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Simulation and Optimization of Wind Turbine, Solar PV, Storage Battery and Diesel Generator Hybrid Power System for a Cluster of Micro and Small Enterprises Working on Wood and Metal Products at Welenchity Site

A Thesis submitted to the School of Graduate Studies of Addis Ababa Institute of Technology in partial fulfillment of the Degree of Masters of Science in Energy Technology

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TABLE OF CONTENT

ACKNOWLEDGEMENT iv
TABLE OF CONTENT v
LIST OF TABLES viii
LIST OF FIGURES ix
ABSTRACT xi
INTRODUCTION 1
1.1 Background 1
1.2 Objective of the study 3
    1.2.1 General Objectives 3
    1.2.2 Specific Objectives 3
1.3 Methodology 3
1.4 Introduction of System 4
1.5 Outline of the Thesis 6
CHAPTER TWO 7
HYBRID POWER GENERATION SYSTEM 7
2.1 Benefits of a Hybrid System 8
2.2 Block Diagram of a Hybrid System 9
CHAPTER THREE 11
WIND AND SOLAR ENERGY RESOURCES AND THEIR ANALYSIS 11
3.1 Wind Energy Resources and Analysis 11
    3.1.1 Wind Power Generation 11
    3.1 .2 the Earth's Wind Systems 12
    3.1.3 Wind Turbine Velocities, Distribution, Power, and Energy 14
    3.1.4 Wind speed data of the site 16
    3.1.5 Power and energy produced by a wind turbine 17
    3.1.6 Effect of height on wind speed 18
    3.1.7 Effect of the Average atmospheric pressure 19
    3.1.8 Effect of annual average temperature 20

3.1.9 Wind Speed Distribution 20
3.2 Solar Energy Resources and Analysis 24
3.2.1 Solar Energy Resources 24
3.2.2 Analysis of Photovoltaic (PV) Power for the Selected Site 25
3.2.3 Solar Data of the site used in HOMER 27
CHAPTER FOUR 29
HYBRID SYSTEM COMPONENTS MODELING AND SIZING 29
4.1 Load Profile 29
4.2 Wind Turbine Modeling and Sizing 30
4.3 PV Panel Modeling and Sizing 31
4.4 Battery Bank Modeling and Sizing 31
4.4.1 Lead acid battery construction and performance 32
4.4.2 Lead acid battery rating and model 32
4.4.3 Battery bank sizing 34
4.5 Diesel Generator Ratings and sizing 34
4.5.1 Diesel generator rating 34
4.5.2 Diesel generator sizing 35
4.6 Charge Controller (Regulator) Modeling and Sizing 35
4.7 Bidirectional Inverter Modeling and Sizing 36
CHAPTER FIVE 38
HYBRID SYSTEM SIMULATION SOFTWARE AND COMPONENTS 38
5.1 Simulation Software 38
5.1.1 Simulation 40
5.1.2 Optimization 41
5.1.3 Sensitivity Analysis 42
5.1.4 Hybrid System Modeling 42
5.2 Simulation Approach 51
5.3 Software Inputs and Outputs 54
CHAPTER SIX 56
RESULTS AND DISCUSSION 56
6.1 Optimization results 56

6.2 Sensitivity Analysis 62
  6.2.1 Net present cost sensitive to diesel price 62
CHAPTER SEVEN 67
CONCLUSIONS AND RECOMMENDATIONS 67
7.1 Conclusion 67
7.2 Recommendations 69
REFERENCES 71
APPENDIXES 73

LIST OF TABLES

Table 3.1: Power curve data of the selected wind turbine

Table 3.2: Monthly Average Wind Speed of the site, 10m

Table 3.3: The probability density function for the welenchity wind site

Table 3.4: Cumulative distribution functions of Welenchity wind system

Table 3.6: Wind Energy Potential Based on Rayleigh Analysis

Table 3.5: Monthly average of daily sunshine hour for Welenchity site (Adama)

Table 3.6: Monthly average of daily solar radiation for Welenchity site (Adama)

Table 4.1: Daily Load profile of the site

Table 5.1: Inputs to the HOMER software

Table 6.1: Categorized optimization results

Table 6:2 System report for the 91 % renewable resource contribution

Table 6.3: Net Present Costs

Table 6.4: Comparison of net present cost, energy cost and green house gas emission diesel-only option with hybrid system

Table 6.5: Sensitivity of net present cost to diesel price

Table 6.6: Sensitivity of net present cost to solar radiation

Table 6.7: Sensitivity of net present cost to wind speed

LIST OF FIGURES

Figure 2.1: Block diagram of the hybrid system
Figure 3.1: Power curve of selected wind turbine
Figure 3.2: Monthly Average Wind Speed of the site at, 10m
Figure 3.3: The probability density functions of Welenchity wind system
Figure 3.4: The cumulative distribution functions of Welenchity wind system
Figure 4.1: Daily load curve for the specified site
Figure 5.1: HOMER diagram for the hybrid system
Figure 5.2: Sufficient energy to supply load & charge batteries case.
Figure 5.3: Sufficient energy to supply load & charge batteries but the extra energy is consumed by the dump load case.
Figure 5.4: Not sufficient energy to supply load, batteries are also used to supply load case
Figure 5.5: Not sufficient energy to supply load & charge batteries, diesel generator is switched on and do this case.
Figure 6.1: Monthly average solar resources
Figure 6.2: Monthly Average Electric Production of the selected hybrid system
Figure 6.3: Cash flow summary of the selected hybrid system
Figure 6.4: Monthly Average Electric Production of this setup
Figure 6.5: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different diesel price
Figure 6.6: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different solar radiation
Figure 6.7: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different wind speed

ABEREVATIONS

a-Si:	Amorphous-Silicon
COE:	Cost of Energy
HAWT:	Horizontal Axis Wind Turbine
ISC:	Short Circuit Current
kWh:	Kilo Watt Hour
LCC:	Life Cycle Cost
MSEs:	Micro and Small Enterprises
MPPT:	Maximum Power Point
NOCT:	Normal Operating Cell Temperature
NPC:	Net Present Cost
PV:	Photovoltaic
rpm:	Revolution per minute
SC-Si:	Single Crystalline-Silicon
TSR:	Speed Ratio
VAWT:	Vertical Axis Wind Turbine
VOC:	Open Circuit Voltage
Wp:	Watt peak
COE:	Cost of Energy

ABSTRACT

This thesis presents the design of a hybrid electric power generation system utilizing both wind and solar energy for supplying a cluster of three micro and small enterprises (MSEs) working on wood and metal products at the Welenchity site. The work was begun by investigating wind and solar energy potentials of the desired site, compiling data from different sources and analyzing them using software.

The wind speed and solar irradiation data for the site understudy are collected from the National Metrological Agency (NMA) and analyzed using the software tool HOMER. The results related to wind energy potential are given in terms of the monthly average wind speed, the wind speed PDF, the wind speed CDF, the wind speed DC, and power density plot for the site. Whereas the solar energy potential, has been given in the form of solar radiation plots for the site. According to the results obtained through the analysis, the site has abundant solar energy potential and the wind energy potential is unquestionably high enough to be exploited for generating electric energy using wind turbines with low cut-in wind speed.

The design of a standalone PV-wind hybrid power generating system has proceeded based on the promising findings of these two renewable energy resource potentials, wind and solar. The simulations and design has been carried out using the HOMER software.

By running the software the simulation results which are lists of power supply systems have been generated and arranged in ascending order according to their net present cost (NPC). Sensitivity variables, such as range of wind speed, solar radiation and diesel price have been defined as inputs into the software and the optimization process has been carried out repeatedly for the sensitivity variables and the results have been refined accordingly.

The model developed is fairly general and may be adequate for preliminary results for energy consumption cost for MSEs willing to adopt renewable energy sources. Therefore the most economical scenario is using wind-PV –Diesel Generator-Battery hybrid system as stated before.

Keywords: hybrid renewable energy system, wind energy, photovoltaic, HOMER, PV-wind hybrid, cluster of micro and small enterprises

CHAPTER ONE`

INTRODUCTION

1.1 Background

It is a well known fact that in many developing countries and less developed countries, a significant proportion of the population lives without usable electrical power. Ethiopia is one of developing countries with more than 80% of its population live without usable electricity [CIA, 2010]. The more noticeable benefits of usable electric power include: improved health care, improved education, better transportation systems, improved communication systems, a higher standard of living, and economic stability. Unfortunately, many of the rural areas of Ethiopia have not benefited from these uses of electricity in the same proportion as the more populated urban areas of the country. A major limitation to the development of many rural communities has been the lack of this usable electricity. Due to the remote location and the low population densities of the rural communities the traditional means of providing power has proven too expensive, undependable, difficult to maintain, and economically unjustifiable. Consequently, many of these communities remain without electricity and may never receive grid power from the utility. The small town of Welenchity and surrounding communities are one of those rural areas which have no access to electricity. The remote location and the small size of this town made it impractical to electrify with traditional diesel power plants. The system of sole central diesel power plants have shown to require high maintenance, use large quantities of fuel, pollute the environment, and have a low level dependability**.** Consequently, a central diesel plant was not considered for micro and small enterprises working on wood and metal products in Welenchity and surrounding area.

The Hybrid Renewable Power Generation System (HRPGS) is a system aimed at the production and utilization of the electrical energy coming from more than one source, provided that at least one of them is renewable [Gupta et. al., 2008]. Such a system often includes some kind of storage in order to satisfy the demand during the periods in which the renewable sources are not available and to decrease the time shift between the peak load and the maximum power produced and power conditioning unit and controller to convert and control one form of energy to other.

As the current international trend in rural electrification is to utilize renewable energy resources; solar, wind, biomass, and micro hydro power systems can be seen as alternatives. Among these, wind and solar energy systems in stand-alone or hybrid forms are thought to be ideal solution for rural electrification due to abundant solar radiation and significant wind distribution availability nearby the rural community in Ethiopia .Ethiopia lies in the sunny belt between northern latitudes of 3o and 15o, and thus the potential benefits of renewable energy resources such as solar and wind energy can be considerable. As mentioned in [Mulugeta, 1999] the total annual solar radiation reaching the territory is of the order of over 200 million tone oil equivalent (toe) per year, over thirteen fold the total annual energy consumption in the country. In terms of geographical distribution, solar radiation that reaches the surface increases as one travels from west to east: the isolation period is approximately 2200 hours of bright sunshine per year in the west increasing to over 3300 hours per year in the eastern semi-arid regions.

The same author mentioned in [Mulugeta, 1999] that the total wind resource potential across Ethiopia amounts to 42 million toe per year, which also exceeds gross energy consumption by about three fold. Temporal and spatial variations in wind resource distribution over Ethiopia are significant, with the most attractive sites located toward the eastern and northern regions where average annual wind speed typically exceeds 3.5 m/s.

So far, these vast renewable energy resources are not exploited sufficiently in the country, primarily due to the lack of scientific and methodological know-how as regards planning, site selection, and technical implementation. A further constraint prohibiting their utilization is that the real potential of these resources is not well-known, partly because of the lack of research emphasis in developing these technologies, and partly because of the insufficient resource data base.

Thus, in this thesis a hybrid renewable power generation system integrating these vast solar and wind resources is designed and modeled, to electrify for cluster of micro and small enterprises working on wood and metal products in Welenchity and area surrounding it.

1.2 Objective of the study

1.2.1 General Objectives

The basic objective of the thesis is to design, and model a stand-alone wind turbine, solar PV, storage battery and diesel generator hybrid Power generation system to investigate alternative power supply options for micro and small enterprises working on wood and metal products around Welenchity villages detached from the main electricity grid and to search for the system which improve the sustainable power supply by replacing existing conventional diesel powered electric supply.

1.2.2 Specific Objectives

While trying to achieve this main objective, the following goals going to be fulfilled:

- Develop a data base of published data on wind speed and solar radiation of the site
- Select a set of photovoltaic modules and wind turbines suitable to generate electricity using the wind and solar resource available in the selected site
- Propose an optimization procedure to determine the amount and type of PV modules, storage battery and wind turbines needed, under standalone conditions, to satisfy a predetermined demand at minimum cost.
- Perform an economic analysis to compute the net present value of the renewable energy systems proposed
- Conducting an economic evaluation of the systems and compare different option.

