power supply system that is inefficient for powering a BS site. As is often the case, the renewable energy systems are usually over-sized, and this imposes high capital and O&M costs to the telecom operators. He also claimed that 99.99% reliability can be achieved if solar and wind are deployed concurrently as a power supply solution and that the calculated, Levelized cost of electricity supplied over the lifetime of the system and for an optimum design was reported to be just under $0.90 per kWh.

Ahmed et al. [10] has discussed a point-to-point communication link where the transmitter has a hybrid supply of energy. Specifically, the hybrid energy is supplied by a constant energy source and an energy harvester, which harvests energy from its surrounding environment and stores it in a battery which suffers from energy leakage.

Olatomiwa L, et al. [11] presents the result of techno-economic analysis of hybrid system comprising of solar and wind energy for powering a specific remote mobile base transceiver (BTS) in Kaduna state, Nigeria. But the optimal system configurations obtained through simulation in HOMER. Two best optimal system configurations, namely PV-Diesel-Battery and PV-wind-diesel-battery system are compared with the conventional stand-alone diesel generator (DG) system.

Kusakana and Vermaak [12] discussed in their study that a PV system showed the lowest net present cost (NPC) which is $8,336 per year compared to a wind system and a diesel system with costs of $11,420 per year and $29,773 per year, respectively, when used to power a BS site in the Democratic Republic of Congo. These NPC values were based on the total sum of capital, replacement, and O&M costs while considering the salvage value of the power supply components.

Sandeep Kumar and Vijay Garg [13] presents the various renewable energy available today with their uses and the impact them in future. Also, it presents unit sizing and an economic evaluation of a hybrid wind/PV/FC generation system and a cost comparison with a wind/PV/battery system more over a computer program has been developed to the system components in order to match the load of the site in the most effective way. The cost of electricity and an overall system cost are calculated for each configuration. The studious way performed using the graphic user interface programmed in MATLAB.

1.7 Organization of the Thesis

This thesis is divided into six chapters. The first chapter is about the background of the study and a statement of the problem, objective, methodology and related works to this thesis. The second chapter presents the basic theory of solar PV system and the potential at Hadnet. The third chapter discusses the basic theories of wind energy systems with its potential estimations at Hadnet, Chapter four discusses the application of HOMER, for the proposed hybrid system, whereas, chapter five is all about the results of optimization and sensitivity analysis of the system. Chapter six summarizes the main findings of the thesis work. Reference is at last.

CHAPTER TWO

SOLAR ENERGY SYSTEMS AND SOLAR ENERGY RESOURCES

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 1.74×10^{17} watts of power from the sun [14]. The sun is a typical star with mass 2×10^{30} kg, beam length 700,000 km and it has roughly 5 billion more years of life. Its surface temperature is about 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 1.67×10^5 kWh. The solar energy is emitted to the universe mainly by electromagnetic radiation. Approximately one-third of energy radiated from sun is reflected back. The rest is absorbed and retransmitted to the space while the earth reradiates just as energy as it receives and creates a stable energy balance at a temperature suitable for life.

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 years [15].

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 5.

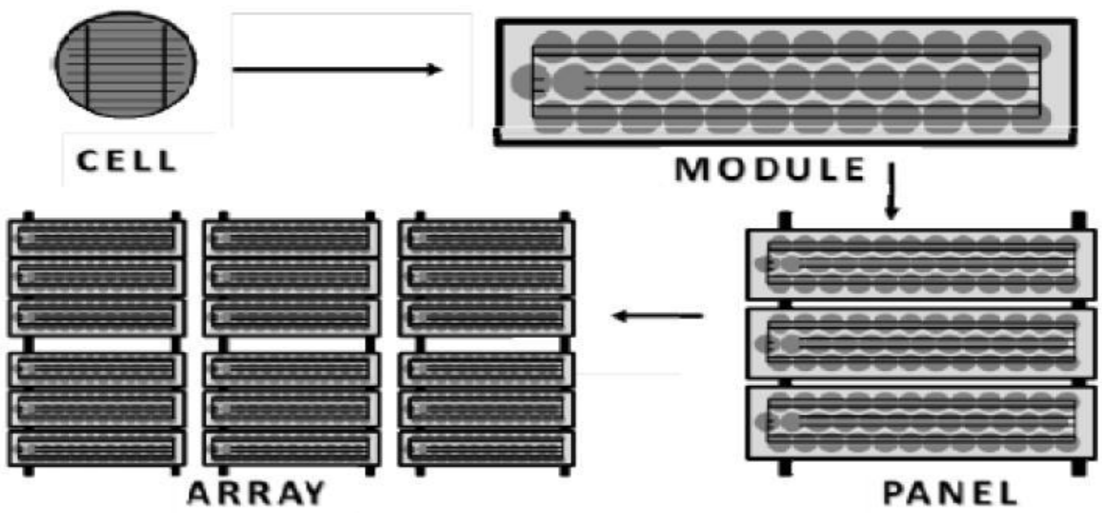

Figure 5: PV Diagram [16]

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

2.3 Working Principle of 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 (Clean Energy Associates). Figure 6 illustrates how photovoltaic cells work.

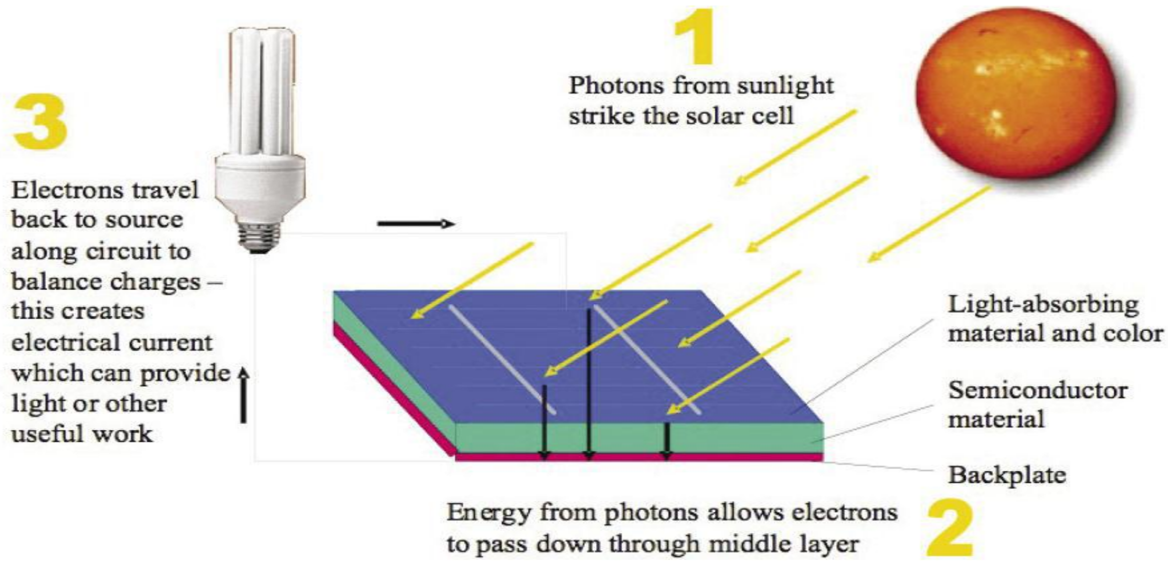

Figure 6: How Photovoltaic Cells Work [16]

2.4 Types of PV Cell

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.

- ***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% [17].
- ***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% [15].
- ***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%**.**
- ***Technology which uses thin film solar cells:*** while the total thickness of a semiconductor is about 1μm. Amorphous or thin film silicon cells are solids in which the silicon atoms are much less ordered than in a crystalline form. By using multiple

junctions this kind of photovoltaic cells achieve maximum efficiency which is estimated at about 13% while the installation cost is reduced. The efficiency of this cell oscillates between 6% and 10% [16]. 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 increase in temperature. Crystalline cells are more sensitive to heat than thin films cells. The output of a crystalline cell decreases approximately 0.5% with every increase of one degree Celsius in cell temperature. For this reason, modules should be kept as cool as possible, and in very hot condition amorphous silicon cells may be preferred because their output decreases by approximately 0.2% per degree Celsius increase [15, 17].

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 $100cm^2$ 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.

2.6 Equivalent Electrical Circuit of PV Cell

The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure 7 below. The following parameters call for consideration. The current I at the output terminals is equal to the light-generated current I_L, less the diode current $I_D$and the shunt leakage current *Ish.* The series resistance Rs represents the internal resistance to the current flow, and depends on the p-n junction depth, impurities, and contact resistance. The shunt resistance Rsh is inversely related to the leakage current to the ground. In an ideal PV cell Rs = 0 and Rsh = ∞. The PV conversion efficiency is sensitive to small variations in Rs, but insensitive to variations in Rsh. A small increase in Rs can decrease the PV output significantly.

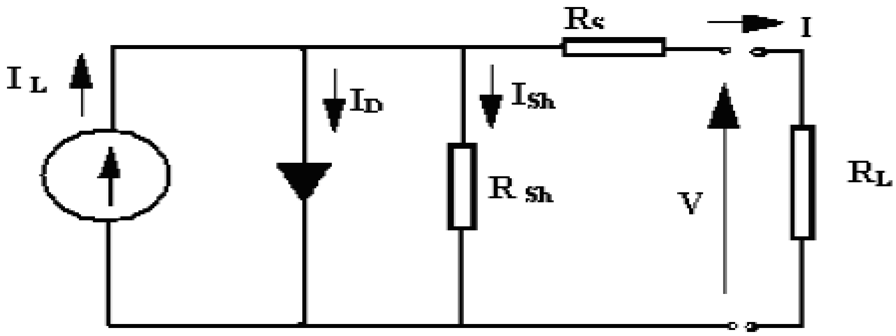

Figure 7: A PV cell equivalent electrical circuit [18]

The open-circuit voltage *Voc* of the cell is obtained when the load current is zero and is given by the following:

$$v_{oc} = (I_L - I_D)R_{sh} \qquad \text{…2.1}$$

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

$$I_D = I_o[exp\left[\frac{qv_{oc}}{AKT}\right]\text{-}1] \qquad \text{…2.2}$$

Where I_o is the saturation current of the diode (A), *q* is electron charge (1.6×10-19 C), *A* is curve-fitting constant, *K* is Boltzmann constant (1.38×10^{-23} J/°K), *T* is temperature on absolute scale ^{o} K.

Thus, the load current is given by the expression:

I=I_L-I_D-Ish

$$\text{I}=I_D - I_o[exp\left[\frac{qv_{oc}}{AKT}\right]\text{-}\frac{v_{oc}}{R_{sh}}] \qquad \text{…2.3}$$

Where; Ish is the leakage current to the ground. In practical cells, it is negligible compared to I_L and I_o and is generally ignored.

The two most important figure of merits widely used for describing PV cell electrical performance are the open-circuit voltage v_{oc} and the short-circuit current I_{sc} under full illumination. The short-circuit current is measured by shorting the output terminals and measuring the terminal current. Ignoring the small diode and ground leakage currents under zero voltage, the short-circuit current under this condition is the photocurrent I_L. The maximum photo voltage is produced under the open-circuit voltage. Again by ignoring the ground leakage current, equation 2.4 with I give the open-circuit voltage as follows:

$$v_{oc} = \frac{AKT}{q} ln\left(\frac{I_L}{I_o} + 1\right) \qquad 2.4$$

2.7 I-V and P-V Curves

The electrical characteristic of the PV cell is generally represented by the current v_s voltage (IV) curve. The figure below (Figure 8) depicts the I-V curve of typical PV cell. This curve shows the variation of current and voltage when cell resistance varies from zero to infinity. In this curve the point at which the voltage is zero is called the short-circuit current. This is the current we would measure with output terminal shorted. On the other hand, the point at which current is zero is known as open-circuit voltage. This is the voltage we would measure with output terminal open. Somewhere in the middle of the two regions, the curve has a knee point.

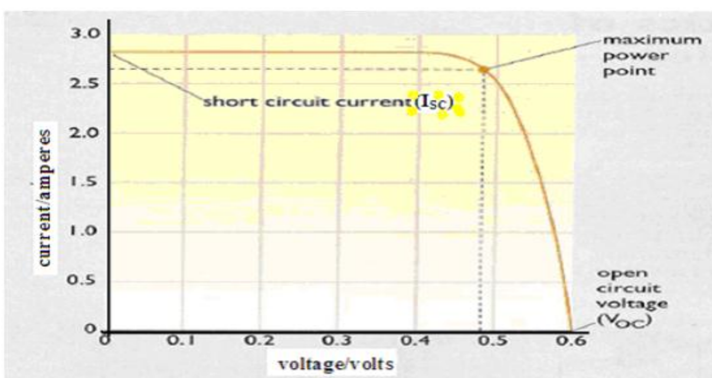

Figure 8: I-V curve of a typical silicon PV [19]

The power output of the panel is the product of the voltage and current outputs. In Figure 9, the power is plotted against the voltage which is P-V curve of the PV cell. Note that the cell produces no power at zero voltage or zero current, and produces the maximum power at the voltage corresponding to the knee point of the I-V curve. This is why the PV power circuit is always designed to operate close to the knee point with a slight slant on the left-hand side. The

PV circuit is modeled approximately as a constant current source in the electrical analysis of the system.

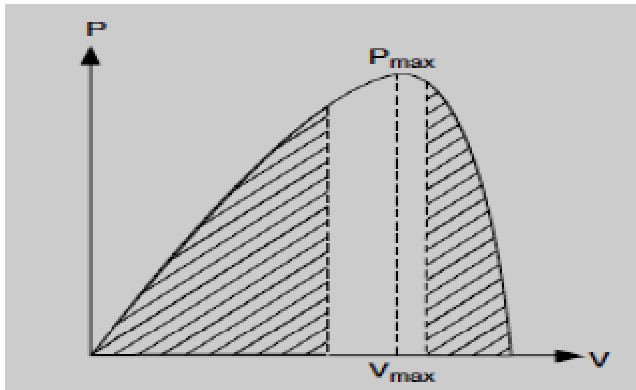

Figure 9: P-V characteristic of the PV cell [17]

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

2.8 Solar Radiation Estimations

For any solar based system design, the most important factors are the position of the sun in the sky, the slope and orientation of a collecting surface, and obstruction and reflection properties of neighboring structures. Figure 10 shows the geometry describing orientation of a collector and position of the sun in the sky.

A point on the earth's surface is expressed by its latitude and longitude. The angle between the collector surface and the horizontal is called slope, β (with $0^0 < \beta < 90^0$) for a surface facing towards the equator; $90^0 < \beta < 180^0$ for a surface facing away from the equator). Surface azimuth angle, γ_s is the angle between the normal to the surface and the local longitude meridian, projected on the horizontal plane. In either hemisphere, γ_s equals 0^0 for a surface facing due south, 180^0 due north, 0^0 to 180^0 for a surface facing westward and 0^0 to $- 80^0$ eastward. For a horizontal surface, γ_s is always 0^0.

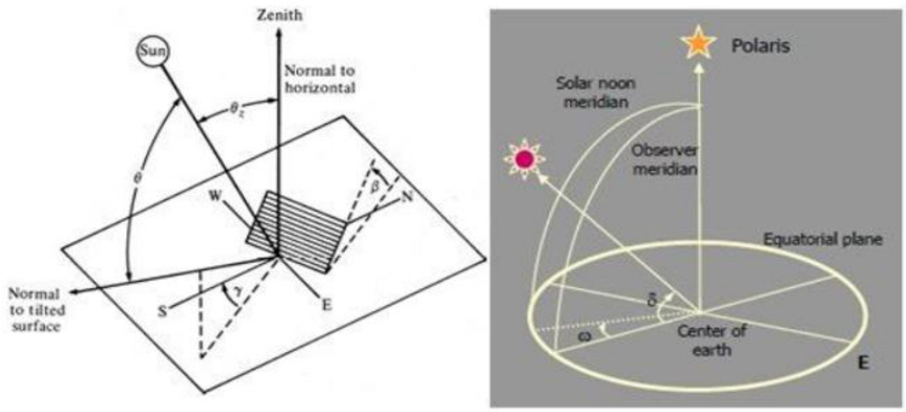

Figure 10: Geometry of solar collector and location of sun relative to earth [20]

Location of the sun in the sky, relative to a point on the ground, can be defined in terms of two angles, the solar altitude, $\propto_s$ (or its complement the solar zenith angle, θ_z) and the solar azimuth γ_s. Solar altitude $\propto_s$, angle of solar beam to the horizontal. Solar azimuth γ_s is the angle between the solar beam and the longitude meridian projected on the horizontal plane. Sign convention is the same as for surface azimuth angle (γ_s) , solar altitude and solar azimuth are functions of location (latitude, φ), time of the year (declination angle,δ) and time of the day (hour angle, ω). Solar declination angle (δ) is the angle between the earth's equatorial plane and the earth sun line. Solar hour angle ω is the angle Earth has rotated since solar noon. The relation between these angles is given below [18, 20, 21].