1.3 Methodology

The methods to be used for the research are:

- Literature review**:** includes reading books, articles, simulation tools and other resources related to the topic.
- collecting and analyzing the data and information of the site
- examining and selecting the most suitable Power Generation and Supply Systems,

- System modeling and simulation: includes mathematical modeling of the system and simulating the modeled system using the available optimization software (HOMER).
- Comparing the cost of electricity produced from renewable energy and the Present cost of fossil fuel (diesel) based electricity generated of site.
- Analysis and interpretation of the result

The wind data used in this study were obtained from the Ethiopian Meteorological Agency, Ministry of water and energy, Ethiopian Electric Power Corporation (EEPCO) and local MSE working on wood and metal products. The mean of both wind speeds and solar are computed for each month. It should be noted that using monthly wind speed has some limitations such as loosing extremely low or high wind speeds within the month as well as inability to observe diurnal variations in the wind speed. However, using monthly mean wind speed, which is mostly available for most locations, can be used to study the seasonal changes in wind speed and facilitates wind data analysis. Simulation software (HOMER) is developed to analyze the operation of the hybrid system

1.4 Introduction of System

Hybrid power systems, which combine conventional and renewable power conversion systems, are the best solution for feeding the mini-grids and isolated loads in remote areas. Properly chosen renewable power sources will considerably reduce the need for fossil fuel leading to an increase in the sustainability of the power supply. At the same time, conventional power source said the renewable sources in hard environmental conditions, which improve the reliability of the electrical system.

Over the present year’s hybrid technology has been developed and upgraded its role in renewable energy sources while the benefits it produces for power production can't be ignored and have to be considered. Nowadays many applications in rural and urban areas use hybrid systems. Many isolated loads try to adopt this kind of technology because of the benefits which can be received in comparison with a single renewable system.

For the Welenchity case, the daily average of solar radiation intensity on horizontal surface is about 6.135 kWh/m2 and day, while the total annual sunshine hours amounts to about 3000 [1]. These figures are relatively high and very encouraging to use PV generators for electrification of certain loads as it has been worldwide successfully used.

The annual average of wind velocity at different places in Ethiopia is about 3 m/s which make the utilization of wind energy converters surely infeasible in such places. In other places it exceeds this number and reaches up to 10.2 m/s (Welenchity is an example and it is the case under study in the thesis) which makes it feasible to be used to operate a wind turbine.

Technically a system which is entirely dependent only on renewable energy sources cannot be a reliable electricity supply, especially for isolated loads in remote areas. This is because the availability of the renewable energy sources cannot be ensured. Therefore, winds, solar PV hybrid systems, which combine conventional and renewable sources of energies, are a better choice for isolated loads.

A hybrid system using wind, solar PV, diesel generator as a backup system, and a battery as a storage system is expected to: satisfy the load demands, minimize the costs, maximize the utilization of renewable sources, optimize the operation of battery bank, which is used as back up unit, ensure efficient operation of the diesel generator, and reduce the environment pollution emissions from diesel generator if it is used as a standalone power supply.

The high capital cost of hybrid systems is affected by technical factors such as efficiency, technology, reliability, location, as well as some nontechnical factors, so the effect of each of these factors shall be considered in the performance study of the hybrid system.

One of the important factors, which directly affect the electricity cost, is correct system-sizing mechanism of the system’s components. Over-sizing of components in hybrid system makes the system, which is already expensive, more expensive, while under-sizing makes the system less reliable. Thus optimum sizing for different components gives economical and reliable benefits to the system.

The software package developed in this thesis is used to simulate the operation of a system by making energy balance calculations for each of the 8760 hours in a year and then to choose the appropriate sizes of the different components in the system.

1.5 Outline of the Thesis

The first step in analyzing any hybrid system is to specify the configuration of the system. Chapter 2 in this thesis introduces a general description of the hybrid system: construction features, and benefits and the block diagram adopted for the hybrid system.

To completely study and analyze any hybrid system, different components constructing the hybrid system shall be studied, identified, specified, chosen and analyzed appropriately. Different issues concerning operation, technology, types, specifications and data analysis of both wind and solar radiation measurements are reviewed and studied through chapters 3 in this thesis. Microsoft Excel software programming package is used to make the wind and solar data analysis required.

Simulation software (HOMER) is developed to analyze the operation of the hybrid system. The first step in developing the software program is to appropriately mathematically model different components constructing the hybrid system. Chapter 4 in this thesis introduces mathematical modeling and appropriate sizing of all components constructing this hybrid system.

An initial step in developing the software simulation program is to identify the models upon which the operation of the hybrid system under different modes and the decision of the energy flow depend. Different diagrams determining the operation of the hybrid system are presented in chapter 5.

To appropriately analyze different scenarios of the hybrid system, and then to choose the optimal one, an evaluation based on economical analysis shall be done. Chapter 6 in this thesis introduces different economic figures and system reports used to compare the different scenarios. Tables and figures present and illustrate different results of the simulation program for the different scenarios and comparison between results are introduced for sensitivity analysis .General conclusions and recommendations concerning results of the simulation are introduced and presented in chapter 7 in this thesis.

CHAPTER TWO

HYBRID POWER GENERATION SYSTEM

A hybrid renewable energy system is a system in which two or more supplies from different renewable energy sources (solar-thermal, solar photovoltaic, wind, biomass, hydropower, etc.) with other technologies such as batteries and diesel generator are integrated to supply electricity or heat, or both, to the same demand. The most frequently used hybrid system is the hybrid which consists of Photovoltaic (PV) modules and wind turbines.

Combining renewable hybrid system with batteries as a storage system, to increase duration of energy autonomy, will make optimal use of the available renewable energy resource and this in turn can guarantee high supply reliability. To deal with different weather conditions and to make the system supplies load demand at the worst conditions, this strategy requires large storage capacity and therefore it is very expensive. It is cheaper to supply peaks or to supply demand during periods of cloudy weather or poor wind days with another back up supply (usually diesel generator), although this lowers the proportion of renewable energy used. Selecting appropriate size of the storage system is such that to minimize diesel running time and to maximize fuel savings.

As an off-grid power generation, the hybrid system offers clean and efficient power that will in many cases be more cost-effective than sole diesel systems. As a result, renewable energy options have increasingly become the preferred solution for off-grid power generation [Ali B. et al, 2010].

The hybrid system studied in this thesis is one combining solar PV and wind turbine with diesel generator(s) and bank of batteries, which are included for backup purposes. Power conditioning units, such as inverters, are also part of the supply system. Hybrid wind turbine and PV modules, offer greater reliability than any one of them alone because the energy supply does not depend entirely on any one source. For example, on a cloudy stormy day when PV generation is low there's likely enough wind energy available to make up for the loss in solar electricity, and as a result the size of the battery storage can be reduced [Patel, 2006].

Wind and solar hybrids also permit use of smaller, less costly components than would otherwise be needed if the system depends on only one power source. This can substantially lower the cost of a remote power system. In a hybrid system the designer doesn't need to weigh the components for worst-case conditions by specifying a larger wind turbine and battery bank than is necessary [Patel, 2006].

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 routine maintenance. In addition to this, as well as being indigenous and free, renewable energy resources also contribute to the reduction of emissions and pollution [Getachew, 2009].

The PV-wind hybrid power generation system makes use of the solar PV and wind turbine to produce electricity as the primary source to supply the load. The configuration of PV-wind hybrid system is analyzed for various PV array and wind turbine sizes with respect to a diesel generator to operate in tandem with the battery system. The power conditioning units will determine the ac conversion of the dc power in relation to optimum diesel generator operation following the load profile. The charge controller will charge the batteries with energy from PV modules and wind turbines as well as from the diesel generator. The main objective of PV-wind hybrid system is to reduce the cost of operation and maintenance and cost of logistic by minimizing diesel runtime and fuel consumption. To achieve this generator only runs as needed to recharge the battery and to supply excess load when renewable sources are not enough to supply the load. A schematic of a typical PV-wind hybrid system can be shown in Figure below.

2.1 Benefits of a Hybrid System

The main benefits (advantages) of a hybrid system can be summarized as:

- The possibility to combine two or more renewable energy sources, based on the natural local potential of the users.
- Environmental protection especially in terms of CO2 emissions reduction.

- Low cost – wind energy, and also solar energy can be competitive with nuclear, coal and gas especially considering possible future cost trends for fossil and nuclear energy.
- Diversity and security of supply.
- Rapid deployment - modular and quick to install.
- Fuel is abundant, free and inexhaustible.
- Costs are predictable and not influenced by fuel price fluctuations although fluctuations in the price of batteries will be an influence where these are incorporated.

2.2 Block Diagram of a Hybrid System

There are many possible configurations of hybrid power systems. One way to classify systems architectures is to distinguish between AC and DC bus systems. DC bus systems are those where the renewable energy components and sometimes even the backup diesel generator feed their power to a DC bus, to which is connected an inverter that supplies the loads. This is for small hybrid systems. Large power hybrid systems use an AC bus architecture where wind turbines are connected to the AC distribution bus and can serve the loads directly.

The configuration used to be evaluated in this thesis has a DC bus which combines the DC output of the PV module, the DC output of the wind turbine, and the battery bank. The AC bus of this configuration combines the output of the bidirectional inverter, the output of the back-up diesel generator and the load. This parallel configuration requires no switching of the AC load supply while maintaining flexibility of energy source, but the bidirectional power inverter shall be chosen to deal with this mode of operation. Figure 2.1 illustrates the block diagram of this configuration.

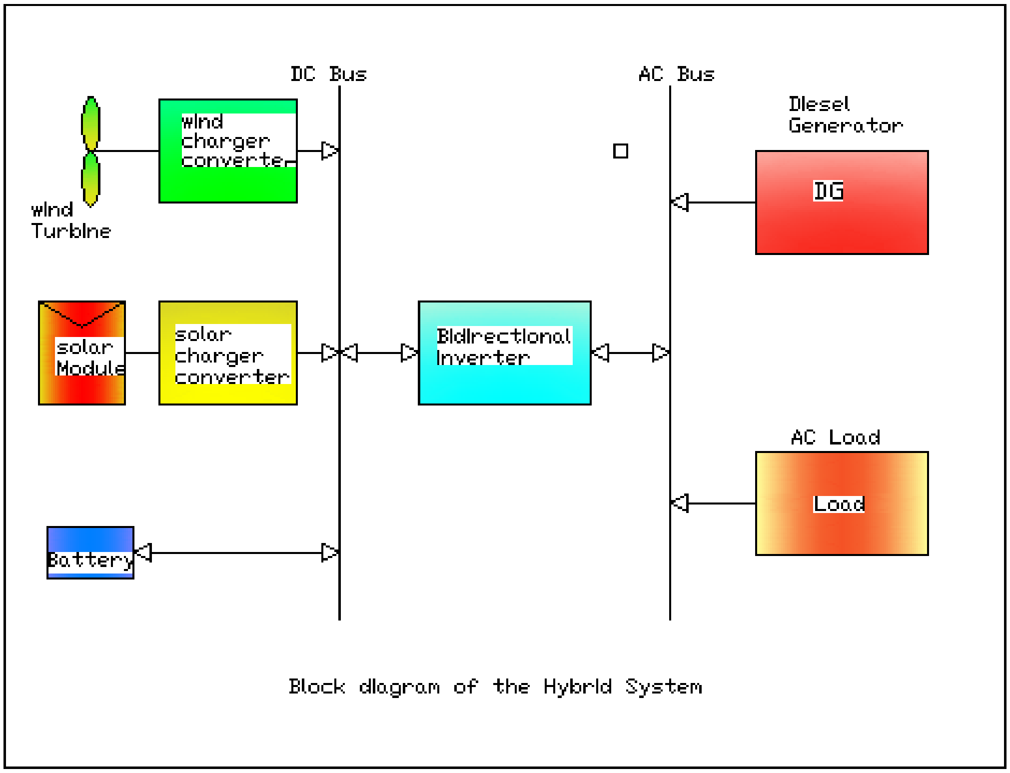

Figure 2.1: Block diagram of the hybrid system

CHAPTER THREE

WIND AND SOLAR ENERGY RESOURCES AND THEIR ANALYSIS

3.1 Wind Energy Resources and Analysis

All renewable energy (except tidal and geothermal power), and even the energy in fossil fuels, ultimately comes from the sun. The sun radiates 174,423,000,000,000 kilowatt hours of energy to the earth per hour. In other words, the earth receives 1.74 x 10 17 W of power [4].

3.1.1 Wind Power Generation

Wind power, like most sources of energy on earth, originates from the sun. As the earth orbits the sun daily, it receives light and heat. Across the earth there are areas with different temperatures, so that heat transfers from one area to another. These heat differences help to create wind: in warmer regions of the earth, the air is hot and is therefore at a high pressure, compared with the air in colder regions, where it is at a low pressure. Wind is the movement of the air from high pressure to low pressure.

The idea of creating something to capture the power from the wind is not a new idea. Wind turbines have been used for thousands of years for milling grain, pumping water, and other mechanical power applications. Today, there are over one million wind turbines in operation around the world. Most of them are used for water pumping and for generating electricity. Wind energy offers the potential to generate substantial amounts of electricity without the pollution problems of most conventional forms of electricity generation [18, 11]**.**

Wind energy has been used for thousands of years for milling grains, pumping water and other mechanical power applications. But the use of wind energy as an electrical supply with free pollution what makes it attractive and takes more interest and used on a significant scale.