$\delta = 23.45 \sin (\mathbf{360}\frac{\mathbf{284+m}}{\mathbf{365}})$ ……………………………………………………………...2.5

Where = solar declination angle (^{0})

m = Day number of the year starting at January 1st as 1

$\omega = (12 - t_L)\, 15^0$ ……………………………………………………………………...2.6

Where t_L= local solar time in hours

ω= solar hour angle (^{0})

$\sin(\alpha_s)=\sin(\phi)\sin(\delta)+\cos(\phi)\cos(\delta)\cos(\omega)$ …………………………………………….. 2.7

Where $\propto_s$ = solar altitude (^{0})

Φ= latitude (^{0})

$$\sin\gamma_s = \frac{\cos(\delta)\sin(\omega)}{\cos\alpha_s} \qquad 2.8$$

Where, γ_s = solar azimuth (^{0})

The sunset/sunrise angle is given by:

$$\omega_s = \cos^{-1}(-\tan(\phi)\tan(\delta)) \qquad 2.9$$

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

$$\sin\theta_i = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \qquad 2.10$$

The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (about $1.5\text{x}10^{11}$m), measured outside the earth's atmosphere is called the solar constant, Gsc (1367 W/m^2) [22, 23]**.**The intensity of radiation received outside the earth's atmosphere varies as the inverse square of the earth-sun distance and can be expressed in relation to time of the year. The extraterrestrial irradiance on a surface at normal incidence (G_{on}) may be expressed as:

$$G_{on} = G_{sc}\left[1 + 0.033\cos\frac{2\pi m}{365}\right] \qquad 2.11$$

Where m is the number of the day in the year with January 1st representing a value of 1 and December 31 a value of 365.

The extra-terrestrial irradiance incident on a horizontal plane at an arbitrary angle of incidence is also of interest and is given by,

$$G_o = G_{on}\cos\theta_z \qquad 2.12$$

Where θ_z=zenith angle (angle between the sun and the vertical line from a point on earth) which equals to the incident angle of a horizontal surface at the point of interest.

The whole daily extraterrestrial radiation, H_o from the sunrise to the sunset can be calculated as follows:

$$H_o = \frac{24*3600*G_{sc}}{\pi}\left(1 + 00.33 * \cos\left(\frac{360m}{365}\right)\right) * \left(\cos\varphi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right) \quad \text{.........2.13}$$

Where, m = day number starting from January 1^{st} as 1.

$G_{sc} = 1367W/m^2$

Φ= latitude of the location (13^0)

δ= Declination angle (^{0})

ω_s=sunset hour angle

Ideally, the data required to predict the solar potential of any site are several years of measurements of irradiance on the proposed collector plane. These are rarely available, so the required data have to be estimated from meteorological data available either (i) from the site, or (ii) from some nearby site having similar irradiance, or (iii) from an official solar atlas or database [20]. Here, the sunshine duration data from the nearby station is used to estimate the monthly average solar radiation using the following angstrom type equation [24, 25, 26, 27].

$$\frac{H}{H_o} = a + b\frac{n}{N_s} \quad \text{.........2.14}$$

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

H0 = monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2)

Ns = the maximum possible daily hours of bright sunshine given by equation

n = monthly average daily number of hours of bright sunshine aandbare regression coefficients having average value of a =0.3and b=0.5 [21].

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

$$N_s = \frac{2}{15} * \omega_s \quad \text{.........2.15}$$

The following relation is used to get the value of Ho and H in kWh (to convert MJ to kWh).

1J = $2.777778*10^{-7}$kWh or 1MJ = 277.78Wh ……………………………...………….2.16

Table 1: Average day of month with declination angle

Month	n for i^{th} day of the month	For the average day of the month		
		date	n, day of the year	$\delta(^0)$
Jan	i	17	17	-20.9
Feb	31+i	16	47	-13.0
Mar	59+i	16	75	-2.4
Apr	90+i	15	105	9.4
May	120+i	15	135	18.8
Jun	151+i	11	162	23.1
Jul	181+i	17	198	21.2
Aug	212+i	16	228	13.15
Sep	243+i	15	258	2.2
Oct	273+i	15	288	-9.6
Nov	304+i	14	318	-18.9
Dec	334+i	10	344	-23.0

2.9 Solar Energy Resource in Ethiopia

Ethiopia receives 4.55 to 6.5 kWh/m^2/day annual average of solar isolation throughout the country [21, 28, 29, 30]. This varies significantly during the year, ranging from a minimum of 4.55 kWh/m^2 in July to a maximum of 6.55 kWh/m^2 in February and March. Other literatures describe the yearly average radiation to be in the range from 4.25 kWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to 6.25 kWh/m^2/d around Adigrat in the Tigray regional state (northern Ethiopia) [26, 29]. There are two basic windy areas in Ethiopia located alongside the main East African Rift Valley, the North Eastern highlands of the country near Tigray regional state, and the southern part of Ethiopia.

2.10 Solar Energy Assessment of Hadnet (the study area)

The assessment of the potential for solar radiation of the selected area is done by taking data from different sources. These are National Metrological Service Agency of Ethiopia (NMSA), and NASA. At the first approach, the data taken from the National Metrological Service Agency is analyzed using mathematical approach based on the sunshine duration collected on the past five consecutive years starting from 2007 to 2011. The sunshine duration data taken from the National Metrological Service Agency of Ethiopia is converted into solar radiation using Angstrom Radiation-Sunshine Relation [21]. Therefore, for calculating the radiation in kWh/m$^{\mathbf{2}}$/d from the sunshine duration, the values for the regression coefficients ɑ and b are taken to be 0.3 and 0.5 respectively [21]. Finally, this result is compared with the data taken from NASA, and it is found that the annual average solar radiation obtained from NMSA is 6.20 kWh/m^2/d and from NASA is 6.09kWh/m^2/d. The sunshine duration data taken from NMSA and sanalysis of the monthly average solar radiation in (kWh/ m^2/d) for year 2010is given in table2and table3respectively.For this study, the calculated monthly average daily radiation summarized in table4 is used for modeling the hybrid system. The monthly average solar radiation of Hadnet for the data taken from NMSA and NASA is shown on Table 4 and Table 5 respectively.

Table 2: Sunshine duration of the study area

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	9.6	9.2	9.5	8.3	8.5	6.4	4.5	4.9	7.0	9.4	9.6	9.8
2008	9.9	8.5	9.0	9.1	9.3	6.0	3.1	4.7	7.9	8.9	9.5	9.0
2009	9.4	8.7	8.3	7.3	7.2	5.5	4.1	3.4	5.8	9.3	9.4	8.3
2010	9.9	10.10	8.4	8.0	8.1	7.3	5.8	4.9	7.9	9.10	9.5	9.7
2011	9.8	9.9	8	8.4	8.8	7.4	5.0	4.2	6.6	8.6	9.6	8.7

Table 3: Analysis of the monthly average solar radiation in (kWh/ m^2/d) for year 2010

Month of year	i^{th} day of the month	n_d(day of year)	δ(^{0})	ω_s(^{0})	N (hours)	n	H_0 (kWh/ m^2/d)	n/N	H(kWh / m^2/d)
Jan	15	15	-21.3	86.01	11.47	9.90	8.82	0.86	5.87
Feb	14	45	-13.7	87.53	11.67	10.10	9.53	0.87	6.35
Mar	15	74	-2.89	89.52	11.94	8.40	10.22	0.70	6.57
Apr	15	105	9.34	91.75	12.23	8.00	10.54	0.65	6.63
May	15	135	18.74	93.56	12.47	8.10	10.45	0.65	6.56
Jun	15	166	23.30	94.51	12.60	7.30	10.29	0.58	6.18
Jul	15	196	21.56	94.14	12.55	5.80	10.32	0.46	5.59
Aug	15	227	13.87	92.60	12.35	4.90	10.44	0.40	5.22
Sep	15	258	2.33	90.47	12.06	7.90	10.30	0.65	6.48
Oct	15	288	-9.49	88.31	11.78	9.10	9.74	0.77	6.40
Nov	15	319	-19.1	86.46	11.53	9.50	8.99	0.82	5.96
Dec	15	349	-23.3	85.58	11.41	9.70	8.58	0.85	5.71

Table 4: Solar radiation of study area in kWh/m^2/day data from NMSA

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	6.11	6.39	6.85	6.95	7.02	6.91	5.56	6.28	6.39	6.1	5.71	5.94
2008	5.81	6.11	6.55	7.50	6.50	6.41	5.46	5.72	6.67	6.42	5.84	5.84
2009	5.63	6.39	6.67	6.67	6.67	5.94	5.62	5.28	5.84	6.23	6.01	5.84
2010	5.87	6.35	6.57	6.63	6.56	6.18	5.22	5.59	6.48	6.40	5.96	5.71
2011	5.43	6.17	6.73	6.99	7.70	7.05	5.68	5.25	6.33	6.04	6.33	4.94
Monthly average	5.77	6.28	6.67	6.95	6.89	6.50	5.51	5.62	6.34	6.24	5.97	5.65
Annual average in kWh/m^2/day												6.20

Table 5: Solar radiation of Hadnet in kWh/m^2/day data from NASA

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des	Annual average
22 year average	5.85	6.27	6.50	6.82	6.62	6.05	5.55	5.47	6.05	6.24	6.01	5.67	6.09

CHAPTER THREE

WIND ENERGY SYSTEMS AND WND ENERGY RESOURCES

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 [31].

3.2 Historical uses of wind

Wind energy is one of the oldest sources of energy used by humankind, comparable only to the use of animal force and biomass [32]. Some 5000 yrs. ago wind was used to sail ships in the Nile. Many civilizations used wind power for transportation and other purposes: The Europeans used it to accomplish some mechanical works such as grind grains and pump water in the 1700s and 1800s. The first wind turbine used to generate electricity was installed in U.S in 1890 [33]. However, for much of the twentieth century there was small interest in using wind energy other than for battery charging for distant dwellings. These low-power systems were quickly replaced once the electricity grid became available. The sudden increases in the price of oil in 1973 stimulated a number of research, development and demonstrations of wind turbines and other alternative energy technologies in different countries [34].

3.3 Distribution of wind speed

The distribution of wind is expressed by Weibull distribution over a certain period of time at a particular site. The Weibull probability density function (PDF) is given by equation 3.1 [35].

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} exp\left(-\frac{u^k}{c}\right) \quad \text{3.1}$$

Where, u = the wind speed,

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

c = a scale parameter in m/s; the larger the scale parameter, the more spread out the distribution. The area under the curve is always unity. The power density can in this case be expressed by equation 3.2.

$$\frac{p}{A} = \frac{1}{2}\sum_{j=1}^{n} \rho V_j^{\ 3} f_j \qquad 3.2$$

Where, V_j is the median velocity in class j and f_j is the frequency of occurrence in the same class. For k = 2 the Weibull PDF is commonly known as the Rayleigh density function in which case equation 3.1 may be rewritten as in equation 3.3.

$$f_u = \frac{2u}{c^2}\exp\left[-\left(\frac{u}{c}\right)^2\right] \qquad 3.3$$

3.4 Wind Turbines

A wind turbine is a machine that converts the kinetic energy from the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator [31]. 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 [36].

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.

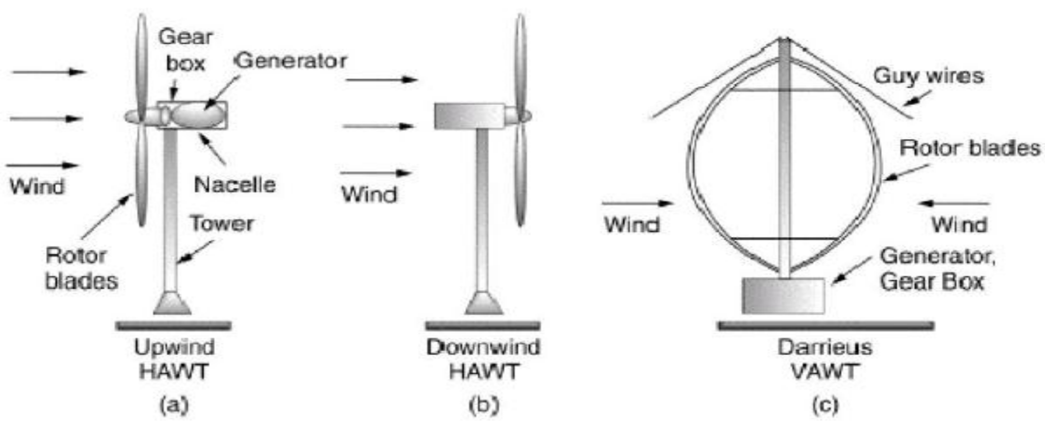

Figure 11: Horizontal axis wind turbines (HAWT) are either upwind machine or down wind machines

(a) Upwind machine (b) down wind machines (c). Vertical axis wind turbines (VAWT) accept wind from any direction [37].

3.5 Wind Turbine Components

The most common turbine type is the horizontal axis wind turbine. A cut-view (Figure 12) helps the reader to get familiar with the components of a wind turbine.

Anemometer:

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

Hub:

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

Gear box:

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

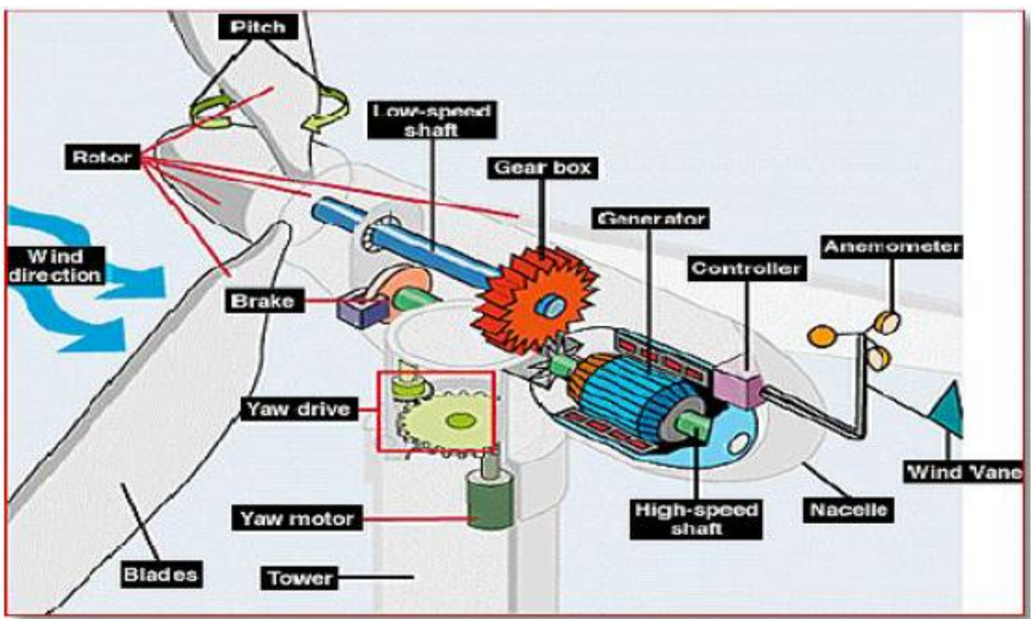

Figure 12: Cut-View Wind Turbine [16]

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 at top of 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.