Attempts to generate electricity from wind energy have been made since the end of nineteenth century. Small wind machines for charging batteries have been manufactured since the 1930s. Wind now is one of the most cost-effective methods of electricity generation available in spite of the relatively low current cost of fossil fuels. The technology is continuously being improved both cheaper and more reliable, so it can be expected that wind energy will become even more economically competitive over the coming decades [5].

3.1 .2 the Earth's Wind Systems

The earth's wind systems are due to the movement of atmospheric air masses as a result of variations in atmospheric pressure, which in turn are the result of differences in the solar heating of different parts of the earth’s surface. One square meter of the earth’s surface on or near the equator receives more solar radiation per year than one square meter at higher latitudes. As a result, the tropics are considerably warmer than the high latitude regions. Atmospheric pressure is the pressure resulting from the weight of the column of the air that is above a specified surface area.

Like all gases, air expands when heated, and contracts when cooled. In the atmosphere, warm air is lighter and less dense than cold air and will rise to high altitudes when strongly heated by solar radiation. A low pressure belt is created at the equator due to warm humid air rising in the atmosphere until it reaches the top of the troposphere (approximately 10 km) and will spread to the North and the South. This air gradually cools until it reaches latitudes of about 30 degrees, where it sinks back to the surface, creating a belt of high pressure at these latitudes. The majority of the world's deserts are found in these high pressure regions.

Power production from a wind turbine is a function of wind speed. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. In general, most wind turbines begin to produce power at wind speeds of about 4 m/s (9 mph), achieve rated power at approximately 13 m/s (29 mph), and stop power production at 25 m/s (56 mph). Variability in the wind resource results in the turbine operating at continually changing power levels. At good wind energy sites, this variability results in the turbine operating at approximately 35% of its total possible capacity when averaged over a year.

Table 3.1: Power curve data of the selected wind turbine

	Wind Speed	Power Output
	(m/s)	(kW)
1	0.00	0.000
2	3.00	0.000
3	4.00	0.060
4	5.00	0.110
5	6.00	0.280
6	7.00	0.560
7	8.00	1.000
8	9.00	1.560
9	10.00	2.110
10	11.00	2.560
11	12.00	2.830
12	13.00	2.940
13	14.00	3.000
14	15.00	3.000
15	16.00	2.890
16	17.00	2.670
17	18.00	2.390
18	19.00	2.170
19	20.00	2.060
20	24.00	2.000

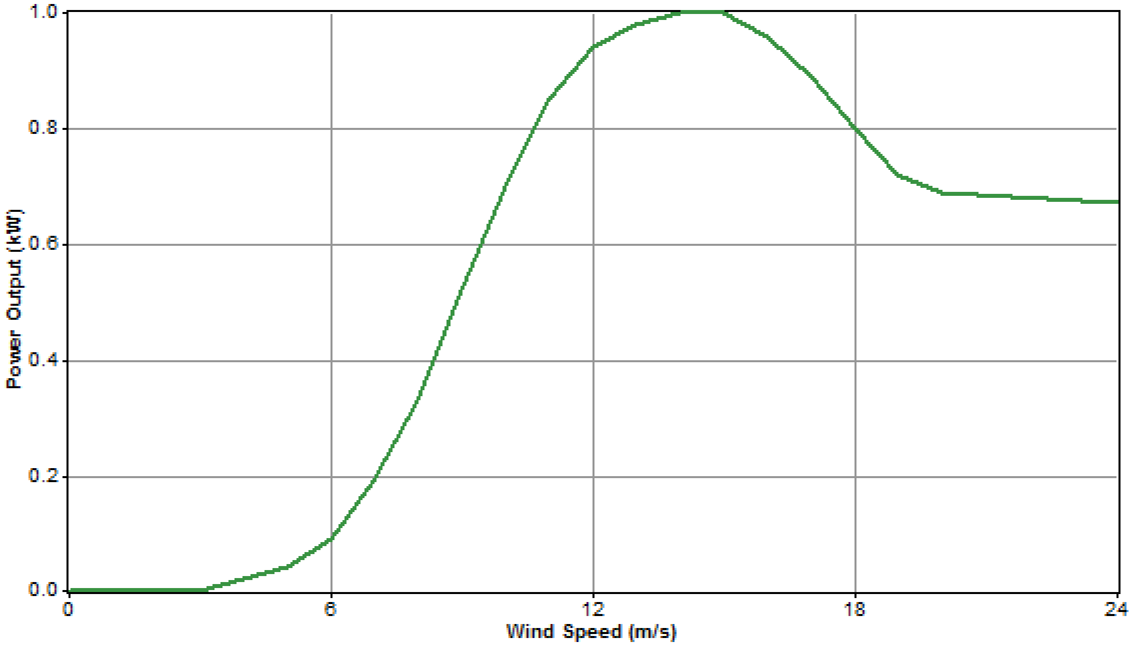

Figure 3.1: Power curve of selected wind turbine

3.1.3 Wind Turbine Velocities, Distribution, Power, and Energy

3.1.3.1 **Velocities,** ***power, and energy*** **available** ***in wind***

The speed of rotation of a wind turbine is usually measured in either rotation speed in revolutions per minute (N in rpm) or angular velocity in radians per second (in rad/s). The relationship between the two is given by:

$$\omega = \frac{2*\pi*R}{60} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Another measure of a wind turbines speed is its tip speed which is the tangential velocity of the rotor at the tip of the blades measured in meter per second and it equals to:

$$v = \omega * r \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

where r is the tip radius in meters.

A non dimensional ratio known as the tip speed ratio (TSR) is obtained by dividing the tip speed by the undisturbed wind speed, Vo. This ratio which provides a useful measure can be used to compare wind turbines of different characteristics.

$$TSR = \frac{v}{v_o} = \frac{\omega * r}{v_o} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

A wind turbine of a particular design can operate over a range of tip speed ratios, but will usually operate with its best efficiency at a particular tip speed ratio. The optimum tip speed ratio for a given wind turbine rotor will depend upon both the number of blades and the width of each blade [5].

A term describes the percentage of the area of the rotor, which contains material rather than air is known as solidity. Wind turbines with large number of blades have high solidity, but wind turbines with small number of narrow blades have low solidity. Multi blade wind pumps have high solidity rotors and modern electricity generating wind turbines (with one, two or three blades) have low solidity rotors. The turbines with low solidity have to turn much faster than the high solidity turbines in order to interact with all the wind passing through. Optimum tip speed ratios for modern low solidity wind turbines range between about 6 and 20 [5].

The energy contained in the wind is its kinetic energy (E_{kin}) and it is equal to [5]:

$$E_{kin} = \frac{1}{2} * m * v^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

Where (m) is the mass of air in kilograms and (V) is speed of air in meters per second. Mass of air flowing through a certain area (A) per second (m.) is:

$$m^{\cdot} = \rho * A * v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

Where ρ : is the density of air in kilograms per cubic meter.

So, kinetic energy in the wind per second which is equal to power (P) in the wind in watts is equal to:

$$P = \frac{1}{2} * \rho * A * v^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.6$$

As it is appeared from the power relation above, wind speed (cubic) has a strong influence on power output.

The power contained in the wind is not in practice the amount of power that can be extracted by a wind turbine. This is because losses are incurred in the energy conversion process, also because some of the air is pushed aside by the rotor and by passing it without generating power.

3.1.4 Wind speed data of the site

The available wind speed measured at Adama (EEPCO's 10 meters station) indicates that wind with minimum speed occurs during August (6.61m/s), while the wind with high velocity occurs during November, December, January and February; 9.95, 10.29, 9.27 and 9.65 m/s respectively. The values calculated over 3 years (2006 to 2008) indicate that mean wind speed is 8.33 m/s. Wind speed at Adama (National Meteorological Service Agency 2 meters station) illustrates that wind with minimum speed occurs during August (1.76), while months which receive high wind speed are November, December and January (2.65, 2.74, and 2.47 m/s respectively). The wind speed at Adama (EEPCO's 40 meters station) shows that a month which gets minimum wind speed is August (6.04) and months of high wind speed are November, December, and January (11.15, 11.05, and 10.56 m/s respectively). Generally, data from all stations show that the wind speed at Adama is high throughout the year but there is decreasing trend during summer months. The wind direction recorded every ten minutes a day in the past three years (2006-2008) indicates that there is seasonal variation of wind direction. However, the prevailing wind direction is Northeasterly.

Table 3.2: Monthly Average Wind Speed of the Site at 10m

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Average
10meters (2006-2008)	9.2	9.6	7.8	7.5	7.3	7.5	8.2	6.6	7.5	8.1	9.9	10.2	8.3

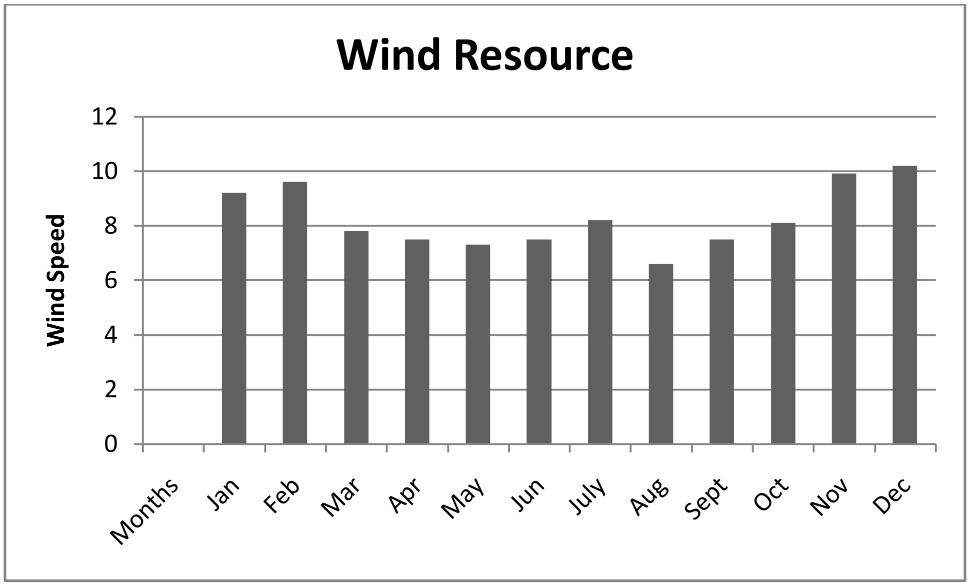

Figure 3.2: Monthly Average Wind Speed of the Site at 10m

3.1.5 Power and energy produced by a wind turbine

Each wind turbine has its own characteristic known as wind speed power curve. The shape of this curve is influenced by the blades area, the choice of airfoil, the number of blades, the blade shape, the optimum tip speed ratio, the speed of rotation, the cut-in wind speed, the shutdown speed, the rated speed, and gearing and generator efficiencies. The power output of a wind turbine varies with wind speed and wind turbine power curve.

The energy that a wind turbine will produce depends on both its power curve and the wind speed frequency distribution at the site. Wind speed frequency distribution is a graph showing the number of hours for which the wind blows at different wind speeds during a given period of time.

Energy produced at any wind speed can be obtained by multiplying the number of hours of its duration by the corresponding turbine power at this wind speed obtained by the turbine's power curve. The total energy produced is calculated by summing the energy produced at all the wind speeds within the operating range of the turbine.

The best way to determine the wind speed distribution at a sight is to carry out wind speed measurements including record of duration for which the wind speed lies within each wind speed band.

Availability of the turbine is one of the factors that affect the total energy generation. Availability is an indication of the reliability of the turbine installation and is the fraction of a given period of time for which a wind turbine is available to generate, when the wind is blowing within the turbine's operating range. Typical values of annual availabilities exceed 90% [5].

A rough initial estimate of electricity production (in kWh / m²/year) at a certain site is [5]:

$$E_{gen} = K_{WT} * (v_{av})^3 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.7$$

Where: E_{gen} is the annual electrical energy generated by a wind turbine (kWh), K_{WT}= 3.2 (kg/m/s) is a factor based on typical turbine performance, and v_{av} is the site average annual wind speed in m/s.

3.1.6 Effect of height on wind speed

The height at which the speed of wind is measured affects the value of the wind speed. As height increases the speed of wind increases, so it is more valuable to increase the height of wind turbine in respect of power that can be captured, but as height increases the initial capital cost of the tower increases and also the maintenance and operation costs increases, so it is a compromise issue.

So when calculating the output of wind generator, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height.

Knowledge of wind speeds at heights of 20 to 120 m above ground is very desirable in any decision about location and type of wind turbine to be installed. Many times, these data are not available and some estimate must be made from wind speeds measured at about 10 m. This requires an equation which predicts the wind speed at one height in terms of the measured speed at another, lower, height. One possible form for the variation of wind speed u (z) with height z is [3]:

$$V = V_{ref}\left[\frac{\ln\left(z/z_0\right)}{\ln\left(z_{ref}/z_0\right)}\right] \text{……………………………………………………………..}3.8$$

where: V=wind velocity at height z above ground level

V_{ref}= reference velocity, i.e., a wind velocity at height z_{ref}

Z= height above ground level for the desired velocity V

Z_0= surface roughness length of the site, 0.12 in our case

Z_{ref} = reference height, i.e., the height where the exact wind velocity

V_{ref}= is known as reference velocity

The annual average wind speed at 10m for welenchity site is already known before which is 8.3m/s and the average wind speed at the hub height of 40m with the wind shear exponent of 0.12 is calculated as follows:`

z=40m, z_{ref}=10m, z_o=0.12,V_{ref}=8.3m/s

Hence, the wind speed at the hub height is:

$$V = 8.3\,m/s\left[\frac{\ln\left(40m/0.12\right)}{\ln\left(10m/0.12\right)}\right] = 10.904\,m/s$$

3.1.7 Effect of the Average atmospheric pressure

The average atmospheric is used on the annual basis, because the power available from the wind depends upon this value. This value s used to calculate the pressure coefficient adjustment. The average atmospheric pressure is inversely proportional to the altitude. The average atmospheric pressure typically ranges from 60 to 103 KPa. The lower end the range corresponds to a site at an elevation of approximately 4,000 m where as the higher end of the range corresponds to sea level. The atmospheric pressure at standard condition is 101.3 KPa [Elliot, 1986].

Note that the atmospheric pressure falls with increasing altitude. Up to about 5,000 m altitude, the mean atmospheric pressure, P (KPa), at altitude of Z meters above sea level can be estimated by:

$$P = P_{sealevel} \times e^{\left(-Z/8200\right)} \text{………………………………………………………………}3.9$$

Where

$P_{sealevel}$ is the atmospheric pressure at sea level of site (i.e., 86.4 KPa)

$$P = 86.4 * e(-60/8200)$$

$$P = 85.8KPa$$

3.1.8 Effect of annual average temperature

The power available from the wind depends on the annual average temperature. This value is used to calculate the temperature coefficient adjustment. The Greater the temperature, the lower the air density and therefore, the lower the power available from the wind and this relation is shown above on effect of temperature and altitude on air density. Accordingly the mean annual temperature (T_m) of the site is $22.4℃$.

3.1.9 Wind Speed Distribution

3.1.9.1 Wind Speed Frequency with Rayleigh distribution

The measured wind speed variation for a typical site throughout a year indicates that the strong gale force winds are rare, while moderate and fresh winds are quite common, and this is applicable for most areas.

Sometimes there are very high wind speeds, but they are very rare. The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface.

The reliability of Weibull distribution in wind system analysis depends on the accuracy in estimating k and c. For the precise calculation of k and c, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period. Under such situations, a simplified case of the Weibull model can be derived; by approximating k as 2.This is known as the Rayleigh distribution.

The probability density function of the Welenchity wind site is calculated as follows using the Rayleigh wind distribution:

Table 3.3: Probability density function of the Welenchity wind site

Months	V [m/s]	V_m [m/s]	f(V)
Jan	9.2	8.43	0.079797
Feb	9.6	8.43	0.076629
Mar	7.8	8.43	0.087997
Apr	7.5	8.43	0.089014
May	7.3	8.43	0.08952
Jun	7.5	8.43	0.089014
Jul	8.2	8.43	0.086196
Aug	6.6	8.43	0.090119
Sept	7.5	8.43	0.089014
Oct	8.1	8.43	0.086692
Nov	9.9	8.43	0.074079
Dec	10.2	8.43	0.071405

The probability density functions of Welenchity wind system, following the Rayleigh distribution are shown in fig. below.

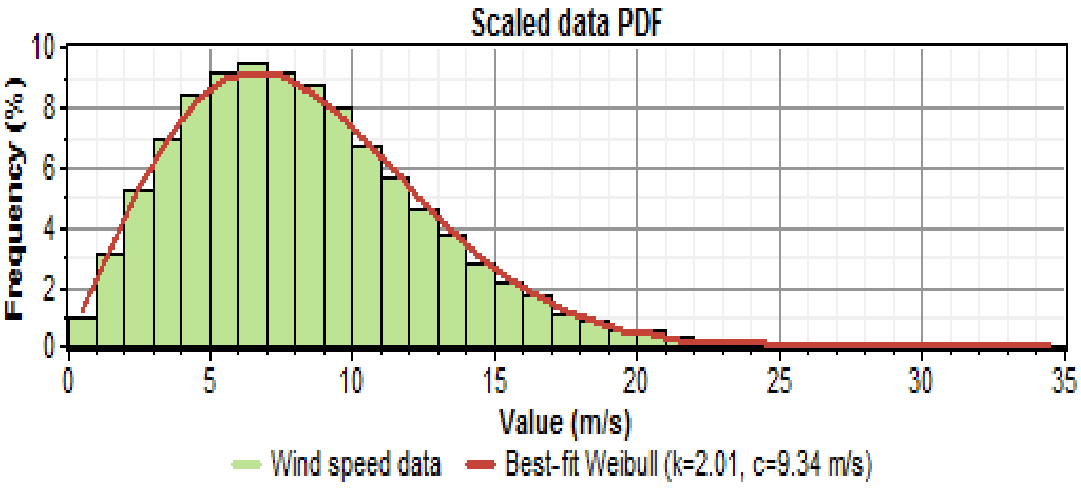

Figure 3.3: Probability density curve for Welenchity wind site

Similarly the cumulative distribution function of a wind system is given by:

$$F(V) = \int_0^{\infty} f(V)\, dv = 1 - e^{-\left(V/_c\right)^k} ----------------------3.10$$

Cumulative distribution functions of Welenchity wind system is calculated as follows:

Table 3.4: Cumulative distribution functions Welenchity wind system

Months	V [m/s]	V_m [m/s]	F(V)
Jan	9.2	8.43	0.607396
Feb	9.6	8.43	0.638691
Mar	7.8	8.43	0.489341
Apr	7.5	8.43	0.462782
May	7.3	8.43	0.444926
Jun	7.5	8.43	0.462782
Jul	8.2	8.43	0.524196
Aug	6.6	8.43	0.381943
Sep	7.5	8.43	0.462782
Oct	8.1	8.43	0.515551
Nov	9.9	8.43	0.661301
Dec	10.2	8.43	0.683126

The cumulative distribution function of the velocity V indicates the fraction of time (or probability) that the wind velocity is equal or lower than V Thus the cumulative distribution which is the integral of the probability density function is show as follows:

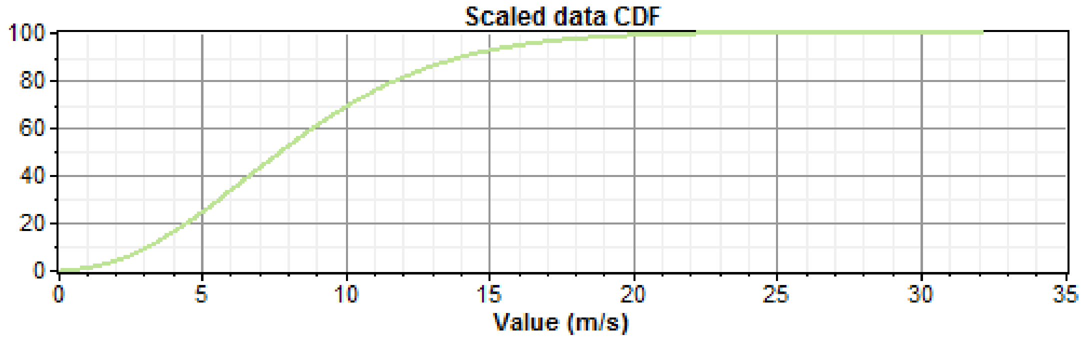

Figure 3.4: Cumulative distribution functions of Welenchity wind speed

3.1.9.2 Rayleigh Approach for Energy Estimation of wind systems

In addition to the mean wind speed, the other two significant wind speeds for wind energy estimation are the most probable wind speed (V_F) and the wind speed carrying maximum energy (V_E) [6,12]:

The most probable wind speed corresponds to the peak of the probability density function, while the wind speed carrying maximum energy can be used to estimate the wind turbine design or rated wind speed. Prior studies have shown that wind turbine system operates most efficiently at its rated wind speed. Therefore, it is required that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [16].

Considering Rayleigh distribution, wind energy density at Welenchity site is given by the expression:

$$E_D = \left({}^{3}\!/_{\prod}\right) \rho_a V_m^3 \qquad 3.11$$

Energy available at Welenchity wind power system site for the unit area of the rotor, over a time period, can be estimated using the expression:

$$E_t = TE_D = \left({}^{3}\!/_{\prod}\right) T \rho_a V_m^3 \qquad 3.12$$

The most frequent wind velocity at the Welenchity wind power system site V_{Fmax} is given by:

$$V_{FMax} = \sqrt[2]{\left({}^{2}\!/_{\prod}\right)}\, V_m \qquad 3.13$$

The velocity contributing maximum energy to Welenchity wind energy system is determined from:

$$V_{EMax} = 2 \times \sqrt[2]{\left({}^{2}\!/_{\prod}\right)}\, V_m \qquad 3.14$$

From the monthly average velocity given in table 3.2 the wind energy density, monthly energy availability, most frequent wind velocity and the velocity corresponding to the maximum energy Welenchity site wind energy are calculated by using the above Rayleigh approach for energy estimation formulas and shown in the table below.

Table 3.5: Wind Energy Potential Based on Rayleigh Analysis

Month	**V_m [m/s]**	**E_D [kW/m^2]**	**E_t [kW/m^2/month]**	**V_{Fmax} [m/s]**	**V_E [m/s]**
Jan	9.2	0.908	675.29	7.3	14.7
Feb	9.6	1.031	717.76	7.7	15.3
Mar	7.8	0.553	411.54	6.2	12.5
Apr	7.5	0.492	354.06	6.0	12.0
May	7.3	0.455	337.36	5.8	11.7
Jun	7.5	0.492	354.06	6.0	12.0
Jul	8.2	0.643	478.16	6.5	13.1
Aug	6.6	0.335	249.32	5.3	10.5
Sept	7.5	0.492	354.06	6.0	12.0
Oct	8.1	0.620	460.87	6.5	12.9
Nov	9.9	1.131	814.31	7.9	15.8
Dec	10.2	1.237	920.29	8.1	16.3

From this it can be concluded that there is potential wind energy from the site to supply parts of the demanded electric load.

3.2 Solar Energy Resources and Analysis

3.2.1 Solar Energy Resources

The sun is the largest energy source of life while at the same time it is the ultimate source of most of renewable energy sources. Solar energy can be used to generate electricity in a direct way with the use of photovoltaic modules. Photovoltaic is defined as the generation of electricity from light where the term photovoltaic is a compound word and comes from the Greek word for light, photo, with, volt, which is the unit of electromotive power.

Solar radiation provides a huge amount of energy to the earth. The total amount of energy, which is irradiated from the sun to the earth's surface, equals approximately 10,000 times the annual global energy consumption [Patel, 2006].

The light of the sun, which reaches the surface of the earth, consists mainly of two components: direct sunlight and indirect or diffuse sunlight, which is the light that has been scattered by dust and water particles in the atmosphere. Photovoltaic cells not only use the direct component of the light, but also produce electricity when the sky is cloudy.

3.2.2 Analysis of Photovoltaic (PV) Power for the Selected Site

To determine the PV electricity generation potential for a particular site, it is important to assess the average total solar radiation received over the year. Unfortunately in most developing countries there is no properly recorded radiation data. What usually available is sunshine duration data.