3.6 Working Principles of Wind Turbines

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

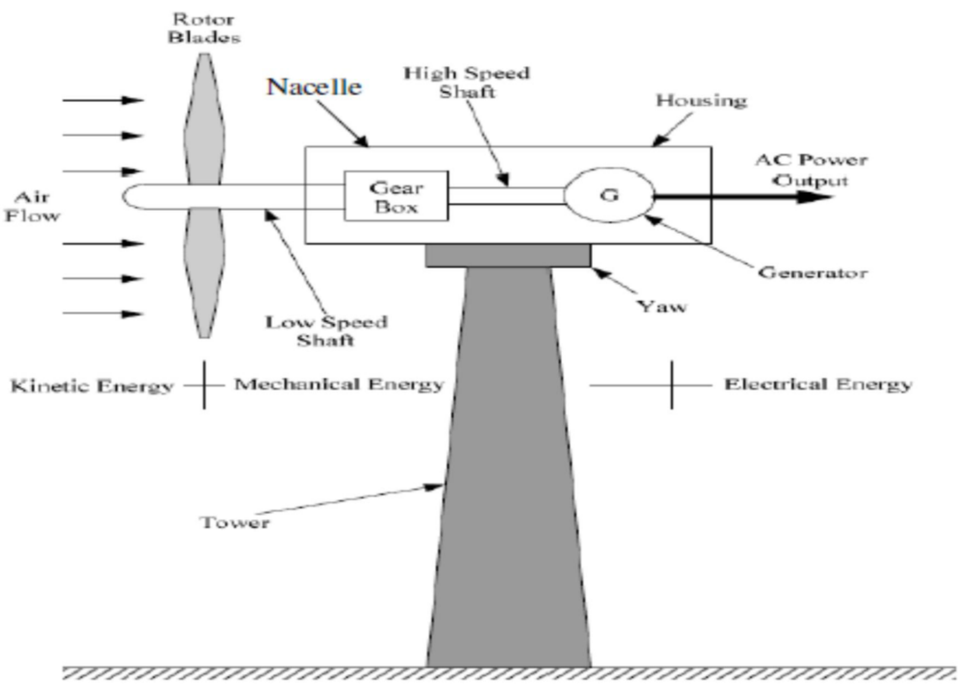

Figure 13: Block diagram of wind energy conversion system [26].

3.7 Wind Energy Extraction by HAWT

The energy of wind is extracted by using an appropriate wind turbine. The wind energy is tapped by the wind turbine which converts the kinetic energy of the wind into mechanical shaft energy. The rotational energy is converted into electrical energy through the transmission system. The transmission system consists of the rotor shaft with bearings, brake(s), an optional gearbox, as well as a generator and optional clutches. The energy available in the wind can be expressed using equation 3.4.

$p_w = \frac{1}{2}\rho A v^3$ ……………………………………………………………………………3.4

Where, ρ =Density of air (kg/m^3)

A = the swept area (m^2)

Pw = power in the wind (W)

v =instantaneous wind velocity (m/s)

Energy conversion from free-flowing fluid streams is limited because full energy extraction implies a decrease of fluid velocity (decrease of kinetic energy of the stream), down to zero which is impossible. Some fluid may not pass through the turbine and may simply flow around it (bypass it). This limitation is expressed in terms of Betz limit defined by the power coefficient Cp as given by equation 3.5.

$c_p = \frac{rotor\ power}{power\ in\ the\ wind}$ ……………………………………………………………………….3.5

The power coefficient, C_P, is a function of the axial induction factor. The optimum of this function (which is a maximum value for C_P) is 0.5926 (=16/27) [20, 26, 38]. Thus the electrical power output from the wind turbine can be expressed by equation 3.6.

$p_w\ out = \eta_t c_p \frac{1}{2}\rho A v^3$ ……………………………………………………………….3.6

Where, Pw out = output power of wind turbine

η_t= Overall efficiency of the transmission system/power train

C_p = the power coefficient

The power coefficient and efficiency of wind turbines vary greatly from the manufactures to the manufacturers. As a result, the power output of wind turbines varies from turbine to turbine and is given by power curve, which plots the output power of a turbine against wind speed (see Figure 14).

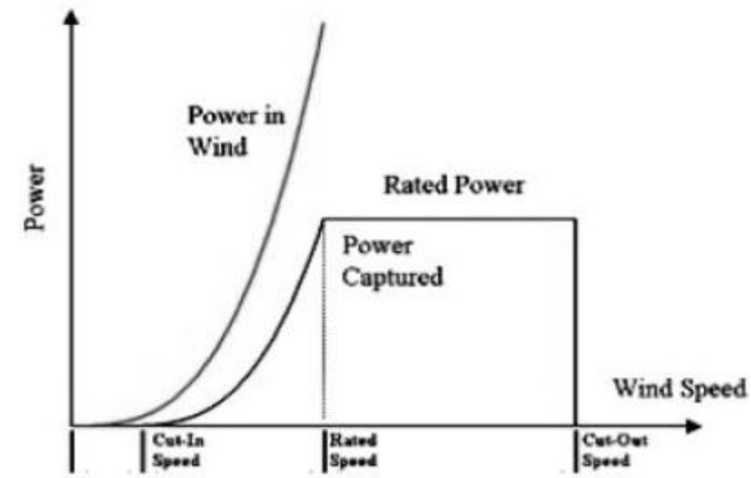

Figure 14: General power curve of wind turbine [26]

The wind speed at which a wind turbine starts generating electrical power is called the cut- in speed. The rated wind speed is the wind speed at which the turbine operates at its maximum efficiency of energy conversion. Rated power is the power output of the wind speed which is equal to, or above, the rated speed. The cut-out speed is the wind speed at which the turbine may shut down to protect the rotor and drive train machinery from damage, or high wind stalling characteristics.

3.8 Wind Turbines Power Control Mechanism

All wind turbines are designed with some sort of power control. There are different ways to control, aerodynamic forces on the turbine rotor and thus to limit the power in very high wind speeds in order to avoid damage to the turbine. There are three commonly used types of power control in the industry [39].

- Stall Control
- Pitch Control
- Active stall regulation

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

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

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

3.9 Wind Energy Resources

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

3.9.1 Wind Speed Measurement

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

Normally, the anemometer is fitted with a wind vane to detect the wind direction. A data logger collects wind speed and wind direction data from the anemometer and wind vane respectively. It is very important that the measuring equipment is set high enough to avoid turbulence created by trees, buildings or other obstructions. The readings would be most useful if they have been taken at hub height where the wind turbine is going to be installed [31].

If the measurement of wind speed was not made at the wind turbine hub height (in this case it is 10 m) it is important to adjust the measured wind speed to the hub height. This can be done using either the logarithmic law, which assumes that the wind speed is proportional to the logarithm of the height above ground, or the power law, which assumes that the wind speed varies exponentially with height. Using the logarithmic law, the wind speed at a certain height above ground level can be given as follows [14]:

$$v(z) * ln\left(\frac{z_r}{z_o}\right) = v(z_r) * ln\left(\frac{z}{z_o}\right) \quad \text{...3.7}$$

Where, Zr = Reference height (m)

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

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

V (z) = Wind speed at the height of Z m (m/s)

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

Using power law, the wind speed at a certain height above ground level can be given as follows [35]:

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^a \quad \text{...3.8}$$

Where: v_1 is wind speed measured at the reference height h_1 (m/s), v_2 is wind speed estimated at height h_2 (m/s), and a is the ground surface friction coefficient.

Table 6: Friction coefficient a of various terrains [17]

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

3.10 Factor affecting wind electricity production

The wind turbine electricity production can be depending on the following factors, namely wind speed, air density and area swept by the rotor blades. From the figure 15clearly understand, that the above mention factor influencing the electricity production of the wind turbine [41].

3.10.1 Wind speed

The wind speed is divided into four category based on the operation of wind turbine.

• **Start-up Speed:** - This is the speed at which the rotor and blade assembly begins to rotate.

• **Cut-in Speed:** - Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7mph and 10mphfor most turbines.

• **Rated Speed:** - The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with the wind speed.

• **Cut-out Speed:** -At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shuts down occurs is called the cut-out speed, or sometimes the furling speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage.

3.10.2 Air density

The denser the air, the more energy received by the turbine. Air density varies with elevation and temperature. Air is less dense at higher elevations than at sea level, and warm air is less dense than cold air. All else being equal, turbines will produce more power at lower elevations and in locations with cooler average temperatures. Air density has a significant effect on wind turbine performance. The power available in the wind is directly proportional to air density. As air density increases the available power also increases. Air density is a function of air pressure and temperature. It increases when air pressure increases or the temperature decreases. Both temperature and pressure decrease with increasing elevation. Consequently, changes in elevation produce a profound effect on the generated power as a result changing in the air density.

3.10.2.1 The Perfect Gas Law

The air density may be estimated from the perfect gas law.

$p * V = n * R_{air} * T$ ……………………………………………………………………...3.9

Where

P is the pressure [Pa]

V is the volume considered [m^3]

n is the number of moles

R_{air} is the specific gas constant for dry air (287.05 J/ (kg*K))

T is the temperature [K]

If the density, ρ_{air}, is defined from the number of molecules in a certain volume, n/V=ρ, then the density may now be expressed from the perfect gas law as:

Air density (ρ) = $\frac{\rho}{R_{air}\, T}$ ………………………………………………………………….3.10

Where

R_{air} = molecular weight of air (J/kg*K) and is given by: $R_{air} = R/M_{air}$= 287.05J/kg*K

R= universal gas constant (J/kg*K) = 8.31432 J/kg*K

M_{air} = molar mass of air (kg/mol) = 28.9644*10^{-3}kg/mol (assumed constant up to approximately 86km altitude)

P = atmospheric pressure (Pa)

T = temperature (K)

3.10.2.2 Swept area of the turbine

The larger the swept area (the size of the area through which the rotor spins), the more power the turbine can capture from the wind. Since swept area is $\pi D^2/4$, where D = diameter of the rotor, a small increase in blade length results in a larger increase in the power available to the turbine.

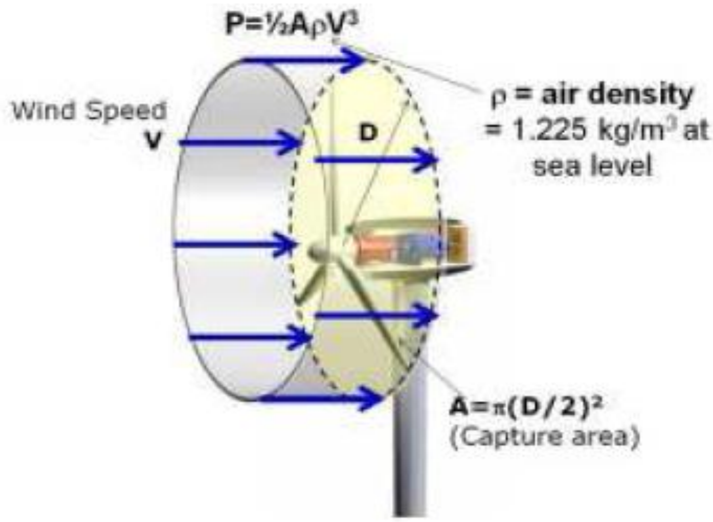

Figure 15: Wind turbine model [41]

The below equation is used to calculate the power production from the wind turbine.

Power (watts) = $\frac{\boldsymbol{\rho A v^3}}{\mathbf{2}}$……………………………………………………………………..3.11

Where

ρ=air density (kg/m$^{\mathbf{3}}$)

A=swept area of the wind turbine rotor (m$^{\mathbf{2}}$)

V=wind speed (m/s)

We can also calculate power from the wind turbines using:

$P_T = C_p * \frac{\rho A v^3}{2}$…………………………………………………………….3.12

Where: $P_{\mathbf{T}}$=Power extracted by wind turbine (watts)

$C_{\mathbf{P}}$= Coefficient of performance

ρ =Air density (kg/m$^{\mathbf{3}}$), 1.225 kg/m^3 at sea level, less in higher altitudes

A=swept area of the wind turbine rotor (m$^{\mathbf{2}}$)

Table 7: International standard atmosphere, mean sea level conditions [41]

Pressure	p_o=101325N/m^2=1013.25hPa
Density	ρ_o = 1.225kg/m3
Temperature	T_o = 288.15
Speed of sound	$\propto_o$ = 340.294 m/sec
Acceleration of gravity	g_o = 9.80665 m/sec^2

3.11 Temprature modelling

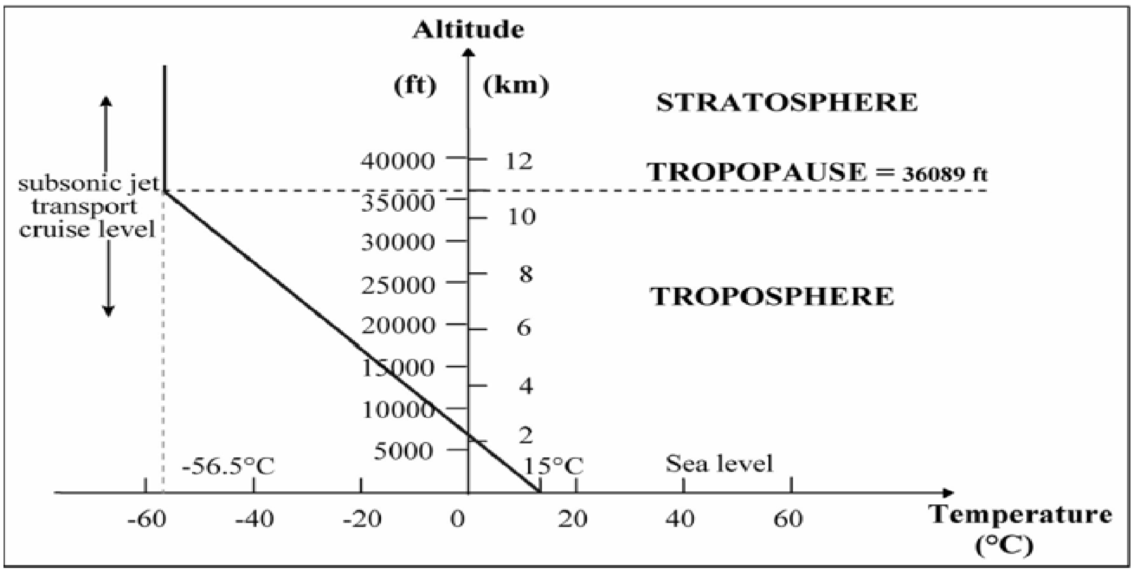

Figure 16: International standard atmosphere temperature variation [41]

Temperature decreases with altitude at a constant rate of -6.5^{o}C/1000m (-1.98^{o}C/1000ft) up to the tropopause. The standard tropopause altitude is 11000m (36089ft). Therefore, the air which is considered as a perfect gas in the ISA model presents the following Characteristics within the troposphere.

$$T = T_o - 6.5\,\frac{h(m)}{1000} \quad \text{……………………………}3.13$$

$$T = T_o - 1.98\,\frac{h(ft)}{1000} \quad \text{……………………………}3.14$$

3.12 Pressure modelling

To calculate the standared pressure p at a given altitude, the temprature is assumed standared, and the air is assumed as a perfect gas.The relationship between the pressure at a troposphere altitude and sea level pressure can be obtaned by:

$$P = P_o \left(1 - 0.0065\frac{h}{T_o}\right)^{5.256} \quad \ldots\ldots 3.15$$

where T^o is temprature in Kelvn, and h is height in meters.

Or

$$P = P_o \left(1 - 2.25577 \times 10^{-5} * h\right)^{5.256} \quad \ldots\ldots 3.16$$

3.13 Wind Resource in Ethiopia

Ethiopia has exploitable reserve of 10 GW wind energy with an average speed of 3.5 – 5.5 m/s, flowing for 6 hours/day [29, 30]. 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 speeds, 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, the average wind velocity reaches maximum values between May and August [18, 24, 27, 31, 32]. Currently, three projects are constructed, one Ashegoda wind park (near Mekelle) with installed capacity of 120MW and the other Adama I Wind Park of nearly 51MW and Adama II wind park of nearly 153MW.

3.14 Wind Potential Assessment in the Study Area

The resource assessment for the wind potential is done by taking the data's only from NASA. This is because of the absence of full data regarding wind speed in the National Meteorological Service Agency of Ethiopia. Therefore, the annual average wind speed for Hadnet which is located at latitude of 13^o39'53''and longitude of 39^o40'00''is found to be 4.3 m/s at a height of 10m. This value is used as an input to the wind resource in modeling the hybrid system. This data can be extrapolated to the selected wind turbine height using equation 3.8 [24, 25]. The value of Z_0 is taken as 0.1 [14]. Table 9 summarizes the wind speed at different heights.