Ethiopia is one of the developing countries which have no properly recorded solar radiation data and, like many other countries, what is available is sunshine duration data. However, given a knowledge of the number of sunshine hours and local atmospheric conditions, sunshine duration data can be used to estimate monthly average solar radiation, with the help of empirical equation 3.15 [Duffie and Beckman, 2006].

$$H = \overline{H}_O\left(a + b\left(\frac{\overline{n}}{N}\right)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.15$$

where H is the monthly average daily radiation on a horizontal surface (MJ/m2), $\overline{H}_O$ is the monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m2), $\overline{n}$ is the monthly average daily number of hours of bright sunshine, N is the monthly average of the maximum possible daily hours of bright sunshine, a and b are regression coefficients Solar radiation, known as extraterrestrial radiation, $\overline{H}_O$, on a horizontal plane outside the atmosphere, is given by equation 3.2.

$$H_o = \frac{24 * 3600 * G_{sc}}{\pi}\left(1 + 0.033 * \cos\left(\frac{360 n_d}{365}\right)\right) * \left(cos\emptyset cos\delta sin\omega_s + \frac{\pi\omega_s}{180}\right) sin\emptyset sin\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.16$$

Where n_d is the day number, G_{sc} is the solar constant (1367 W/m^2), $\emptyset$ is the latitude of the location (°), δ is the declination angle (°),which is the angular position of the sun at solar noon, with respect to the plane of the equator and its value in degrees is given by Cooper's equation [11]:which is given as follows:

$$\delta = 23.45 \sin\left(248 + n_d\left[\frac{360}{365}\right]\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.17$$

The solar hour angle (ω_s) is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. The sunset hour angle s w is the solar hour angle corresponding to the time when the sun sets and it is given by:

$$\omega_s = \cos^{-1}(-tan\emptyset tan\delta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.3.18$$

The maximum possible sunshine duration N is given by

$$N = \frac{2}{15}\omega_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.19$$

Equations (4.1) and (4.5) are used to calculate the daily extraterrestrial radiation and the maximum possible daily hours of bright sunshine respectively at the specified location. The regression coefficients a and b for M number of data points can be calculated from the following equations (4.6) and (4.7) respectively [Getachew, 2009].

$$a = \frac{\sum\frac{\overline{H}}{\overline{H_o}}\sum((\frac{\overline{n}}{\overline{N}})^2) - \sum\frac{\overline{n}}{\overline{N}}\sum\frac{\overline{n}}{\overline{N}}\frac{\overline{H}}{\overline{H_o}}}{M\sum(\frac{\overline{n}}{\overline{N}})^2 - (\sum\frac{\overline{n}}{\overline{N}})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.20$$

$$b = \frac{M\sum\frac{\overline{n}}{\overline{N}}\frac{\overline{H}}{\overline{H}_o} - \sum\frac{\overline{n}}{\overline{N}}\sum\frac{\overline{H}}{\overline{H}_o}}{M\sum(\frac{\overline{n}}{\overline{N}})^2 - (\sum\frac{\overline{n}}{\overline{N}})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.21$$

Results estimated in this way are compared with the data which are obtained from sources such as NASA's surface solar energy data set or the SWERA global meteorological database. Drake and Mulugetta developed sets of constants a and b for various locations in Ethiopian [Drake and Mulugetta, 1996]. In this thesis, regression coefficients developed in their work was used.

3.2.3 Solar Data of the site used in HOMER

Sunshine hour data during a year are very important and essential for design and sizing of PV power systems. Solar radiation measurements in addition to temperature measurements are necessary to calculate the output power of the PV system. Solar radiation and temperature measurements shall be available on hourly basis to be used by the simulation program for the evaluation process. For Welenchity site the temperature measurements are not available, so due to their almost similar latitude, data from Adama can be used for simulation program to evaluate feasibility of the site. Accordingly, the daily average sunshine hour of Welenchity site from 2003-2005 will be shown in the following table:

Table 3.5: Monthly average of daily sunshine hour for Welenchity site (Adama) [2]

Month		Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
Average of daily sunshine hour per year	2003	10.4	9.6	9.7	8.4	8.9	7.7	6.5	6.9	5.5	6.7	7.8	8.6
	2004	7.9	7.4	7.7	8.7	10.1	7.8	7.2	7.6	7.9	8.8	9	6.2
	2005	7.8	6.5	8.6	8.7	7.2	7.6	6.1	8.8	7.5	9.5	9.4	10.4
	2006	9.5	8.9	7.5	7.6	9	7.9	6.5	5.9	7.4	7.3	9.9	8.6
	2007	9.2	8.7	9.2	8.3	8.8	7.6	7.6	6.4	6.5	6.3	9.3	10.6
Monthly average of daily sunshine hour		8.96	8.22	8.54	8.34	8.8	7.72	6.78	7.12	6.96	7.72	9.08	8.88

Table 3.6: Monthly average of daily solar radiation for Welenchity site (Adama) [2]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly average of daily sunshine hour	8.96	8.22	8.54	8.34	8.8	7.72	6.78	7.12	6.96	7.72	9.08	8.88
Daily Solar radiation @Lat = 8.468^O N and Lon = 39.159^O E	6.24	6.50	6.66	6.56	6.51	5.88	5.30	5.31	5.90	6.41	6.28	6.07

These figures which are the main inputs for the software are relatively high and very encouraging to use PV generators for electrification of certain loads as it has been worldwide successfully used.

CHAPTER FOUR

HYBRID SYSTEM COMPONENTS MODELING AND SIZING

The most frequent combination of renewable energy sources for electric power supply is wind and solar photovoltaic. The components and subsystems of a standalone power supply system based on renewable sources are interconnected to optimize the whole system. The design of a hybrid system will depend on the requirements of the load (isolated or not isolated, rural or urban, DC or AC) and on the power supply system.

Off-grid hybrid systems can also incorporate energy storage in batteries to increase duration of energy autonomy. If a permanent electric power supply is required, a backup diesel generator can be connected to the system to provide electric energy for peak loads which can't be covered by the hybrid system.

It is so important to determine the appropriate size of hybrid system components. The system shall not be oversized (expensive without increasing performance) or undersized (not capable to operate load).

4.1 Load Profile

Load profile study and determination are the first steps for the design of any electric power system. Nature of operation of loads and behavior of consumers are the parameters that determine the load profile. In Welenchity case, most of loads are lighting fixtures, radio/TV and work appliances (for welding, spraying, varnishing and machines, etc.). Natures of operation of these loads, ON and OFF between day and night which make the load profile as shown in **Table 4.1** and **Figure 4.1**, respectively. The hybrid system is designed to supply this daily load curve.

Table 4.1: Daily load profile of the site

Hour of operation	00:00 - 01:00	01:00 - 02:00	02:00 - 03:00	03:00 - 04:00	04:00 - 05:00	05:00 - 06:00	06:00 - 07:00	07:00 - 08:00	08:00 - 09:00	09:00 - 10:00	10:00 - 11:00	11:00 - 12:00
Load demanded (kW)	15.500	15.000	15.500	14.500	15.000	14.000	14.500	19.000	18.000	15.000	15.000	15.000
Hour of operation	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00	19:00 - 20:00	20:00 - 21:00	21:00 - 22:00	22:00 - 23:00	23:00 - 00:00
Load demanded (kW)	15.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	12.500	14.000

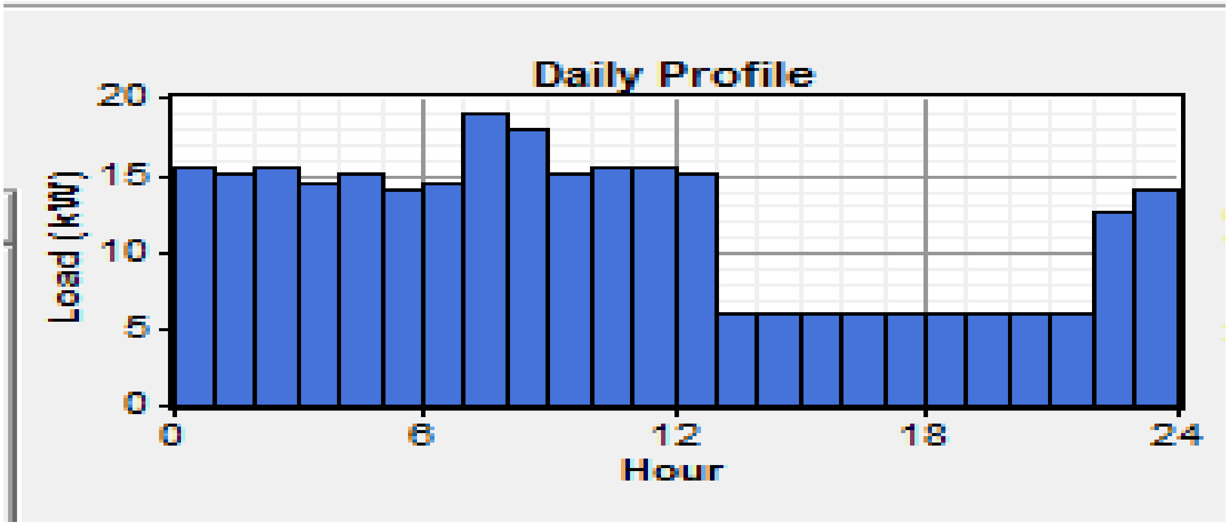

Figure 4.1: Daily load curve for the specified site

4.2 Wind Turbine Modeling and Sizing

The power output of a wind turbine is determined by its power curve and the instantaneous wind speed at the sight of installing this wind turbine. A mathematical model for the power curve of a wind turbine taking into account these parameters is as follows [19]:

$$P_W = \begin{cases} 0 & V < V_{ci} \\ a * v^3 - b * P_r & V_{ci} < V < V_r \quad and\ 0\ for\ V > V_{co} \\ P_r & V_r < V < V_{co} \end{cases} . 4.1$$

Where, P_W (in W/m2): is the output power density generated by a wind turbine,

$$a=\frac{P_r}{{V_r}^3-{V_{ci}}^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.2$$

$$b=\frac{{V_{ci}}^3}{{V_r}^3-{V_{co}}^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

and , P_r,V,V_{ci},V_r,V_{co},are rated power (w) , instantaneous , cut-in , rated and cut-out wind speeds in (m /s) respectively.

The real electrical power delivered is calculated as

$$P_{wout} = P_w * A_w * \eta_w \ldots\ldots\ldots\ldots\ldots\ldots 4.4)$$

where Aw is the total swept area of the wind turbine in $m^2$and η_w is the electrical efficiency of the wind generator and any other electrical components connected to the generator.

4.3 PV Panel Modeling and Sizing

The total peak power of the PV generator required to supply certain load depends on load, solar radiation, ambient temperature, power temperature coefficient, efficiencies of solar charger regulator and inverter and on the safety factor taken into account to compensate for losses and temperature effect. This total peak power is obtained as follows:

$$P(r - pv) = \frac{EL}{(\eta PVR * \eta V * PSH)} * S_F \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.5$$

Where E_L is the daily energy consumption in kWh, PSH is the peak sun hours (in Welenchity case PSH = 9.08) and as a figure it represents the yearly average of daily solar radiation intensity on horizontal surface in (kWh/m^2 / day),η_{PVR},η_V are efficiencies of solar charger regulator and inverter and S_F is the safety factor.

4.4 Battery Bank Modeling and Sizing

The output power from the wind turbine varies with wind speed variations through the day. Also the maximum power output of the PV generator varies according to variations in solar radiation and temperature. So the PV generator and the wind turbine may not be able to meet the load demands at all times. A battery between the DC bus of the hybrid system and the load will compensate and act as a power supply during these times.

Excess energy during times when the output power from the wind turbine and the PV generator exceed the load requirement is stored in the battery to supply load at times when the wind turbine and the PV generator are not able to supply load.

The two main types of batteries used in hybrid systems are nickel-cadmium and lead-acid. Nickel-cadmium batteries are restricted in use for few systems due to higher cost, lower energy efficiency and limited upper operating temperature. A lead-acid battery is still the most common type for the hybrid systems [20].

4.4.1 Lead acid battery construction and performance

A lead acid battery in its basic construction is made of more than one electrochemical cells interconnected in such a way to provide the required voltage and current. Lead acid battery is constructed of two electrodes, the positive one consists of lead dioxide $PbO2$ and the negative consists of pure lead. The empty space between the two electrodes is filled with diluted sulphuric acid. The voltage of the battery depends on cell temperature and the density of the acid solution, also its density changes with temperature and charge state. A battery with a 12V nominal voltage is constructed of 6*2V lead acid cells. The upper and lower limits of charging and discharging open circuit voltage at 25 C^o are 14.4V and 10.5V respectively [20].

The depth of discharge (DOD) is the state of charge of the battery. The relation between battery voltage and its depth of discharge is almost linear until a cut-off-voltage point is reached. Operating battery beyond this point will result in increasing the internal resistance of the battery and may result in damaging of it. A charge controller (regulator) is used to control operation of battery within its design limits so that not to exceed its cut-off point, also not to exceed overcharge limit.

A lead acid battery loses some of its capacity due to internal chemical reaction. This phenomenon is called self of discharge (SOD) of the battery and it increases with increasing in battery temperature. Providing batteries with lead grid or lead-calcium grid will minimize its SOD [20].

Long life-time, cycling stability rate and capability of standing very deep discharge are the main design points shall be taken into account when choose a battery for certain application.

4.4.2 Lead acid battery rating and model

Battery rating is commonly specified in terms of its Ampere-hour (Ah) or Watt-hour (Wh) capacity. The ampere-hour capacity of a battery is the quantity of discharge current available for a specified length of time at a certain temperature and discharge rate. High discharge current would result in reduction of the battery capacity and will decrease its life time.

The ampere-hour efficiency of a battery (η_{Ah}) is the ratio of amount of total Ampere-hours the battery provides during discharge to that required to charge it back to its original condition. The battery efficiency can be specified as Watt-hour efficiency (η_{wh}), its definition is in the same manner as $\eta_{Ah}*\eta_{wh}$ has values lower than η_{Ah} because the variation in voltage is taken into account [20].

When the power generated from the renewable system (wind and PV in the case under study) exceeds the load requirement, energy is stored in the battery. A minimum storage level is specified for a battery so that should not be exceeded it. This level is a function of battery DOD so that

$$Emin = \mathrm{E_{BN}} * (1 - DOD) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.6$$

where

E_{min} : minimum allowable capacity of the battery bank,

E_{BN}: is the nominal capacity of battery bank,

DOD: is the depth of discharge.

Energy stored in the battery at any time during charging mode can be expressed as [3]:

$$E_b(t) = E_b(t-1) * (1-\alpha) + \left[E_w(t) + E_{PV}(t) - \frac{E_L(t)}{\eta_v}\right] * \eta_{wh} \dots 4.7$$

Energy stored in the battery at any time during discharging mode can be expressed also as [3]:

$$E_b(t) = E_b(t-1) * (1-\alpha) - \left[\frac{E_L(t)}{\eta_v} \llbracket -(E \rrbracket_w(t) + E_{PV}(t))\right] \dots\dots 4.8$$

where

α : is hourly self discharge rate,

$E_{w(t)}$: is the energy from wind turbine during the time interval,

$E_{pv(t):}$ is the energy from PV system during the time interval,

E_L(t:)is the load requirement during the time interval

$E_b(t)$ and $E_b(t-1)$: are the charge capacity of battery bank at the time t and (t-1) respectively,

η_v and η_{wh} : are the efficiency of inverter and battery bank respectively as stated before.

4.4.3 Battery bank sizing

The two types of lead-acid batteries available at high capacities are the regular and the block types. The block type has long life time (>10 years), high cycling stability-rate (> 1000 times) and capability of standing very deep discharge, but has higher price than regular batteries [1].

The ampere-hour capacity (CAh) and watt-hour capacity (CWh) of a battery bank required to supply a load for a certain period (day) when an energy from renewable resources is not available can be specified as follows [1] :

$$C_{Wh} = \frac{E_L * AD}{\eta_v \ * \ \eta_{wh} * DOD} \dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.9$$

where AD: is the daily autonomy.

It is obvious from relation (4.9) that total capacity of the battery depends on daily autonomy which represents number of days that battery will be capable to supply the load in case of shortage of the renewable sources.

4.5 Diesel Generator Ratings and sizing

A back up Diesel generator can be connected to the hybrid system to provide electric energy for peak loads which can't be covered by this hybrid system if a permanent electric power supply is required or in case of incapability of the renewable sources to supply the load .

4.5.1 Diesel generator rating

Diesel generator is used in the system for following tasks: To supply load when the output power from wind and PV is not enough to operate this load, as well as to bring the SOC of batteries to an acceptable level. The Diesel generator rating shall be large enough to achieve these tasks. Optimal unit sizing of a Diesel generator requires careful consideration of several factors including detailed analysis of daily and seasonal load fluctuations, annual load growth, and incorporation of practical constraints for feasible and reliable Diesel operation. If Diesel units are only sized based on peak and/or average load values, on an annual base, with some safety margins and additional capacity for future expansion, the Diesel plant will generally be very oversized. The reason is that remote community loads are normally characterized as being highly variable, with the peak load as high as many times the average load.

Number of hours of operation depends on the size of wind turbine and PV system, size of Diesel generator and the climate conditions.

Type of Diesel generator - according to its number of poles - shall be selected considering the expected number of hours of operation per year. For applications require less than about 400 hours of operation per year, 2-pole generators are recommended since these generators have higher rpm. Otherwise 4-pole generators are selected [9].

4.5.2 Diesel generator sizing

The Diesel generator should be selected to cover the load so its ratings are determined according to load specifications. The optimum selection of the generator rating is such that the generator with other sources shall provide load with power it needs at all cases. A practical approach for large loads is to employ multiple units, e.g. a set of two or three Diesels, with various sizes and apply a Diesel cycling and dispatch strategy to optimize the loading of each unit to achieve maximum fuel efficiency.

4.6 Charge Controller (Regulator) Modeling and Sizing

Charge controller is an essential component in hybrid systems where a storage system is required. It protects battery against both excessive overcharge and deep discharge. Charge controller shall switch off the load when a certain state of discharge is reached, also shall switch off battery from the DC bus when it is fully charged. Charge controller can be adjusted to deal with different charge and discharge conditions. Charge controller act as interface between each of wind turbine and PV panel and the DC bus where the battery is connected. So charge controller is modeled by its efficiency where its output is

$$P_{WR} = P_{Wout} * \eta_{WR} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.4.10$$

And

$$P_{PVR}=P_{PV\,out}*\eta_{PVR}\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.4.11$$

where

P_{WR}: is the output power of the wind charge controller,

P_{Wout}: is the wind turbine output power,

H_{WR}: is the efficiency of the wind charge controller,

P_{PVR}: is the output power of the PV charge controller,

P_{pvout}: is the PV panel output power, and

η_{PVR}: is efficiency of the PV charge controller.

The charge controller ratings are chosen according to the battery voltage and the output power from each of wind turbine and PV panel.

4.7 Bidirectional Inverter Modeling and Sizing

A bidirectional inverter is essential in the hybrid system where a storage system and a backup Diesel generator are involved in the system. It can transfer power simultaneously in both directions. The inverter can supply DC and charge the batteries so it provides a path from the AC bus to the DC bus, in this case it acts as rectifier circuit which changes AC Diesel generator voltage to DC voltage. In the other way, it provides path from DC bus to the AC load so it acts as an inverter which changes DC voltage to AC voltage needed by the load.

Shape of the output waveform, power rating and efficiency are the parameters that shall be considered to choose a certain bi-directional inverter for certain application.

In a charger (rectifier) mode a bidirectional inverter can be modeled as follows:

$$P_{dicm} = P_{Gout} * \eta_{dicm} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . \dots\dots .. 4.12$$

where

P_{dicm}: is output power of bidirectional inverter in its charge mode,

P_{Gout}: is Diesel generator output power, and

η_{dicm}: is the efficiency of bidirectional inverter in its charge mode.

In this mode of operation (charger mode) the charger is characterized by its nominal AC voltage and voltage range, nominal DC output voltage that shall matched with DC bus voltage and it's charging current.

In an inverter mode a bidirectional inverter can be modeled as follows:

$$P_{invm} = P_{DCB} * \eta_{invm} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.13$$

where

P_{invm}: is output power of directional inverter in its inverter mode,

P_{DCB}: is the DC bus power

η_{invm}: is efficiency of bidirectional inverter in its inverter mode (usually equals the efficiency of bidirectional inverter in its rectifier mode (η_{dicm}) and thus called η_V.

In this mode of operation (inverter mode) an inverter is characterized by its nominal voltage and voltage range that shall be matched with the DC bus voltage, nominal output voltage and its output power that shall fulfill the load power.

The efficiency of converting the direct current to alternative current of most inverters today is 90% or more [Rivera, 2008]. Many inverters claim to have higher efficiencies but for this thesis the efficiency that was used is 90%.

CHAPTER FIVE

HYBRID SYSTEM SIMULATION SOFTWARE AND COMPONENTS

5.1 Simulation Software

A software program using HOMER was developed to simulate the hybrid system behavior. An hourly time step is used through this simulation. By using computer simulation, the optimum system configuration can be found by comparing the performances and energy production costs of different system configurations.

The Hybrid Optimization Model for Electric Renewable (HOMER), which is copyrighted by Midwest Research Institute (MRI) is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist the design of power systems and facilitate the comparison of power generation technologies across a wide range of applications [HOMER, ver. 2.68 Beta]. HOMER is used to model a power system physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life time. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

The design of a stand-alone PV-wind hybrid power supply system to a model ca cluster of MSEs, with average of daily demand of 281 kWh/day was carried out based on the theoretical background discussed so far. HOMER software is used as a tool to accomplish the research. As mentioned earlier, the main objective of the study is to design and model hybrid PV–Wind–diesel–battery based standalone power generation systems to meet the load requirements of the community specified earlier.

A schematic diagram of the standalone hybrid power supply system required is shown in figure 2.1 and its representation by HOMER is shown in figure 5.1. The power conditioning units are dc-dc and ac-dc converters, with the sole purpose of matching the PV, batteries and wind turbine voltages to that of the bus voltage at the dc bus. The ac load is of primary type and it is an electric demand that must be served according to a particular schedule, whereas deferrable load is electric demand that can be served at certain period of time, the exact timing is not important.

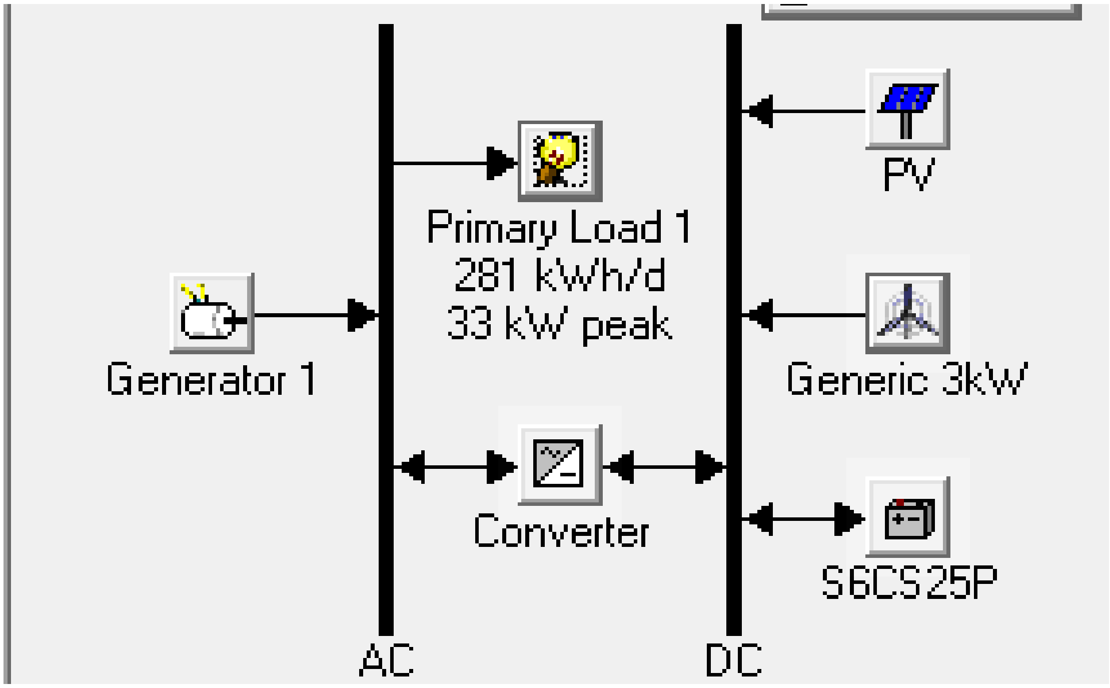

Figure 5.1: HOMER diagram for the hybrid system

HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis based on the raw input data given by user. In the simulation process, the performance of a particular power system configuration for each hour of the year is modeled to determine its technical feasibility and NPC. In the optimization process, many different system configurations are simulated in search of the one that satisfies the technical constraints at the lowest NPC. In the sensitivity analysis process, multiple optimizations are performed under a range of input assumptions to judge the effects of uncertainty or changes in the model inputs. Optimization determines the optimal value of the variables over which the system designer has control such as the mix of components that make up the system and the size or quantity of each. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price.

5.1.1 Simulation

The simulation process determines how a particular system configuration, a combination of system components of specific sizes, and an operating strategy that defines how those components work together, would behave in a given setting over a long period of time.

HOMER can simulate a wide variety of micro power system configurations, comprising any combination of a PV array, one or two wind turbines, a run-of-river hydro-turbine, and up to three generators, a battery bank, a dc-ac converter, an electrolyzer, and a hydrogen storage tank.

The system can be grid-connected or autonomous and can serve ac and dc electric loads and a thermal load.

Systems that contain a battery bank and one or more generators require a dispatch strategy, which is a set of rules governing how the system charges the battery bank. Dispatch strategy is thoroughly discussed in section 6.1.4.

The simulation process serves two purposes. First, it determines whether the system is feasible. The feasible system is one which can adequately serve the loads and satisfy any other constraints imposed by the user. Second, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The life-cycle cost is a convenient metric for comparing the economics of various system configurations.

A particular system configuration is modeled by performing an hourly time series simulation of its operation over one year. Simulation steps through the year one hour at a time, calculating the available renewable power, comparing it to the electric load, and deciding what to do with surplus renewable power in times of excess, or how best to generate additional power in times of deficit. When one year’s worth of calculations is completed, it is determined whether the system satisfies the constraints imposed by the user on such quantities as the fraction of the total electrical demand served, the proportion of power generated by renewable sources, or the emissions of certain pollutants, etc. The quantities required to calculate the system’s life-cycle cost, such as the annual fuel consumption, annual generator operating hours, expected battery life are also computed.