Table 8: Monthly average wind speed (m/s) at the site from NASA

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
At 10m height	4.5	4.6	4.6	4.2	3.7	5.0	5.2	4.8	4.1	3.1	3.6	4.0	4.3

Using the logarithmic law, the wind speed at a certain height above ground level can be given as follows [18]:

$$v(z) * ln\frac{z_r}{z_0} = v(z_r) * in\left(\frac{z}{z_0}\right) \quad \text{.......}3.17$$

Table 9: Monthly average wind speed (m/s) at different height

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
At 20m height	5.18	5.29	5.29	4.83	4.26	5.75	5.98	5.52	4.72	3.57	4.14	4.6	4.93
At 25m height	5.40	5.52	5.52	5.04	4.44	5.99	6.23	5.76	4.92	3.72	4.32	4.80	5.14
At 30m height	5.57	5.70	5.70	5.20	4.58	6.19	6.44	5.95	5.08	3.84	4.46	4.95	5.31

CHAPTER FOUR

HYBRID SYSTEM SIMULATION AND OPTIMIZATION USING HOMER

4.1 Introduction

A hybrid power system is one in which the electrical load is served by two or more power sources. Because renewable energy sources, such as Solar and Wind, are inherently intermittent, frequently they are combined with dispatchable power sources such as utility grid and diesel generators, to ensure the continuous supply of power.Energy storage is often included in hybrid systems that can deliver a certain amount of energy on power demand until its stored energy is exhausted (i.e. Provide a constant flow of uninterrupted power), but it must be recharged at that point. Other advantages of the hybrid system are the stability and immobility of the system and a lower maintenance requirement, thus reducing downtime during repairs or everyday maintenance. In addition to this, as well as being indigenous and free, renewable energy resources also contribute to the reduction of emissions and pollution [39].

4.2 Overview of HOMER software

HOMER has three main windows which are used to enter the necessary data to the software. The first is Add/Remove window where technologies to be considered are selected. The second window is the Resource window which shows the type of energy source that are to be used corresponding to the equipment’s selected in the Add/Remove window. The third one is the other window where economics, emission, constraints and system controls are defined. Details of each element in these windows should be defined. In this study, wind turbine (Type, cost, hub height, life time and number), PV (size, cost, slope, ground reflectance, derating factor, Life time), converter (cost, efficiency, size and lifetime), diesel generator (cost, size, minimum load ratio, fuel curve, Type of fuel and life time), battery (type, cost and number of strings, life time), primary load (hourly data for the year, daily and hourly noise) are added to the system. Details of solar, wind, hydro and diesel resources are defined.

In the solar resource window, monthly averaged daily solar radiation data, location and time zones are defined which are used by the software to calculate the hourly incident solar radiation on the PV panel. In the wind resource window, monthly averaged wind speed data, altitude, anemometer height, variation with height, Weibull k, autocorrelation factors, diurnal pattern

Strength, hour of peak wind speed are defined which are used by HOMER to estimate the wind Distribution and output power. The diesel cost is defined in the diesel resource window. A dispatch strategy is a set of rules that govern the operation of the generator(s) and the battery bank. HOMER can model two dispatch strategies, cycle charging and load following. Which is optimal depends on many factors, including the sizes of the generators and battery bank, the price of fuel, the O&M cost of the generators, the amount of renewable power in the system, and the character of the renewable resources. If we choose to model both, HOMER will simulate each system using both dispatch strategies and you will be able to see which is optimal.

Under the load following strategy, whenever a generator is needed, it produces only enough power to meet the demand. Load following tends to be optimal in systems with a lot of renewable power, when the renewable power output sometimes exceeds the load. Under the cycle charging strategy, whenever a generator has to operate, it operates at full capacity with surplus power going to charge the battery bank. Cycle charging tends to be optimal in systems with little or no renewable power. If you can apply a set point state of charge to the cycle charging strategy, the generator(s) will not stop charging the battery bank until it reaches the specified state of charge. The sensitivity button to the right allows us to do a sensitivity analysis on this set point. Interest rate and project lifetime are defined in the economics window. The greenhouse gas emission penalty is defined in the emission window. Maximum annual capacity shortage, minimum renewable fraction and operating reserves are defined in the constraint window.

4.3 Basic Components of the Hybrid System

The basic components of the hybrid system are the wind plant and the PV system. Others are additional/auxiliary components which help in the full time functioning of the hybrid system. The principle of operation of the basic components has been covered before. The power conditioners are set of power electronics converters which enable to handle the variability of wind and solar resources. They are composed of DC/DC, AC/DC, DC/AC converters. When there is an excess of energy (from the wind and PV), it is directed to the battery through the converter and DC center. In addition, frequency and voltage regulation, control circuitry are to be included in the operation and control center. Similarly, the DC output of the PV panel is connected to the system via the DC center. The DC center is integrated with the system through

DC/AC and AC/DC converters. As well as, it is connected to PV and battery components. Since the scope of this study is limited to the feasibility assessment of wind and solar energy resources, detailed analysis of each component of the hybrid system are not covered.

a) Converter

Converters are generally four types: DC/DC, DC/AC, AC/DC and AC/AC. Power electronics devices (such as IGBT, power MOSFET, power Transistor, Thyristors, etc.) are used as a switching gate in a different pattern of arrangement to achieve the required conversion output. DC/DC converters are classified as boost, buck and buck-boost converters based on their output voltage relative to their input (possibility of "step-up", "step-down" or both respectively). They convert a given DC voltage level to the required voltage level. DC/AC converters (also called, inverters) can be classified based on the triggering signal as square wave, sine wave or modified sine wave. These devices use a given DC voltage as input and output the required voltage of a given amplitude and frequency. AC/DC converters (also called rectifiers) operate in the reverse principle of inverters. The AC voltage source is used as input, which passes through half or full bridge circuit (with a firing angle control) to result a rectified DC voltage output. AC/AC converters are used for conversion of AC voltage of a given frequency and amplitude to another AC voltage of the required amplitude and frequency.

b) Battery

The one important reason of a hybrid system is to reduce component over-sizing by storing the excess energy available at one time for usage during the shortage time. There are different types of storage mechanism such as batteries, pumped storage, hydrogen, flywheels, etc. Rechargeable batteries are widely used for the implementation of hybrid energy systems because of their cheapness and easy operation. A battery is a device in which the chemical energy of an electrolyte is converted into electrical energy through electrodes by the process of electrolysis. They are referred to as secondary cells (which can be recharged). The main parameters of selecting batteries are maximum throughput and minimum state of charge. Maximum throughput is measured by the output of the battery (in ampere-hour) that can be delivered throughout its lifetime.

Minimum state of charge is the measure of how low the battery can be discharged as a percentage of its full capacity without losing its performance. There are very deep cycle batteries which can be discharged up to 40% such as Block type lead acid battery [23]. The two battery types that have been used for PV systems are lead–acid and nickel–cadmium. Due to higher cost, lower cell Voltage (12V), lower energy efficiency and limited upper operating temperature (40^{o}C). The lead– acid battery will remain the most important storage device in the near future, especially in PV systems of medium and large size [29].

The depth of discharge (DOD) is the obverse of state-of-charge. Cell voltage decreases almost linearly with depth of discharge to a point called cut-off-voltage is reached. Battery cells should not be operated beyond the cut off voltage, because further discharge will result in increasing the internal resistance of the battery and can result in permanent damage. On the other hand, overcharging the batteries until gassing leads also to cell damage [30]. Therefore, batteries have to be connected to the output of the PV generators and the load via a charge regulator. This regulator protects the battery against deep discharge and excessive overcharge. Lead–acid battery cells are available with either pure lead or lead–calcium grids to minimize the self-discharge rate. All lead–acid cells have some loss in capacity on standing due to internal chemical reactions. Self-discharge rate, increases with increasing cell temperature and remain relatively low for cell with lead calcium grids [29].

4.4 Load Estimation

The term load refers to a demand for electric or thermal energy, if any. Three types of loads can be modeled using HOMER: primary load which is electric demand that must be served according to a particular schedule, deferrable load which is electric demand that can be served at certain period of time, the exact timing is not important and thermal load which is a demand for heat.

4.5 Load profile of the base station

The facilities at the BTS site are radio equipment, power conversion equipment, antenna equipment, transmission equipment, and auxiliary equipment. These facilities are all ON for 24hrs (12:00am – 11:00pm) per day except the auxiliary equipment (aviation light) that comes ON only for 13hrs (06:00pm – 7:00am) per day. The power consumptions are assumed to be identical for every day of the year. The daily energy consumption is 100kWh/day. The daily average load variation for the base station equipment is shown in table 10.

Table 10: Load Inputs for the Base Station

Hour	Base Station Baseline Data Load (kW)
00:00 – 1:00	4.5
1:00 – 2:00	4.5
2:00 – 3:00	4.5
3:00 – 4:00	4.5
4:00 – 5:00	4.5
5:00 – 6:00	4.5
6:00 - 7:00	4.5
7:00 – 8:00	3.75
8:00 – 9:00	3.75
9:00 – 10:00	3.75
10:00 – 11:00	3.75
11:00 – 12:00	3.75
12:00 – 13:00	3.75
13:00 – 14:00	3.75
14:00 – 15:00	3.75
15:00 – 16:00	3.75
16:00 – 17:00	3.75
17:00 – 18:00	3.75
18:00 – 19:00	4.5
19:00 – 20:00	4.5
20:00 – 21:00	4.5
21:00 – 22:00	4.5
22:00 – 23:00	4.5
23:00 – 00:00	4.5
Total	100kWh/day

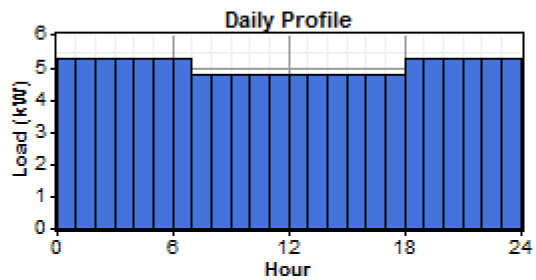

Figure 17: Daily load profile of the site

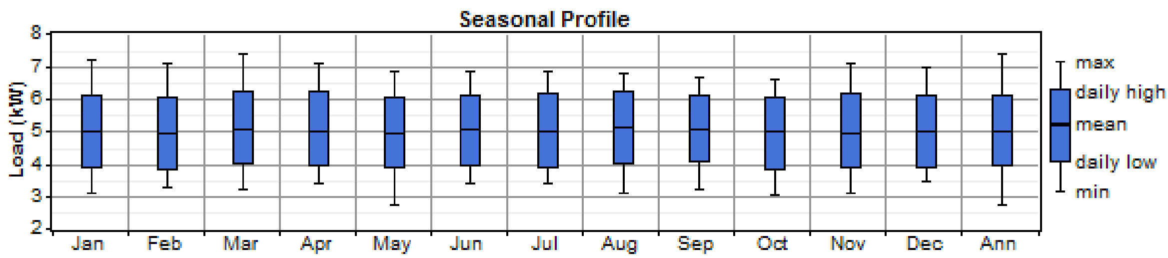

Figure 18: Diurnal variation of load during different months of the year

4.6 Renewable Energy Resources Assessment

The term resource applies to anything coming from outside the system that is used by the system to generate electric power. That includes the four renewable resources (solar, wind, hydro, and biogas) as well as any fuel used by the components of the system. Renewable resources depend extremely on location. The solar resource depends strongly on latitude and climate, the wind resource for large-scale atmospheric circulation patterns and geographic influences, the hydro resource for local rainfall patterns and topography, and the biomass resource on local biological productivity. Moreover, at any one location a renewable resource may exhibit strong seasonal and hour-to-hour variability. 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. In this section how to model the renewable resources used in this thesis is described.

A. Solar energy 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 the Earth's surface in a typical year. The data can be in one of three forms: hourly average global solar radiation on the horizontal surface (kWh/m^2), monthly average global solar radiation on the horizontal surface ($kWh/m^2/day$), or monthly average clearness index. The clearness index is the ratio of the solar radiation striking earth's surface to the solar radiation striking the top of the atmosphere. A number between zero and one, the clearness index is a measure of the clearness of the atmosphere.

The average solar irradiation is 6.09 $kWh/m^2/day$ from NASA and 6.20$kWh/m^2/day$ from NMSA. Clearness index and the average daily radiation for a year are shown in table 11 while figure 19 shows the solar radiation in a year produced by HOMER.

Table 11: Clearness Index and average daily radiation for a year from NMSA

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des
Monthly average	5.77	6.28	6.67	6.95	6.89	6.50	5.51	5.62	6.34	6.24	5.97	5.65
Clearness Index	0.573	0.605	0.635	0.681	0.714	0.699	0.584	0.567	0.614	0.602	0.592	0.570

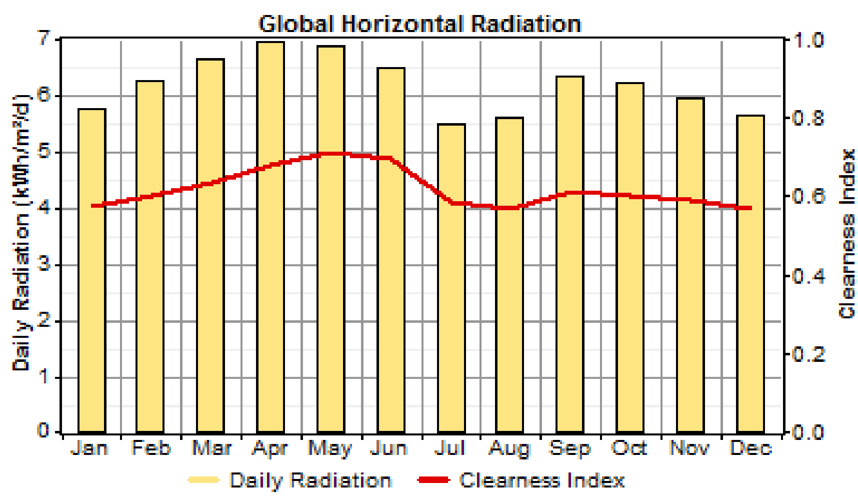

Figure 19: Monthly solar radiation

B. 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 user can provide measured hourly wind speed data if available. Otherwise, HOMER can generate synthetic hourly data from 12 monthly average wind speeds and four additional statistical Parameters: The Weibull shape factor, the autocorrelation factor, the diurnal pattern strength, and the hour of peak wind speed. 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 [33]. 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 [33]. An average value of 0.85 is used here because the selected area is 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 [33].

Typical values for diurnal pattern strength range from 0 to 0.4. A value of 0.25 has been selected for calculations. The hour of peak wind speed is the hour of the day that tends, on average, to be the windiest throughout the year. The typical range for the time of peak wind speed is 14:00-16:00[33]. This has also been observed in the available raw data for some of the months. In addition to this, the software has been run to different times between 14:00 and 18:00, and the time of 15:00 has been chosen for the calculations. The anemometer height, which is the height above ground at which the wind speed data were measured, has been defined. The elevation of the site above sea level, which is used to calculate the air density according to equations 3.7-3.8, is also defined. The monthly average wind speed of the site, together with other related data, such as values of Weibull parameter k, diurnal pattern, autocorrelation, etc., was fed into HOMER. Figure 20 shows the wind speed resource data measured at 10 m height.