The quantity used to represent the life-cycle cost of the system is the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. The total net present cost includes the initial capital cost of the system components, the cost of any component replacements that occur within the project lifetime, the cost of maintenance and fuel.

5.1.2 Optimization

The simulation process models a particular system configuration, whereas the optimization process determines the best possible system configuration. The best possible, or optimal, system configuration is the one that satisfies the user-specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the dispatch strategy the system should use. In the optimization process, many different system configurations are simulated; the infeasible ones are discarded, the feasible ones are ranked according to total net present cost, and the feasible one is presented with the lowest total net present cost as the optimal system configuration.

The goal of the optimization process is to determine the optimal value of each decision variable that interests the modeler. A decision variable is a variable over which the system designer has control and for which multiple possible values can be considered in the optimization process. Possible decision variables include:

a) The size of the PV array
b) The number of wind turbines
c) The size of each generator
d) The number of batteries
e) The size of the dc-ac converter

Here optimization can help the modeler find the optimal system configuration out of many possibilities. Multiple values for each decision variable can be entered in search space, which is the table that contains the set of all possible system configurations over which HOMER can search for optimal system configuration. In the optimization process, every system configuration in the search space is simulated and the feasible ones are displayed in a table, sorted by total net present cost.

5.1.3 Sensitivity Analysis

In the sensitivity analysis process multiple optimizations are performed, each using a different set of input assumptions. A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs.

In a sensitivity analysis, a range of values for a single input variable are fed to HOMER. A variable for which the user has entered multiple values is called a sensitivity variable. Almost every numerical input variable that is not a decision variable can be a sensitivity variable. Examples include the PV module price, the fuel price, etc.

A sensitivity analysis can be performed with any number of sensitivity variables. Each combination of sensitivity variable values defines a distinct sensitivity case. A separate optimization process for each sensitivity case is performed and the results are presented in various tabular and graphic formats.

One of the primary uses of sensitivity analysis is in dealing with uncertainty. If a system designer is unsure of the value of a particular variable, he/she can enter several values covering the likely range and see how the results vary across that range. But sensitivity analysis has applications beyond coping with uncertainty. A system designer can use also sensitivity analysis to evaluate trade-offs between different options.

5.1.4 Hybrid System Modeling

In this section how HOMER models the physical operation of a system is provided in greater detail. A power system must comprise at least one source of electrical or thermal energy (such as a wind turbine, a diesel generator, or the grid), and at least one destination for that energy (electrical or thermal load). It may also comprise conversion devices such as a dc-ac converter or an electrolyzer, and energy storage devices such as a battery bank or a hydrogen storage tank.

The following subsections devoted to how to model the loads that the system must serve, the components of the system and their associated resources, and how that collection of components operates together to serve the loads.

5.1.4.1 Electric Loads

The electric loads are usually the largest single influence on the size and cost of hybrid system components. So, deciding on the loads is one of the most important steps in the design of the hybrid system.

The term loads 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 demand for heat.

Primary Load: Primary load is electrical demand that the power system must meet at a specific time. Electrical demand associated with lights, radio, TV, household appliances, computers, and industrial processes is typically modeled as primary load. If electrical demand exceeds supply, there is a deficit that is recorded as unmet load.

The user specifies an amount of primary load in kW for each hour of the year, either by importing a file containing hourly data or by allowing HOMER to synthesize hourly data from average daily load profiles. When synthesizing load data, HOMER creates hourly load values based on user-specified daily load profiles. Different profiles for different months and different profiles for weekdays and weekends are specified. A specified amount of randomness can be added to synthesize load data so that every day’s load pattern is unique. In this thesis 5% hourly and daily load noise is defined to account for variability of load demand.

Among the three types of loads, primary load receives special treatment in that it requires a user-specified amount of operating reserve [HOMER, ver. 2.68 Beta].

Deferrable Load: Deferrable load is electrical demand that can be met anytime within a certain time span, which exact timing is not important. Water pumping and battery-charging are examples of deferrable loads because the storage inherent to each of those loads allows some flexibility as to when the system can serve them. The ability to defer serving a load is often advantageous for systems comprising intermittent renewable power sources, because it reduces the need for precise control of the timing of power production. If the renewable power supply ever exceeds the primary load, the surplus can serve the deferrable load rather than going to waste.

For each month, the user specifies the average deferrable load, which is the rate at which energy drains out of the tank. The user also specifies the storage capacity in kWh (the size of the tank), and the maximum and minimum rate at which the power system can put energy into the tank.

According to Getachew, electric load in the rural villages of Ethiopia can be assumed to be composed of lighting, radio receiver and television set, water pumps, health post and primary schools load [Getachew, 2009]. Bimrew considered only lighting, radio and television as a community load [Bimrew, 2007]. As introduced earlier, the community understudy has a cluster of MSEs with an average 6 members per group.

In the calculation of the load or, in general, the design of hybrid system includes those components which are locally available without considering their efficiencies. This is done for both load and power generation sides. Each enterprise is assumed to use a power for night external lighting, radio receiver and light bulbs to be used between 18:00 to 23:00 in the evening.

5.1.4.2 Resources

The term resource applies to anything coming from outside the system that is used by the system to generate electric or thermal power. That includes the four renewable resources (solar, wind, hydro, and biomass) 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 on large-scale atmospheric circulation patterns and geographic influences, the hydro resource on local rainfall patterns and topography, and the biomass resource on local biological productivity. 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 and the fuel is described.

A. Solar Resource: To model a system containing a PV array, the solar resource data for the location of interest has been provided. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes Earth’s surface in a typical year. The data can be in one of three forms: hourly average global solar radiation on the horizontal surface (kW/m2), monthly average global solar radiation on the horizontal surface (kWh/m2.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.

HOMER generates synthetic hourly global solar radiation data from monthly solar resource data using the Graham algorithm [HOMER, ver. 2.68 Beta]. The inputs to this algorithm are the monthly average solar radiation values and the latitude. The output is an 8760-hour data set with statistical characteristics similar to those of real measured data sets.

B. Wind Resource: To model a system comprising one or more wind turbines, the wind resource data indicating the wind speeds the turbines would experience in a typical year has been provided. The user can provide measured hourly wind speed data if available. Otherwise,

HOMER can generate synthetic hourly data from 12 monthly average wind speeds and four additional statistical parameters: the Weibull shape factor, the autocorrelation factor, the diurnal pattern strength and the hour of peak wind speed.

The Weibull shape factor is a measure of the distribution of wind speeds over the year (see section 3.5). 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 [HOMER, ver. 2.68 Beta]. 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 [HOMER, ver. 2.68 Beta]. An average value of 0.85 is used here because the selected areas are of averagely uniform topography. The diurnal pattern strength is a measure of how strongly the wind speed tends to depend on the time of day [HOMER, ver. 2.68 Beta]. 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 [HOMER ver. 2.68 Beta]. This has also been observed in the available raw data for some of the months. In addition to this, the software has been run for different times between 14:00 and 18:00, the results have been checked against the measured data 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, is also defined.

5.1.4.3 Components /Equipments considered in HOMER Software

A component is any part of a power system that either generates, delivers, converts, or stores energy. HOMER models 10 types of components. Three of components generate electricity from intermittent renewable sources: photovoltaic modules, wind turbines, and hydro turbines. Another two types of components, generators and the grid are dispatchable energy sources, meaning that the system can control them as needed. Two types of components, converters and electrolyzers, convert electrical energy into another form. Converters convert electricity from ac to dc or from dc to ac. Electrolyzers convert surplus ac or dc electricity into hydrogen via the electrolysis of water. Other component a reformer generates hydrogen by reforming a hydrocarbon, typically natural gas. The system can store the hydrogen produced by electrolyzer and reformer and use it as fuel for one or more generators. Finally, two types of components store energy: batteries and hydrogen storage tanks.

Cost minimization is the primary criterion considered when selecting the components. . One of the main criteria for the selection of the wind turbine is the cost. The wind turbines have been selected from different sources; the various wind turbine websites

To describe the cost of the PV array, its initial capital cost in dollars, replacement cost in dollars, and operating and maintenance (O&M) cost in dollars per year has been specified. The replacement cost is the cost of replacing the PV array at the end of its useful lifetime, which is specified in years. By default, the replacement cost is equal to the capital cost, but the two can differ for several reasons. For example the user may want to account for a reduction over time in the purchase cost of a particular technology.

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

Each hour, the power output of the wind turbine is calculated in a four-step process. First, the average wind speed for the hour at the anemometer height is determined by referring to the wind resource data. Second, the corresponding wind speed at the turbine's hub height is calculated using either the logarithmic law or power law. Third, the power output of wind turbine is calculated at that wind speed referring to its power curve assuming standard air density. Fourth, that power output value is multiplied by the air density ratio, which is the ratio of the actual air density to the standard air density.

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

In case of wind turbine some of selection criteria used is: the type of current they generate (AC or DC), how low the cut-in wind speed is, how expensive the wind turbine is and for what application the wind turbine be used for. The cut-in wind speed is one of the main criteria, as the wind resource at the sites is not very high. As the turbine price would also affect the total net present cost, this has been checked with the respective vendors the type of current they generate, whether AC or DC, is also considered as this would have effect on the size of the inverter. A wind turbine that generates AC current has been chosen, as the load assumed for the households is of an AC type. As the aim of the research is to supply electric energy to remotely located communities, the wind turbines selected should be those which are applicable for home or off-grid use.

Based on the selection criteria mentioned above, different wind turbines have been tested by running the simulation several times. From those wind turbines which were candidates for this application, the Generic 3kw type has been found to be the best in terms of the cut-in wind speed and also in respect to other criteria mentioned earlier. This wind turbine was selected from those suggested by HOMER.

B. Generators: A generator consumes fuel to produce electricity, and possibly heat as a by-product. The generator module is flexible enough to model a wide variety of generators, including internal combustion engine generators, micro-turbines, fuel cells, etc.

The principal physical properties of the generator are its maximum and minimum electrical power output, its expected lifetime in operating hours, the type of fuel it consumes, and its fuel curve, which relates the quantity of fuel consumed to the electrical power produced.

C. Battery Bank: The battery bank is a collection of one or more individual batteries. A battery is a device capable of storing a certain amount of DC electricity at fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs replacement.

The key physical properties of the battery are its nominal voltage, capacity curve, lifetime curve, minimum state of charge, and round-trip efficiency. The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes.

Manufacturers determine each point on this curve by measuring the ampere-hours that can be discharged at a constant current out of a fully charged battery. Capacity typically decreases with increasing discharge current. The lifetime curve shows the number of discharge–charge cycles the battery can withstand versus the cycle depth. The number of cycles to failure typically decreases with increasing cycle depth. The minimum state of charge is the state of charge below which the battery must not be discharged to avoid permanent damage. The round-trip efficiency indicates the percentage of the energy going into the battery that can be drawn back out.

To calculate the battery's maximum allowable rate of charge or discharge, the kinetic battery model is used, which treats the battery as a two-tank system [HOMER, ver. 2.68 Beta].

Three parameters describe the battery: The maximum capacity of the battery which is the combined size of the available and bound tanks; the capacity ratio which is the ratio of the size of the available tank to the combined size of the two tanks and the rate constant which is analogous to the size of the pipe between the tanks. It is assumed that lifetime throughput is independent of cycle depth and estimate the life of the battery bank simply by monitoring the amount of energy cycling through it [HOMER, ver. 2.68 Beta].

D. Converter: A converter is a device that converts electric power from dc to ac in a process called inversion, and/or from ac to dc in a process called rectification. The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power. The rectifier capacity, which is the maximum amount of dc power that the device can produce by rectifying ac power, as a percentage of the inverter capacity has been specified.

The final physical properties of the converter are its inversion and rectification efficiencies, which are assumed to be constant. The economic properties of the converter are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years.

Additional information input into HOMER is summarized in Table 6.2. The values given in this table are primarily chosen according to the size of the load for the assumed hypothetical enterprises. The monthly average daily electrical energy consumption is given in Table 6.1. As mentioned previously the components are chosen by considering the local availability of the components without giving attention to their efficiencies.

The costs are estimated according to the current local and global price of the components. Other inputs into the software, such as the range of sizes for the PV, wind turbines and the converter and the number of batteries, are given so as to give flexibility to the software and optimize the output results.

Table 5.1: Inputs to the HOMER software

	PV	**Wind Turbine**	**Diesel Generator**	**Battery**	**Converter**
Size(kW)	12 kW	12 Generic 3kW	20kW	32 Surrette 6CS25P	20 kW
Capital($)	30000	72000	18000	28800	16000
O&M cost($/yr)	0	100	0.5	20	0
Size considered (kW)	1	1	1	1	1
Quantities considered	0,3,6,9,12	0,1,3,6,9,12	0,5,10,15,20,25	0,1,4,8,16,24,32	0,10,15,20
Life time	25yrs	25yrs	20000hrs	308646 hrs	15yrs

For the analysis, diesel is considered for the generator fuels with prices used are 1, 1.1, 1.2 and 1.3 US dollars per liter. The current diesel price considered is 1.1 USD per liter. Inverter and rectifier efficiencies are assumed as 90%. The project life time is 25 years, and the interest rate is assumed to be the present rate, 6%.