Table 12: Monthly average wind speed (m/s) for the site at 10m

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
At 10m height	4.5	4.6	4.6	4.2	3.7	5.0	5.2	4.8	4.1	3.1	3.6	4.0	4.3

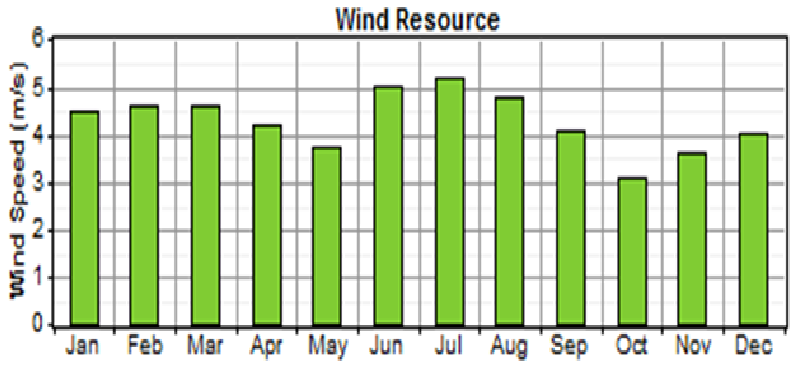

Figure 20: One year wind resource data

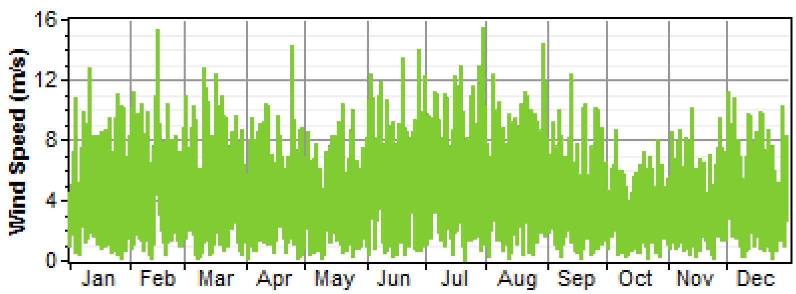

Figure 21: Average Hourly wind speed for 1 year

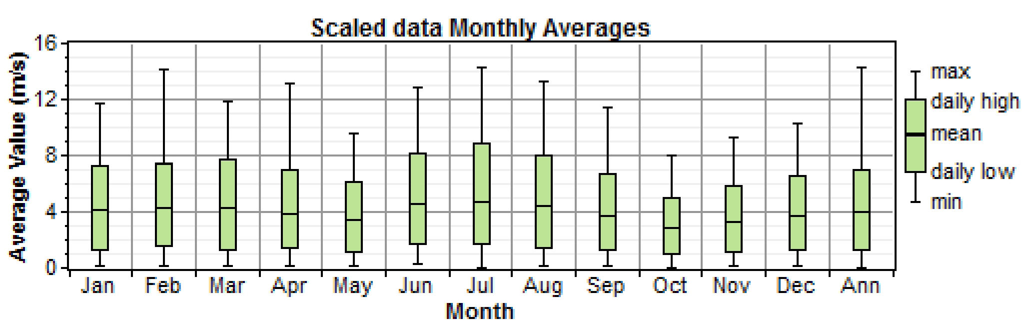

Figure 22: Average monthly wind speed for 1 year

4.7 Cost Data and Size Specifications of Each Component

The HOMER software is used to determine the best optimal sizing and feasibility study of the system. The initial choice of the components size is based on the site load profile. 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. The main purpose of the work is searching the optimum power system configuration that would meet the load demand with minimum NPC and COE.

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 schema components considered in this study have 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 worn out components at the end of its life cycle. This cost is different from the initial cost of the component, due to the following reasons. At the end of its lifecycle not all of the spheres of the component need to replace, Costs from donors may eliminate or can reduce initial costs, however replacement cost may not account travel costs but initial costs do.

4.7.1 Solar PV Size and Cost

The solar panel considered to be a 1kW, which is with 4 numbers of solar modules having 250 W capacities from Trina-solar Company. The selected panel was poly-crystalline silicon made which is known as TSM 250-PA05 model with an efficiency of 14 to 15 %, and a price of $0.7/watt [44]. The initial installation costs of the SPV, the replacement costs, and the annual O&M costs per 1 kW are $700, 700, and $7, respectively. The lifetime of an SPV array is 25 years; a derating factor of 0.9, a reflectance of 20%, and no tracking system for the SPV array are used in this paper. The sizes of the simulation values of the applied SPV panels are4, 8, 12, 16,20,24,28 kW.

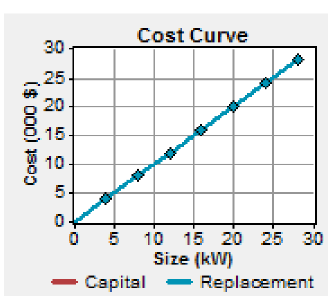

Figure 23: cost of PV panels

Table 13: PV module specification

Description	Specification
PV module material	Poly / Multi - Crystalline silicon
Peak power	250Wp + 3%
Voltage at peak power (V_m)	29.95 V
Current at peak power (I_m)	8.35 A
Open circuit voltage (V_{oc})	37.25 V
short circuit current (I_{sc})	8.70 A
Efficiency	14.29%
Estimated lifetime	25 years

4.7.2 Wind Turbine Size and Cost

Depending on the wind speed sources the turbine has to generate large amounts of energy to contribute significant renewable fraction and this can be performed using single large wind turbine or a number of smaller turbines. Quantities of turbines, service time, hub height, cost of the component, type of electricity generated, cut-in wind speed is the restrictive values to select wind turbine. A 3kW horizontal-axis, Whisper 500 wind turbine type is chosen for this system. Availability of energy from the wind turbine depends greatly on wind variations. Thus, the wind turbine rating is generally much higher compared to the average electrical load. In this analysis, 3kW Whisper 500 wind generator model is considered. It has a rated capacity of 3kW and provides 48V DC as output. The cost of one unit is considered to be $7,857, replacement and maintenance costs are taken as $5,500 and $50/year respectively. The lifetime of a turbine is taken to be 20 years and hub height is 25m. The O&M cost of the wind turbine was proposed about 2% of its initial capital cost as given in [45]. The replacement cost of the wind turbine considered in this case is about 70% of the capital cost after 20-year service life. For optimum solution, the use of 2, 4, 6, 8units of wind turbine were considered.

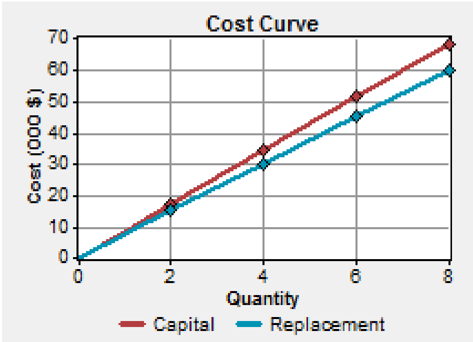

Figure 24: cost of wind turbines

Table 14: 3 kW wind turbine specification

Description	Specification
Rotor diameter	4.5 m
Rated power	3 kW
Cut-in wind speed	3.4 m/s
Equivalent rated wind speed	10.5 m/s
Blade material	Carbon reinforced fiber glass
Generator type	Permanent magnet 3 phase alternator
Estimated lifetime	20 years

4.7.3 Battery Size and Cost

Like the other components of the power system, input parameters inserting into the software are cost and number of batteries. Note the following definitions; the battery rated/nominal capacity is the quantity of energy discharged from the battery. Minimum state of charge of the batteries is the state of charge below which the battery is never discharged to prevent from damage. From 30-50 percent is the recommended minimum state of charge. Round-trip battery efficiency is the energy flow into the battery that can be extracted for later use. Lifetime throughput is the energy quantity that circulated in the battery through its lifelong. The storage battery chosen is Surrette 6CS25P from the manufacturer Rolls/Surrette, which is given in the HOMER tool library. The replacement cost of the battery is assumed about 70% of its capital cost. The cost of one unit is considered to be $1200/battery; replacement cost is taken as $1000/battery and the O&M cost is taken as $12/year. In this study 8, 16,24,32,40,48,56,64 units of the battery were also considered for the simulation.

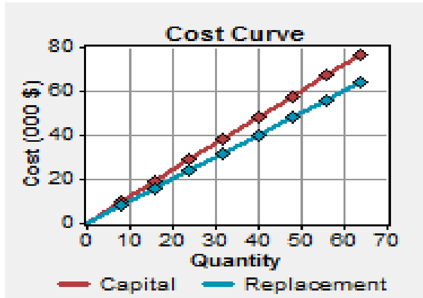

Figure 25: cost of battery

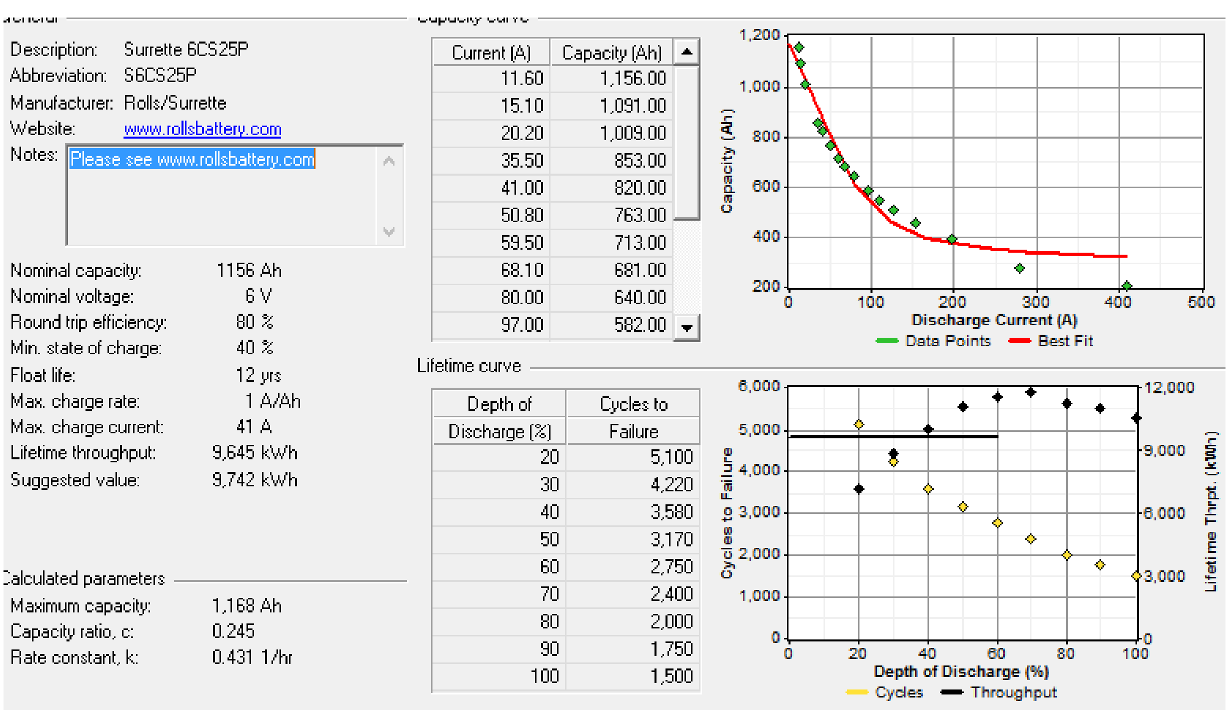

Figure 26: Battery specification

4.7.4 Diesel Generator Size and Cost

The cost of diesel generators available in the market varies, but the DG used in the particular Ethio-telecom BTS site is Deutz air cooled DG with rated output power of 8 kW and 10 kVA with the initial cost of $5700 and the fuel consumption at full load is less than 3 litters. The initial capital cost of the DG is assumed $570/kW. Replacement and operational costs were assumed $570/kW and $0.35/h, respectively. The operating lifetime was also considered 15,000

h. currently, per liter price of diesel in Ethiopia is around $0.8. In this study 2,4,6,8 and 10 kW sizes of DGs were also considered for the simulation. The minimum load ratio was set at 10%.

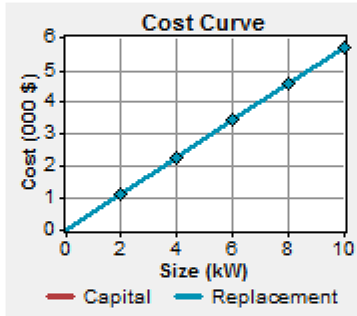

Figure 27: Cost of generator

4.7.5 Power Converter Size and Cost

A converter needs to maintain the flow of energy between AC and DC power system components. The rated power of the inverter should be equal to or larger than the peak load. The initial installation cost, the replacement cost, and the annual O&M cost per 1 kW are considered $400, $400, and $10, respectively. The lifetime of the inverter and the efficiency are set at 15 years and 95% respectively. The sizes of the simulation-values of the applied inverter are 0, 2, 4, 6, 8 and 10 kW.

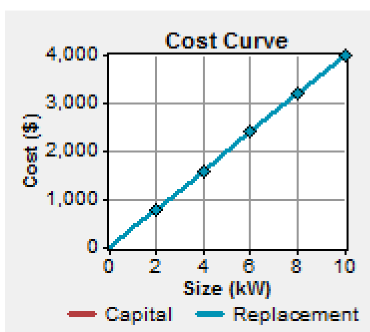

Figure 28: Cost of convertor

4.8 Other Inputs that Affect Power System Optimization

4.8.1 Economic Inputs:

HOMER is provided also with economic input 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 ranking system. In this paper; fixed capital cost, fixed O&M cost and capacity shortage penalty was taken as zero. Real interest rate is the difference between inflation rate and nominal interest rate. HOMER discounted the capital cost of each component of the power system into an annual cost of 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 20 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 hybrid system [46].

4.8.2 Constraint Inputs

A 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 a certain time period. The needed operating capacity includes the surplus demand and operating reserve loads. The operating reserve is the 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 of this when the battery bank is fully charged so unable to store the produced energy.For this study the following constraint inputs are considered and no thermal load is accounted for this site of interest since it is outdoors type site. Maximum annual capacity shortage of 0%, minimum renewable fraction, 0%, 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 by 50%.

4.8.3 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 an industrialized continent emission penalty is not adopted yet. In this paper no emission penalty is considered at all for the system. The power flow control mechanism is an important input parameter of 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 a 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 a 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 get 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.

4.9 System Architecture and Sizing

This system is sized for a 6.2kW GSM/UMTS type telecommunications base station in Hadnet which is an isolated area of wukro town, Tigray, Ethiopia. The system architecture adopted is DC coupled. As shown in the figure 29 below, in the hybrid energy system, the primary renewable sources are placed in parallel with a standby secondary non-renewable resource (in this case the diesel generator). The HOMER software is used for this optimization study. As shown in the system architecture, the renewable sources (wind and PV systems) feed into the DC side of the network; the converter converts the DC output of the renewable sources to AC and back, for battery storage, as the case may be. The load is connected to the AC bus side of the network. The diesel generator shown feeds directly into the AC bus of the network.

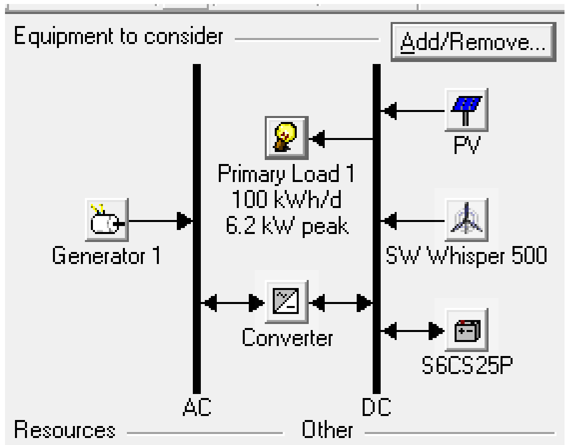

Figure 29: System architecture implemented in HOMER

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Optimization and Simulation Results

After introducing all of the input variables, the HOMER software is run repeatedly to get the feasible system configuration; component sizes that meet the load requirement and the input constraints at the lowest NPC and then presents the results of the simulation in terms of optimal systems and sensitivity analysis. The Optimization result displays ten different configurations according to the lowest NPC for further analysis and to increase the chance of finding most optimized system. A hybrid system with less NPC, less COE, higher renewable fraction, less capacity shortage, and minimum fuel consumption would be suggested as optimum system. HOMER simulates every system in all set of component combination (search space) and ranks all the feasible systems according to increasing net present cost. In the case of this study, it has 81 sensitivity performing 31,680 simulations.

PV (kW)	W500	Label (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
28	4	6	32	8	$ 107,220	3,952	$ 157,737	0.282	0.98	650	461
28	4		56	8	$ 132,600	3,762	$ 180,691	0.323	1.00		
28		6	56	8	$ 101,820	6,917	$ 190,242	0.340	0.91	1,796	1,056
	8	6	32	8	$ 113,420	11,925	$ 265,867	0.475	0.79	4,257	2,398
28	2	8		8	$ 52,860	24,898	$ 371,134	0.663	0.75	8,865	5,639
28		8		8	$ 35,760	26,402	$ 373,269	0.667	0.66	10,278	5,856
		6	8	6	$ 15,420	30,735	$ 408,322	0.729	0.00	15,330	7,745
	8	8		8	$ 76,160	32,005	$ 485,295	0.867	0.69	10,036	7,332
		8			$ 4,560	40,299	$ 519,712	0.928	0.00	16,556	8,760

Figure 30: Optimization results of the system

The two best optimal hybrid system configurations PV/Wind/Generator/Battery/Converter and PV/Wind/Battery/Converter systems which ranked first and second by the net present cost (NPC) with the Levelized cost of energy (LCOE), are compared with the conventional DG/Battery/Converter system ranked in seven. The performance analysis of the two selected hybrid system configuration and standalone DG system are discussed in the preceding sections. The parameters used for the comparison and analysis of hybrid power systems are NPC, COE, Renewable fraction, fuel consumption, capacity shortage, and excess electricity generation as shown in table 16 to 19.

Table 15: Percentage production of components

Component	Production (kWh/yr)	Fraction
PV array	50,677	66%
Wind turbines	24,071	32%
Generator 1	1,714	2%
Total	76,462	100%

5.2 Simulation Results

The detailed result analyses obtained at the end of the simulations are presented in tables 16, 17, 19, and 20. These are described below:

Table 16: Comparison of simulation results of economic cost of the three configurations

Parameter	Diesel/Battery System	PV/ Wind/ Battery system	PV/Wind/Generator /Battery system
PV size (kW)	0	28	28
Wind Turbine (quantity)	0	4	4
Generator Size (kW)	6	0	6
Battery Bank (Quantity)	8	56	32
Converter Size (kW)	6	8	8
Dispatch Strategy	Load following	Load following	Load following
Initial Cost	$ 15,420	$ 132,600	$ 107,220
Operating Cost	$ 30,735/yr	$ 3,762/yr	$ 3,952/yr
Annualized Cost	$31,942/yr	$14,135/yr	$12,339
COE	$ 0.729/kWh	$ 0.323/kWh	$ 0.282/kWh
Total NPC	$408,322	$ 180,691	$ 157,737

Table 17: Comparison of simulation results of emissions for three configurations

Pollutant	Emissions (kg/yr)		
	PV/Wind/Battery system	**PV/Wind/Generator/ Battery system**	**Generator/Battery system**
Carbon dioxide	0	1,711	40,368
Carbon monoxide	0	4.22	99.6
Unburned hydrocarbons	0	0.468	11
Particulate matter	0	0.318	7.51
Sulfur dioxide	0	3.44	81.1
Nitrogen oxides	0	37.7	889

Table 18: DC load consumption of the site

Load	**Consumption** (kWh/yr)	**Fraction**
DC primary load	43,765	100%
Total	43,765	100%

Table 19: Comparison of simulation results of the electricity production (kWh/yr), and excess energy of the energy system configurations

	PV/Wind/Battery system		**PV/Wind/Generator/Battery system**			**Generator/Battery system**
	PV	**Wind**	**PV**	**Wind**	**Generator**	
Total electricity production(kWh/year)	50,677 (68%)	24,071 (32%)	50,677 (66%)	24,071 (32%)	1,714 (2%)	46,442 (100%)
Total	74,748 kWh/yr		76,462 kWh/yr			46,442kWh/yr
Excess Electricity (KWh/year)	24,254		26,210			0.0000782
Renewable fraction (%)	100		98			0
Capacity Shortage (%)	0.1		0			0
Unmet load (kWh/year)	35.4		0.0956			0.000000477

Table 20: Comparison of simulation of Diesel-only System and Diesel in Hybrid System

Quantity/Unit	Diesel Generator only System	Generator in PV/Wind /Battery System	Generator in PV/Wind/Generator/ Battery System
Operational life (yr)	1.94	0	32.5
Capacity factor (%)	88.4	0	3.26
Hours of operation (hr/yr)	7,745	0	461
Fuel consumption (L/yr)	15,330	0	650
Fuel energy input (kWh/yr)	150,843	0	6,393

i) PV/ Wind/ Generator/ Battery configuration

The best optimal combination comprised of 28 kW PV array, four SW Whisper 500 wind turbine, 6kW diesel generator, 32 units Surrette 6CS25P battery and 8kW converter at 6.2 kWh/m^2 per day average global solar radiation, 4.3 m/Sec annual average wind speed and 0.8/L diesel price. It has a renewable fraction of 97.8%, i.e. 66% solar energy with 32% inclusion of wind energy. The cost summary of this system has a total net present cost of $157,737, Levelized cost of energy of $0.282/kWh and operating cost of $3,952 per year. The total NPC for the stand-alone diesel system is $408,322 which is 3 times higher than PV/Wind/Generator/Battery configuration. The total average electric production of the hybrid system is found to be 76,462kWh per year, of which PV array contributes 66%, wind turbine provides 32% and the generator provides 2% of the total annual production. But the consumption as per the DC telecom load is found to be 43,800kWh per year, resulting excess electricity in 26,210kWh per year with unmet electric load of 0.0956kWh per year and capacity shortage of 0.705kWh per year.

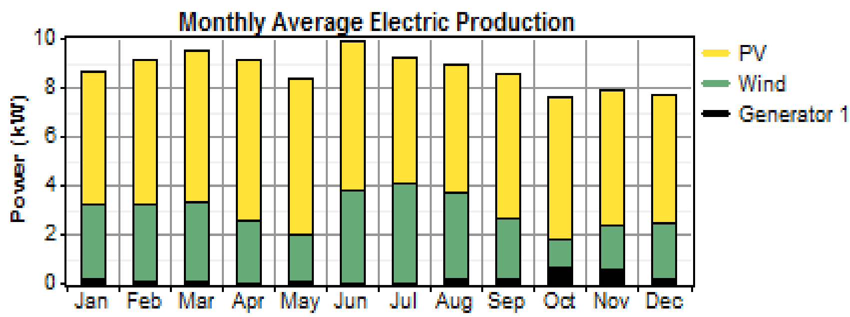

Figure 31: Monthly average electricity production of PV/wind/generator/battery hybrid system.

Table 21: Net Present Costs of PV/ Wind/ Generator/ Battery configuration

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	28,000	0	0	0	0	28,000
SW Whisper 500	34,200	9,354	3,579	0	-5,242	41,891
Generator 1	3,420	0	12,376	6,645	-185	22,256
Surrette 6CS25P	38,400	23,806	4,909	0	-6,835	60,281
Converter	3,200	1,335	1,023	0	-249	5,309
System	107,220	34,496	21,886	6,645	-12,510	157,737

Table 22: Annualized Costs of PV/ Wind/ Generator/ Battery configuration

Component	Capital	Replaceme nt	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	2,190	0	0	0	0	2,190
SW Whisper 500	2,675	732	280	0	-410	3,277

Generator 1	268	0	968	520	-14	1,741
Surrette 6CS25P	3,004	1,862	384	0	-535	4,716
Converter	250	104	80	0	-19	415
System	8,387	2,698	1,712	520	-979	12,339

ii) PV/Wind/Battery configuration

The next optimal combination consists of 28 kW PV array, four SW Whisper 500 wind turbine and 56 unitsSurrette 6CS25P battery and 8kW converter because. The result is based upon the system with 100kWh/day telecom load at 6.2kWh/m$^{2/}$day of solar radiation, 4.3m/s of wind speed and $0.8/L diesel price. The COE of this hybrid system is $0.323/kWh and the total NPC and operating costs of the system were found to be $180,691and $ 3,762/yr respectively. On the other hand, NPC of the stand-alone diesel system is more than 2 times higher than this configuration. The total average electric production of the hybrid system is found to be 74,748 kWh per year, of which PV array contributes 68% and wind turbine provides 32% of the total annual production. But the consumption as per the DC telecom load is found to be 43,765 kWh per year, resulting excess electricity of 24,254 kWh per year with unmet electric load of 35.4kWh per year and capacity shortage of 41.4kWh per year.

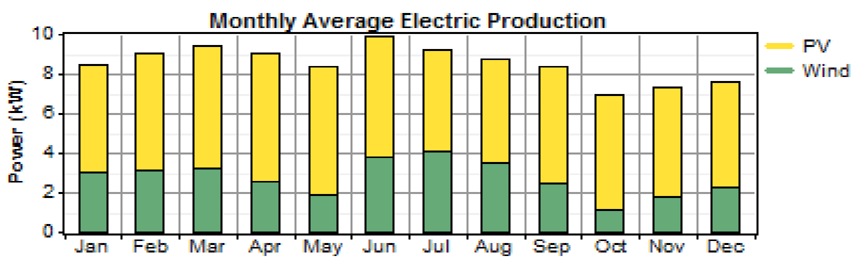

Figure 32: Monthly average electricity production of PV/wind/battery hybrid system.

As Figure 32 shows the PV system will operate more compared to the wind turbine, which means the PV array serves the base load more than the wind system. And the renewable energy fulfills the telecom load demand 100%.

Table 23: Net Present Costs of PV/Wind/Battery configuration

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	28,000	0	0	0	0	28,000
SW Whisper 500	34,200	9,354	3,579	0	-5,242	41,891
Surrette 6CS25P	67,200	41,661	8,590	0	-11,961	105,491
Converter	3,200	1,335	1,023	0	-249	5,309
System	132,600	52,351	13,192	0	-17,452	180,691

Table 24: Annualized Costs of PV/Wind/Battery configuration

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	2,190	0	0	0	0	2,190
SW Whisper 500	2,675	732	280	0	-410	3,277
Surrette 6CS25P	5,257	3,259	672	0	-936	8,252
Converter	250	104	80	0	-19	415
System	10,373	4,095	1,032	0	-1,365	14,135

iii) DG/Battery/Converter configuration

The conventional standalone generator system consists of 6 kW DG, 8-unitbattery, and 6 kW converter. This study reveals that DG-Battery System is very costly with the cost of energy (COE) $0.729/kWh and takes large total NPC of $408,322 due to the huge operation cost of $30,735per year when compared with the above hybrid systems. So, the DG NPC cost takes more than 95% of the total NPC cost and the NPC cost of the battery and the converter are around 4% and 1% of the total NPC cost respectively. The reason is the cost of Fuel and O&M are very large. On the other hand, the standalone diesel system consumes a total of 15,330L/year and run for 7,745hr/year. The total electrical energy production from the DG system is found to be 46, the 442 kWh/year and DC primary load consumption of 43,800 kWh per year; resulting in almost no excess electricity production, no capacity shortage and zero unmet electric loads. It has also environmental impact.

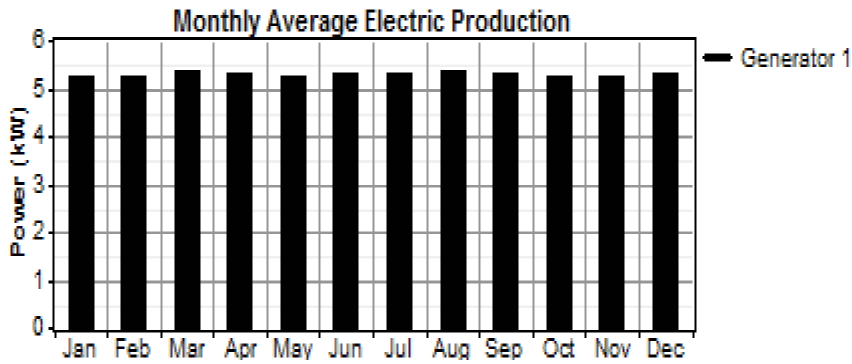

Figure33: Monthly average electricity production of Generator/battery hybrid system.

Table 25: Net Present Costs of Generator//Battery system

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	3,420	21,237	207,915	156,771	-73	389,270
Surrette 6CS25P	9,600	5,952	1,227	0	-1,709	15,070
Converter	2,400	1,001	767	0	-186	3,982
System	15,420	28,190	209,909	156,771	-1,968	408,322

Table 26: Annualized Costs of Generator//Battery system

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
Generator 1	268	1,661	16,265	12,264	-6	30,451
Surrette 6CS25P	751	466	96	0	-134	1,179
Converter	188	78	60	0	-15	312
System	1,206	2,205	16,421	12,264	-154	31,942

5.3 Discussions

A) Economic Cost

The economic cost used in comparing the energy systems was annualized cost, operating cost, COE and total NPC.

i) PV/Wind/Generator/Battery system vs Generator/Battery system

In the annualized cost, the PV/Wind/Generator/Battery hybrid system has $12,339/yr, while the diesel system has $31,942/yr, as shown in table 16. In comparison, the PV/Wind/Generator/Battery hybrid system saves $19603/yr to the network operator.

In the operating cost, the PV/Wind/Generator/Battery hybrid system has $3,952/yr, while the diesel system has $30,735/yr, as shown in table16. In comparison, the PV/Wind/Generator/Battery hybrid system saves $26783/yr to the network operator.

In the COE, the PV/Wind/Generator/Battery hybrid system has $0.282/kWh, while the diesel system has $ 0.729/kWh, as shown in table 16. In comparison, the PV/Wind/Generator/Battery hybrid system saves $0.447/kWh to the network operator.

In the total NPC, the PV/Wind/Generator/Battery hybrid system has $157,737, while the diesel system has $408,322, as shown in table16. In comparison, the PV/Wind/Generator/Battery hybrid system saves $250,585 to the network operator. Finally, based on the comparison parameters, i.e. annualized cost, operating cost, COE and total NPC of power generation for the BTS site, the hybrid system is the best in the perspective of economic analysis.

ii) PV/Wind/Battery System Vs Generator/Battery System

In the annualized cost, the PV/wind/battery hybrid system has $14,135/yr, while the diesel system has $31,942/yr, as shown in table 16. In comparison, the PV/wind/battery hybrid system saves $17807/yr to the network operator.

In the operating cost, the PV/wind/battery hybrid system has $3,762/yr, while the diesel system has $30,735/yr, as shown in table 16. In comparison, the PV/wind/battery hybrid system saves $26937/yr to the network operator.

In the COE, the PV/wind/battery hybrid system has $0.323/kWh, while the diesel system has $ 0.729/kWh, as shown in table 16. In comparison, the PV/wind/battery hybrid system saves $0.406/kWh to the network operator.

In the total NPC, the PV/wind/battery hybrid system has $180,691, while the diesel system has $408,322, as shown in table 16. In comparison, the PV/wind hybrid system saves $22,7631 to the network operator. Finally, based on the comparison parameters, i.e. annualized cost, operating cost, COE and total NPC of power generation for the BTS site, the hybrid system is the best in the perspective of economic analysis.

iii) PV/Wind/Generator/Battery System Vs PV/Wind/Battery System

In the annualized cost, the PV/wind/Generator/Battery hybrid system has $12,339/yr, while the PV/Wind/Battery system has $14,135/yr, as shown in table 16. In comparison, the PV/wind/Generator/Battery system saves $1796/yr to the network operator.

In the operating cost, the PV/wind/Generator/Battery hybrid system has $3,952/yr, while the PV/Wind/Battery system has $3,762/yr, as shown in table 16. In comparison, the PV/wind/Battery hybrid system saves $190/yr to the network operator.

In the COE, the PV/wind/Generator/Battery hybrid system has $0.282/kWh, while the PV/wind/Battery system has $ 0.323/kWh, as shown in table 16. In comparison, the PV/wind/Generator/Battery system saves $0.041/kWh to the network operator.

In the total NPC, the PV/wind/Generator/Battery hybrid system has $157,737, while the PV/wind/Battery system has $180,691, as shown in table 16. In comparison, the PV/wind/Generator/Battery hybrid system saves $22,954 to the network operator. Finally, based on the comparison parameters, i.e. annualized cost, operating cost, COE and total NPC of power generation for the BTS site, the proposed hybrid system is the best in the perspective of economic analysis.

B) Electricity Production

i) Diesel only Vs PV/Wind system

In the PV/Wind hybrid system, the PV array has a capacity factor of 20.7% and supplies 68% of the annual electricity production, and the wind system contributes 32% of the total electricity with a capacity factor of 22.9%; while the diesel-only system generates 100% of the total electricity with a capacity factor of 88.4% as shown in table 19.

ii) Diesel only Vs PV/Wind/Generator system

In the PV/Wind/Generator hybrid system, the PV array has a capacity factor of 20.7% and supplies 66% of the annual electricity production, and the wind system contributes 32% of the total electricity with a capacity factor of 22.9% and the generator provides 2% of the annual electricity production with a capacity factor of 3.26%; while the diesel-only system generates 100% of the total electricity with a capacity factor of 88.4% as shown in table 19.

iii) PV/Wind system Vs PV/Wind/Generator system

In the PV/Wind/Generator hybrid system, the PV array has a capacity factor of 20.7% and supplies 66% of the annual electricity production, and the wind system contribute 32% of the total electricity with a capacity factor of 22.9% and the generator provides 2% of the annual electricity production with a capacity factor of 3.26%; In the PV/Wind hybrid system, the PV array has a capacity factor of 20.7% and supplies 68% of the annual electricity production, and the wind system contributes 32% of the total electricity with a capacity factor of 22.9% as shown in table 19.

C) Environmental Impact

i) Generator/Battery Vs PV/Wind/ Battery system

The generator in the Generator/Battery system operates for 7,745hr/annum, has a fuel consumption of 15,330L/annum. It generates 40,368kg/yr of CO_2, 99.6 kg/yr of CO, 11kg/yr of UHC, 7.51kg/yr of PM, 81.1kg/yr of SO_2, and 889kg/yr of NOx as shown in table 17; while in the PV/Wind/Battery hybrid system, diesel generator operates for 0h/annum and has a fuel consumption of 0L/annum. This system emits 0 kg/yr of CO_2, 0 kg/yr of CO, 0 kg/yr of UHC, 0 kg/yr of PM, 0kg/yr of SO_2, and 0 kg/yr of NOx annually into the atmosphere of the location of the BTS station site as shown in table17. A 100% decrease was noticed in each pollutant. This was due to the 100% renewable penetration into the existing power system. The reduction in the quantity of different air pollutants for the 100% renewable penetration compared to that of diesel-only are thus: 40,368 kg/yr of CO_2, 99.6 kg/yr of CO, 11 kg/yr of UHC, 7.51 kg/yr of PM, 81.1 kg/yr of SO_2, and 889 kg/yr of NOx. In terms of fuel consumption, this hybrid system when compared with the diesel-only system saves about 15,330 liters of fuel per annum to the network operator.

ii) Generator/Battery Vs PV/Wind/Generator/Battery system

The generator in the Generator/Battery system operates for 7,745hr/annum, has a fuel consumption of 15,330L/annum. It generates 40,368 kg/yr of CO_2, 99.6 kg/yr of CO, 11 kg/yr of UHC, 7.51 kg/yr of PM, 81.1 kg/yr of SO_2, and 889 kg/yr of NOx as shown in table 17; while in the PV/Wind/Generator/Battery hybrid system, diesel generator operates for 461h/annum and has a fuel consumption of 650L/annum. This system emits 1,711 kg/yr of CO_2, 4.22 kg/yr of CO, 0.468 kg/yr of UHC, 0.318 kg/yr of the PM, 3.44 kg/yr of SO_2, and 37.7 kg/yr of NOx annually into the atmosphere of the location of the BTS station site as shown in table17. A 96% decrease was noticed in each pollutant. This was due to the 98% renewable penetration into the diesel-only (existing) power system. The reduction in the quantity of different air pollutants for the 98% renewable penetration compared to that of diesel-only are thus: 3,8657 kg/yr of CO_2, 95.38 kg/yr of CO, 10.532 kg/yr of UHC, 7.192 kg/yr of the PM, 77.66 kg/yr of SO_2, and 851.3kg/yr of NOx. In terms of fuel consumption, this hybrid system when compared with the diesel-only system saves about 14,680 liters of fuel per annum to the network operator.

iii) PV/Wind/Battery Vs PV/Wind/Generator/Battery system

The diesel generator in the PV/Wind/Generator/Battery system operates for 461h/annum and has a fuel consumption of 650L/annum. This system emits 1,711 kg/yr of CO_2, 4.22 kg/yr of CO, 0.468 kg/yr of UHC, 0.318 kg/yr of the PM, 3.44 kg/yr of SO_2, and 37.7 kg/yr of NOx annually into the atmosphere of the location of the BTS station site as shown in table 17. While in the PV/Wind/Battery hybrid system, diesel generator operates for 0h/annum and has a fuel consumption of 0L/annum. This system emits 0 kg/yr of CO_2, 0 kg/yr of CO, 0 kg/yr of UHC, 0 kg/yr of PM, 0 kg/yr of SO_2, and 0 kg/yr of NOx annually into the atmosphere of the location of the BTS station site as shown in table 17. A 100% decrease was noticed in each pollutant. This was due to the 100% renewable penetration. The reduction in the quantity of different air pollutants for the 100% renewable penetration compared to that of PV/Wind/Generator/Battery system are thus: 1,711 kg/yr of CO_2, 4.22 kg/yr of CO, 0.468 kg/yr of UHC, 0.318 kg/yr of the PM, 3.44 kg/yr of SO_2, and 37.7 kg/yr of NOx. In terms of fuel consumption, this hybrid system when compared with the diesel-only system saves about 650liters of fuel per annum to the network operator.

In summary, the total Net Present Cost (NPC) for the Generator/Battery system is $408,322 and it burns 15,330L of fuel per year and annual generator run time is 7,745 hours. In twenty years the diesel generator will burn 306,600L of fuel. The total fuel cost during these 20 years will be $245,280 and the total cost for the whole system will be $653,602.

And for the hybrid system, the total Net Present Cost (NPC) is $157,737. The system will consume only 650 liters of diesel fuel per year and annual generator run time is expected to be 461hours. The lifetime of this system is 20 years and is used to make the comparison between the two systems (i.e. the existing and the hybrid one). In twenty years the diesel generator will burn 13,000L of fuel and it will cost $10,400. The total cost of the system will be around $168,137. The difference in cost between two systems is $485,465 which is a very significant number for the system operator. Diesel generator run times are reduced and diesel generator in the hybrid system will produce only 2% of the total power production. Moreover, the reduction of yearly diesel fuel consumption from 15,330L to 650L has a large impact on the environment and it will reduce the transportation trips to the site. Also, the diesel generator will require less maintenance and operation cost and longer period of service before a replacement.

To conclude, the PV/wind/Generator/Battery hybrid system needs high initial capital cost, but in the end it has less total NPC for the whole project lifetime; while diesel-only system has the least initial capital cost, but in the end has the highest total NPC as a result of fuel consumption. On the environmental impact perspective, an increase in the operational hours of diesel generator brings about an increase in the fuel consumption and as well an increase in GHG emission, whereas a reduction in the operational hours of diesel generator brings about a reduction in the fuel consumption thereby a reduction in GHG emission.

5.4 Sensitivity Analysis

The modeling tool permits to take an account for future dynamic changes, meaning increasing or decreasing demand, renewable and non-renewable resource 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 to 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 the 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 a larger memory computer. Taking the limitations into account in this thesis work four sensitivity parameters were considered, namely: solar radiation (4, 6 & 8 kWh/m^2/day), wind speed (3, 4.3& 6 m/Sec), annual average energy (80,120 & 140 kWh/day) and diesel price (0.6, 0.8 & 1.2$/L).

5.4.1 Sensitivity result

There are six different sensitivity results scenarios of the Optimal System Type (OST) they are: Variation in wind speed and solar radiation, Variation in wind speed and diesel price, Variation sin solar radiation and diesel price, Variation in solar radiation and Load average energy, Variation in diesel price and Load average energy, and Variation in load average energy and wind speed.

i) Varying average wind speed and average solar radiation value

In this sensitivity analysis, optimal system types (OSTs) are investigated for three different values of load average energy of BTS and diesel prices as presented in above of sensitivity analyses for which the wind speed range 3.0 and 6 m/Sec in the X-axis and solar radiation range 4.0 and 8.0kWh/m^2/day in the Y axis as shown in Figure 34.

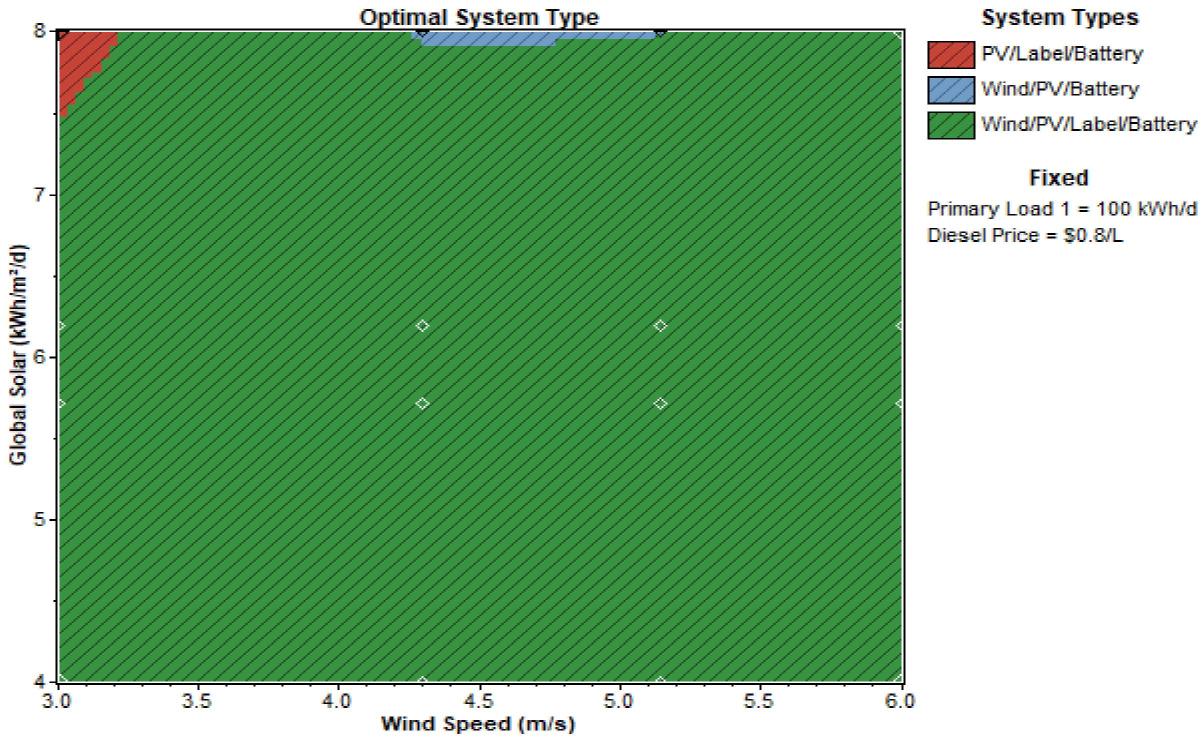

Figure 34: Optimal system types for varying solar radiation and wind speed values.

It is obvious from this Figure 34 that for the specified value of Primary load (100 kWh/day) and diesel price ($0.08/L) there are three best optimal configurations PV/Wind/DG/Battery, PV/Wind/Battery and PV/DG/Battery at the considered site.

ii) Variation in wind speed and diesel price

In this sensitivity analysis, OSTs is investigated for three different values of load average energy of BTS and Global Solar Radiation as presented in above of Sensitivity analyses for which the wind speed range 3.0 and 6 m/Sec in the X-axis and the diesel price range 0.6 and 1.2$/L as shown in Figure 35.

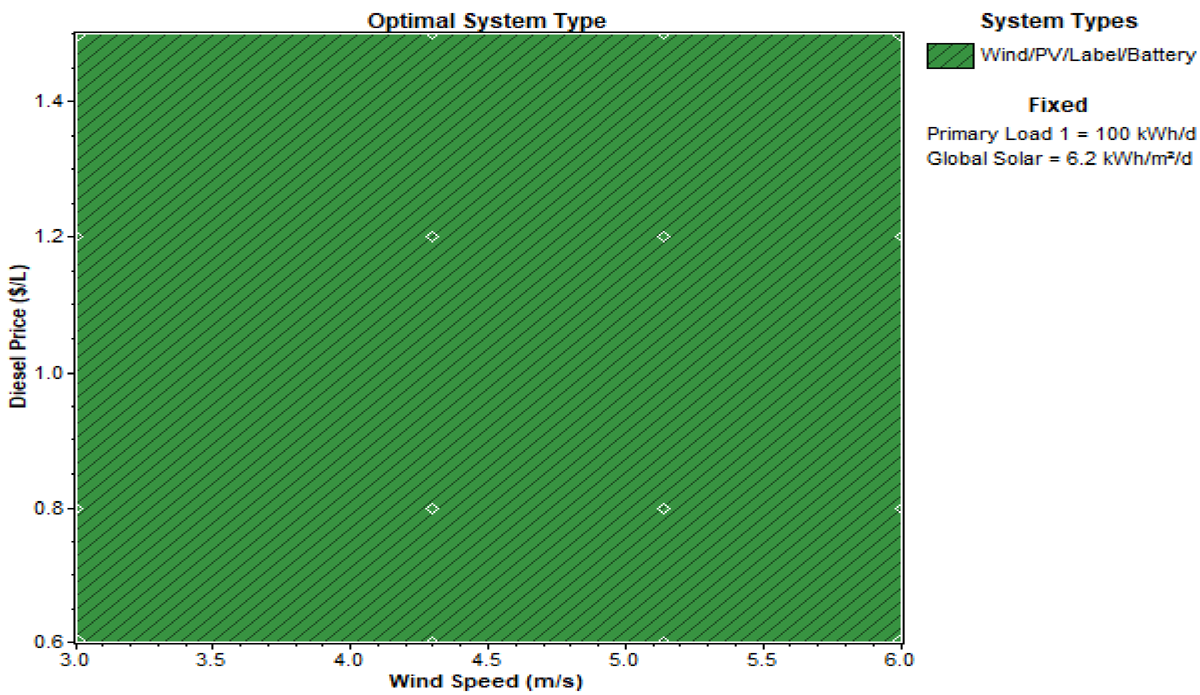

Figure 35: Optimal system types for varying diesel price and wind speed values.

It can be seen from figure 35 that for the specified value of Primary load (100 kWh/day) and average solar radiation (6.2kWh/m^2/d) there is one best optimal configuration Wind/PV/DG/Battery at the considered site.

iii) Variation in solar radiation and diesel price

In this sensitivity analysis, OSTs is investigated for three different values of load average energy of BTS and wind speed as presented in above of Sensitivity analyses for which the solar radiation ranges 4.0 and 8 m/Sec in the X-axis and solar radiation range diesel price range 0.6 and 1.2$/L as shown in figure 36.

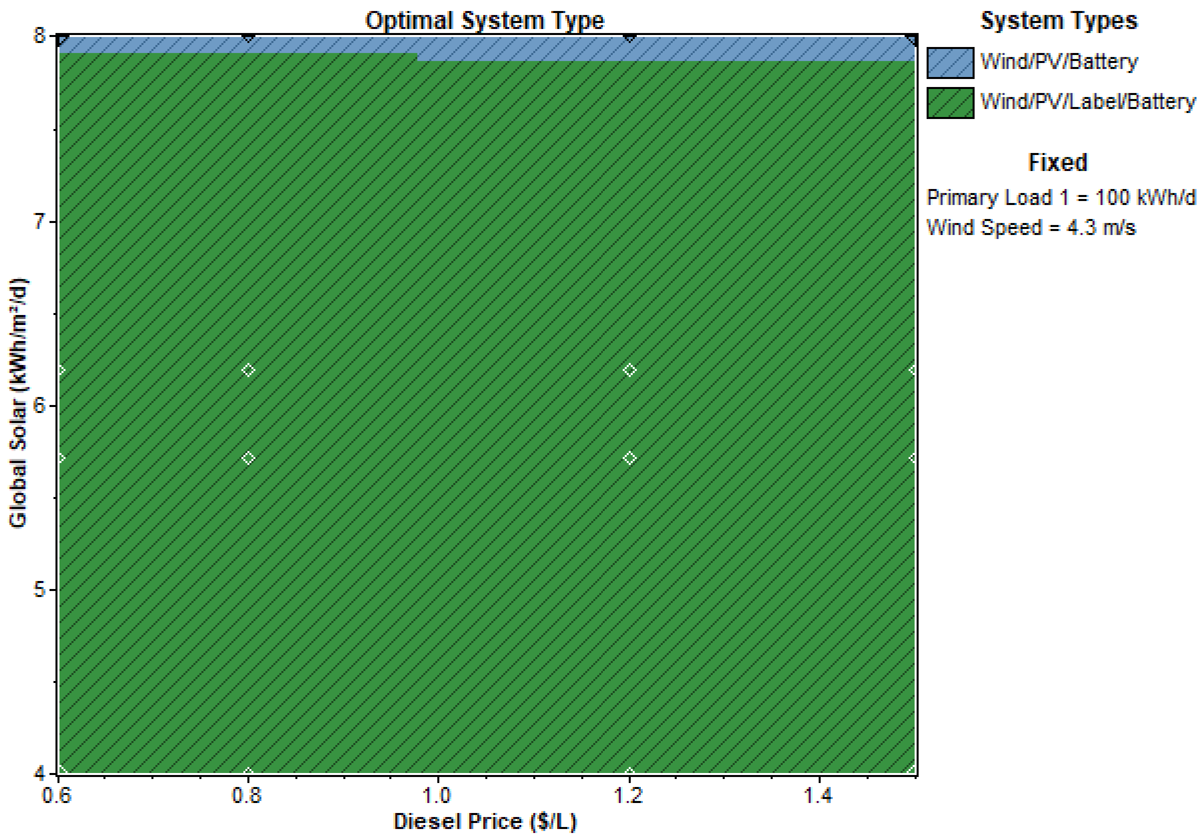

Figure 36: Optimal system types for varying solar radiation and diesel price values.

It is obvious from this figure 36 that for the specified value of Primary load (100 kWh/day) and average wind speed (4.3m/Sec) there are two best optimal configurations PV/ Wind/DG/Battery and PV/Wind/Battery at the considered site.

iV) Variation in solar radiation and Load average energy

In this sensitivity analysis, OSTs is investigated for three different values of wind speed and diesel prices as presented in above of Sensitivity analyses for which the Load average range 80 and 140kwh/d in the X-axis and solar radiation range 4.0 and 8.0kWh/m^2/day as shown in Figure 37.

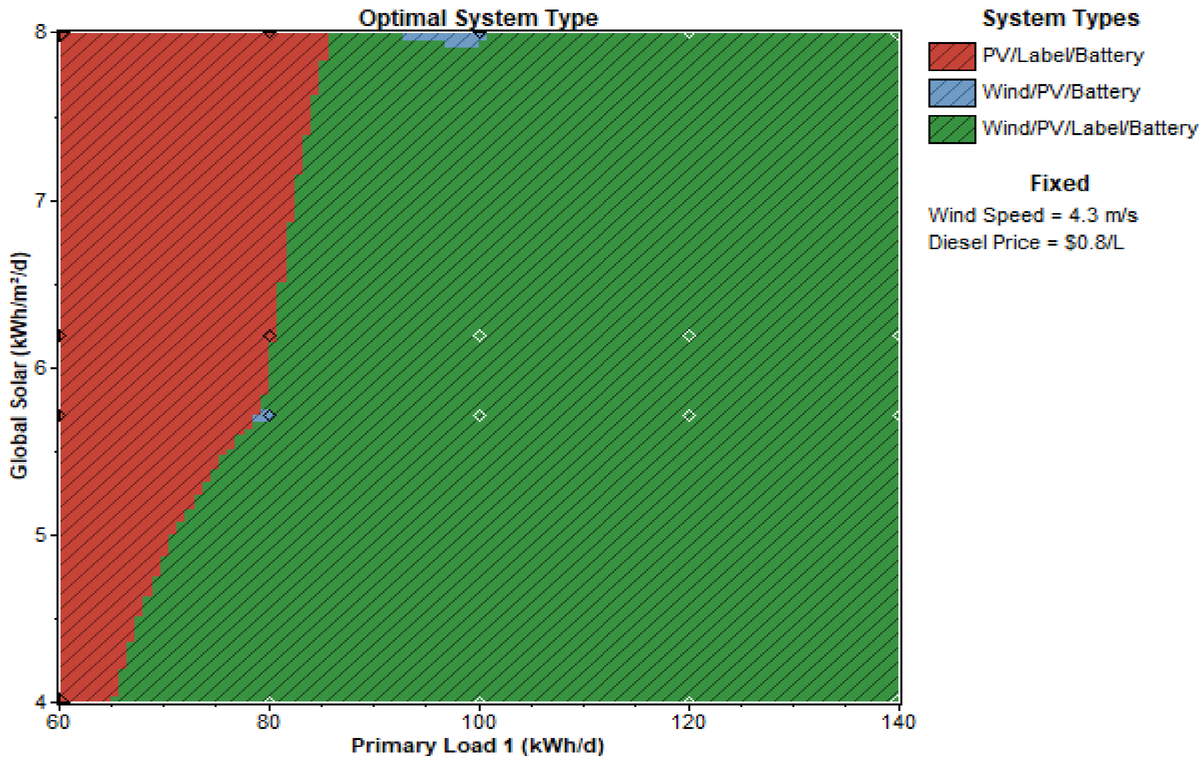

Figure 37: Optimal system types for varying solar radiation and primary load values.

It is obvious from this Figure 37 that for the specified values of wind speed (4.3m/Sec) and diesel price ($0.08/L) there are three best optimal configurations PV/DG/Battery, PV/ Wind/Battery and PV/Wind/DG/Battery at the considered site.

V) Variation in diesel price and Load average energy

In this sensitivity analysis, OSTs is investigated for three different values of average solar radiation and average wind speed as presented in above of Sensitivity for which the diesel price range 0.6 and 1.2$/L in the X-axis and Load average energy 80 and 140kWh/d in the Y axis as shown in Figure 38.

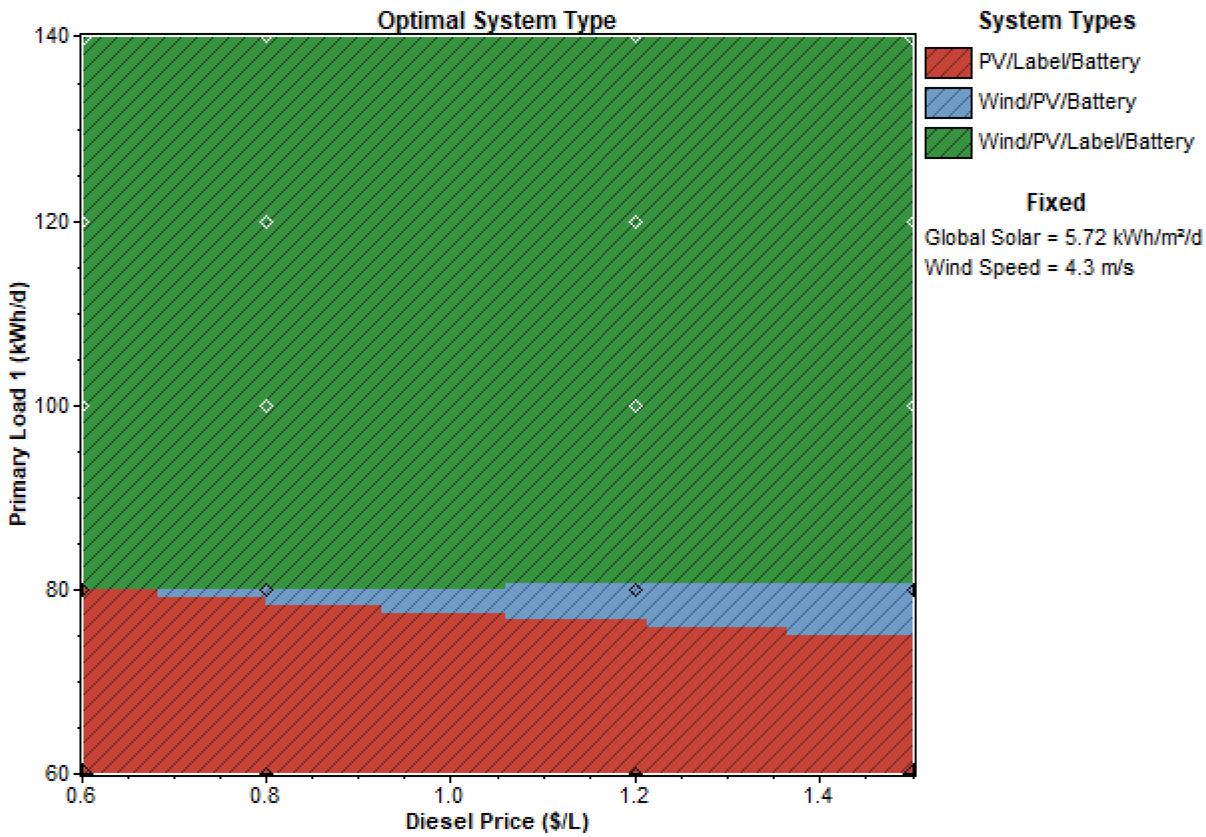

Figure 38: Optimal system types for varying primary load and diesel price values.

It is obvious from this Figure 38 that for the specified values of average solar radiation (5.72kWh/m^2/day) and average wind speed (4.3m/s) there are two best optimal configurations, PV/ Wind/DG/Battery and PV/DG/Battery at the considered site.

Vi) Variation in load average energy and wind speed

In this sensitivity analysis, OSTs is investigated for three different values of average solar radiation and diesel price as presented in above of Sensitivity analyses for which the average wind speed range 3 and 6 in the X-axis and Load average energy 80 and 140kWh/d in the Y axis as shown in Figure 39.

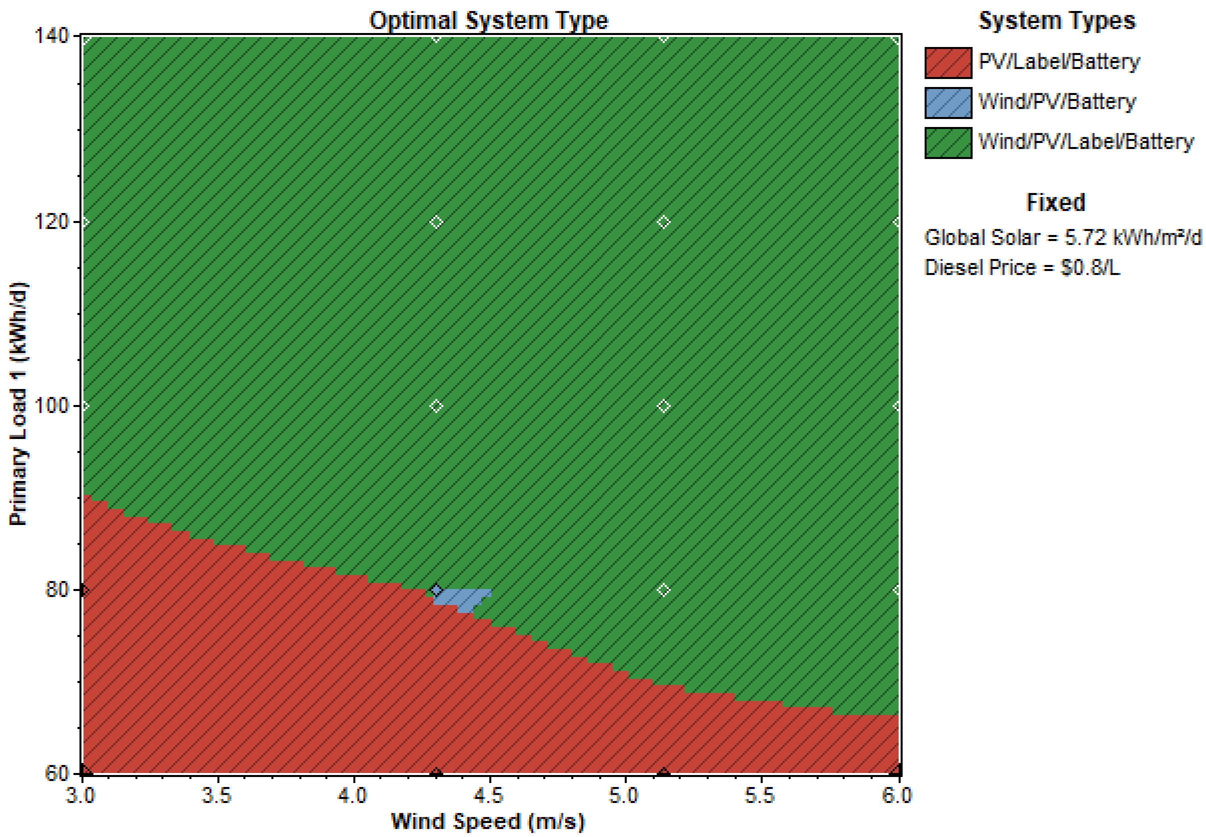

Figure 39: Optimal system types for varying primary load and wind speed values.

It is obvious from this Figure 39 that for the specified values of average solar radiation (5.72 kWh/m^2/day) and diesel price ($0.08/L) there is two best optimal configurations, PV/DG/Battery and PV/Wind/DG/Battery at the considered site.

As it is seen from all sensitivity cases considered above in this study, it is clear that the PV/Wind/DG/Battery hybrid system is best of all other hybrid systems for all sensitivity cases considered. As a result, it can be concluded that it is better to power the BTS site in the study area through a renewable based hybrid system, i.e. PV/Wind/DG/Battery system than the diesel generator alone.

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Providing a reliable, secure power and energy system is one of the main issues in cellular networks. Accordingly, this study examined supplying the needed energy for a GSM/UMTS type base station located at Hadnet, wukro, Tigray, by solar PV, wind and diesel generator hybrid system with storage element so as to provide feasibility and reliable electric power. The optimum criteria, including economic and technical feasibility parameters, were analyzed using the HOMER software package developed by the U.S. National Renewable Energy Laboratory (NREL).

Moreover, the best optimal hybrid system configurations PV/Wind/Generator/Battery/Converter system which ranked first by the net present cost (NPC) with the Levelized cost of energy (LCOE), has been compared with the conventional DG/Battery/Converter system ranked in seven in terms of: (i) OPEX savings and (ii) GHG emissions. Findings indicated that PV/Wind/Generator/Battery hybrid system is the most economically viable option with a total cost of $168,137 for the whole system project life time, i.e. 20 years and for the diesel generator system the total cost is $653,602 for the whole system project life time. And the levelized cost of energy (COE) for both systems is $0.282/kWh and $0.729/kWh respectively. This implies the hybrid system saves $485,465 in terms of NPC and $0.447/kWh in terms of COE to the network operator.

Also, simulation results show that the renewable energy source (RES) based hybrid energy system can decrease amount of air pollutants as compared to the conventional diesel generator only and so a reduction of 38,657kg/yr of CO_2, 95.38 kg/yr of CO, 10.532 kg/yr of UHC, 7.192 kg/yr of PM, 77.66 kg/yr of SO_2, and 851.3 kg/yr of NOx is observed and saves about 14,680 liters of fuel per annum to the network operator. A sensitivity analysis is also done to analyze the effects of probable variation in solar radiation, wind speed, diesel price and average annual energy usage of the system load in the optimal system configurations and the simulation results show that the proposed system is effective to supply the site at all conditions.

In summary, the proposed hybrid system needs high initial capital cost, but in the end it has less total NPC for the whole project; while diesel-only system has the least initial capital cost, but in the end has the highest total NPC as a result of fuel consumption. On the environmental impact perspective, an increase in the operational hours of diesel generator brings about an increase in the fuel consumption and as well an increase in GHG emission, whereas a reduction in the operational hours of diesel generator brings about a reduction in the fuel consumption thereby a reduction in GHG emission. As a result, this paper has verified the predictions that the proposed hybrid system is superior to the diesel-only system for power generation at the BTS site from the perspective of both economic and environmental analyses.

5.2 Recommendation

The researcher has recommended that to implement a renewable-energy based hybrid system for ensuring reliability and cleanly powering of the site since utilizing renewable-energy based hybrid system for powering BTS sites will decrease the operating cost of the telecom company which has direct impact on the low-income rural telecom subscriber, but also reduce the diesel fuel usage, thereby bring low greenhouse gas emission to the environment. Finally, the information gained from the entire project can be applied in the design, execution, or development of HRES for any mobile tower applications in other locations in the country.

5.3 Future work

Further follow up studies are required to be carried for the design and development of reliable hybrid systems of the BTSs considering shelter and indoor type BTS load consumptions including fuel and controlling system for enhancing the reliability of a hybrid system for remote and inaccessible locations.

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