The software generates the results which are a list of feasible power supply system sorted according to their net present cost. Furthermore, sensitivity variables, such as the range of wind speeds, solar radiation, PV panel price, and diesel price are supplied, and then the software is tuned for optimum results.

5.2 Simulation Approach

The system simulation is performed by considering the system reliability as 100%, so no interruption is assumed during operation of the system.

The developed optimization software enables to change the variables of the hybrid system model in terms of sizing and operation. In such a way the life cycle cost of the hybrid systems respecting the demand requirements are minimized.

In this approach the renewable energy sources (wind & PV) plus the energy stored in the battery are used to cover the demand. The diesel generator is switched on as a back-up source when the battery is discharged to a certain level. For each hour step the simulation program compares the required energy demand and the supplied energy, and according to the difference a decision to operate the diesel generator or to charge the battery or discharge it will be taken.

The following cases will be considered with the illustrated priority while developing the simulation software:

Case1: Sufficient generated energy by renewable sources (wind & PV).The use of this energy to supply load has priority over using batteries or diesel generator. The extra energy is used to charge batteries, figure 6.1.

Case 2: As case 1 but surplus energy is generated by the system greater than the need to supply the load and the batteries. In this case the surplus energy is consumed by the dump load, figure 6.2.

Case 3: The generated energy by the renewable sources is not sufficient to supply the load. The priority here is to use the stored energy in the batteries in addition to the generated energy by the renewable sources rather than operating the diesel generator, figure 6.3.

Case 4: The generated energy by the renewable sources is not sufficient to cover the load demands and the battery is also discharged to its minimum value. In this case the diesel generator is switched on, and in addition to the generated energy by the renewable sources, it supplies the load and charge the batteries. The hybrid systems still in this mode of operation until the batteries are recharged to their full capacity, figure 6.4.

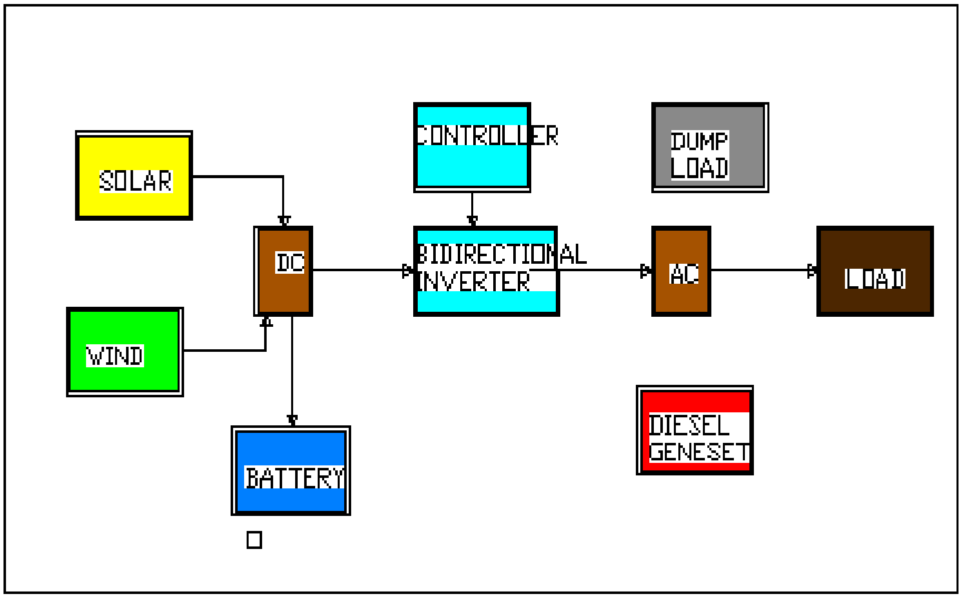

Figure 5.2: Sufficient energy to supply load & charge batteries case.

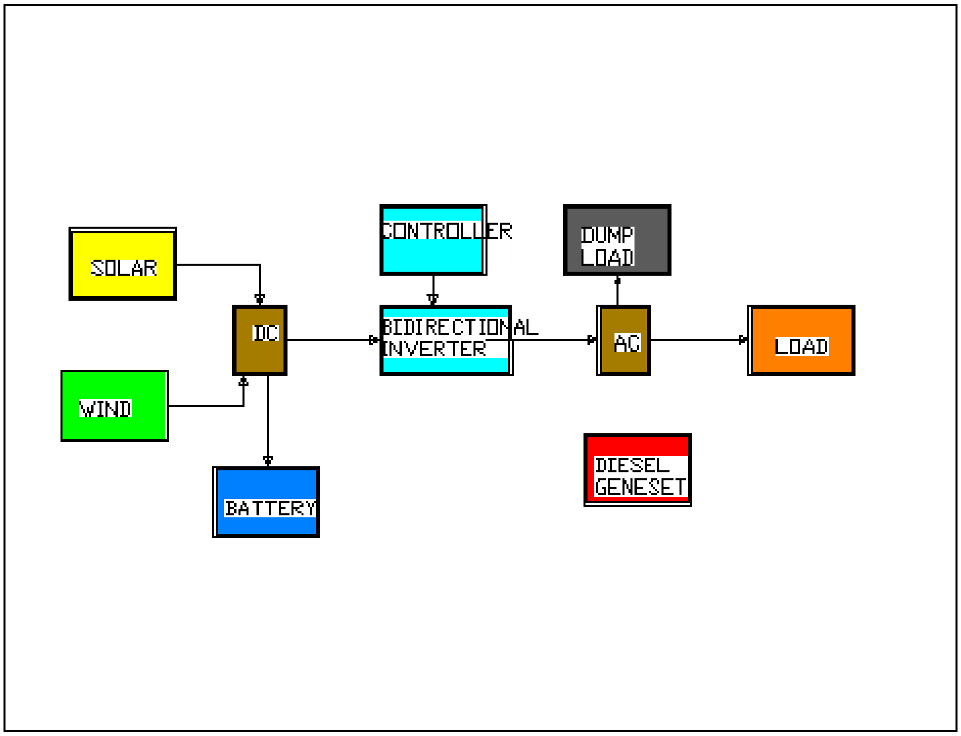

Figure 5.3: Sufficient energy to supply load & charge batteries but the extra energy is consumed by the dump load case

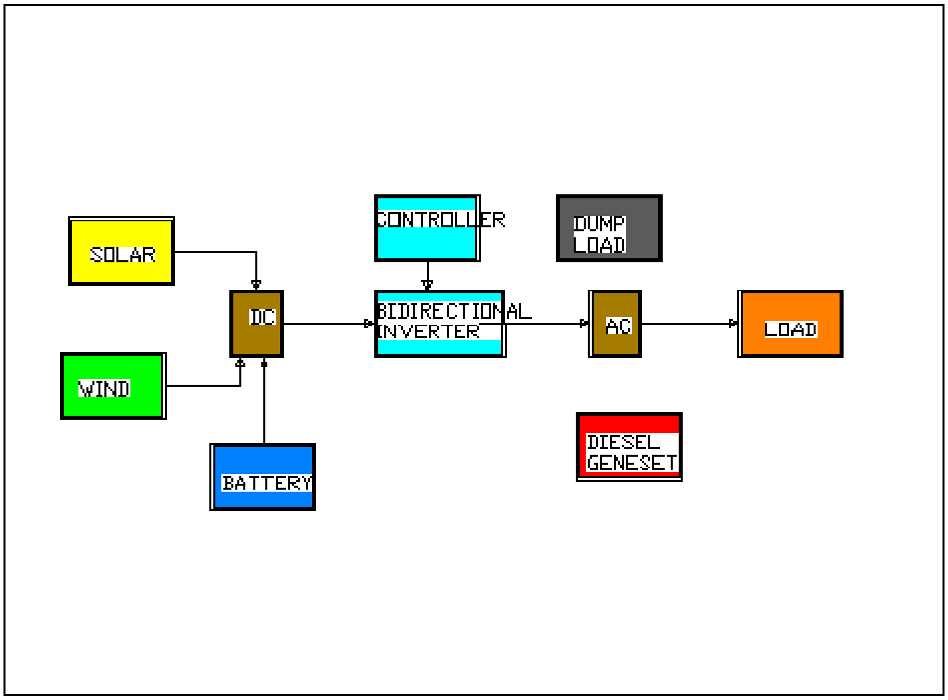

Figure 5.4: Not sufficient energy to supply load, batteries are also used to supply load case

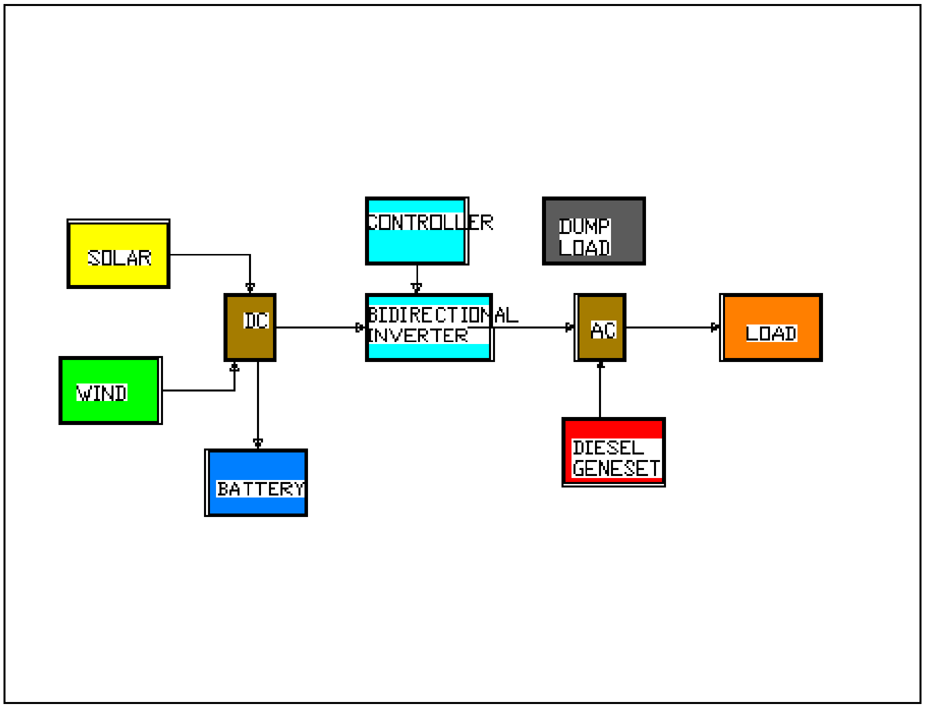

Figure 5.5: Not sufficient energy to supply load & charge batteries, diesel generator is switched on and do this case.

5.3 Software Inputs and Outputs

The input variables and parameters to the simulation program are: Load demand, measured solar radiation averaged on hour basis over a year, measured temperature averaged on hour basis over a year, measured wind speeds averaged on hour basis over a year, latitude of the location, tilt angle of the PV arrays, azimuth angle of the tilted PV arrays, ground reflection index, PV contribution, number of autonomy days, height at which wind measurements are performed, height of wind turbine tower, ground surface friction coefficient, rated power of wind turbine, cut-in, rated, and cut-off wind speeds of the wind turbine, component costs, and economical factors. The outputs from the simulation program are: PV generator rated power, battery storage capacity, yearly energy contributed by wind turbine, PV modules, and diesel generator, operating hours of diesel generator, diesel fuel consumption, dump energy, state of charge of battery, CO2 generated as a result of operation of diesel generator, cost of energy production, and net present value. In addition to numerical results, graphs of different variables can be obtained.

Wind speeds input to the program shall be corrected to take into account the height of the wind turbine tower. In addition to this, solar radiation input to the simulation program is measured on a horizontal plane and shall be corrected to take into account the tilted and azimuth angles of the tilted modules. Simulation program shall do that.

CHAPTER SIX

RESULTS AND DISCUSSION

In this chapter the results of the design of a PV-wind hybrid power generation system is presented, discussion about the findings will done and at the end decision for selecting the best scenario among the simulation results shall be made. The design of hybrid system, which supplies electricity to model for a cluster of MSEs, was introduced previously. As mentioned in the earlier sections in the design the system components that are locally available have been included without much concern to the efficiency. The results of the investigation will be presented in the following paragraphs.

6.1 Optimization results

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.

Similarly, the solar energy potential of the site was fed into HOMER and this is depicted in **Figure 5.2**. This figure also shows the clearness index, the ratio of the solar radiation striking Earth's surface to the solar radiation striking the top of the atmosphere, which HOMER generated from global solar radiation for the analysis. Typical values for the monthly average clearness index range from 0.25 (a very cloudy month) to 0.75 (a very sunny month).

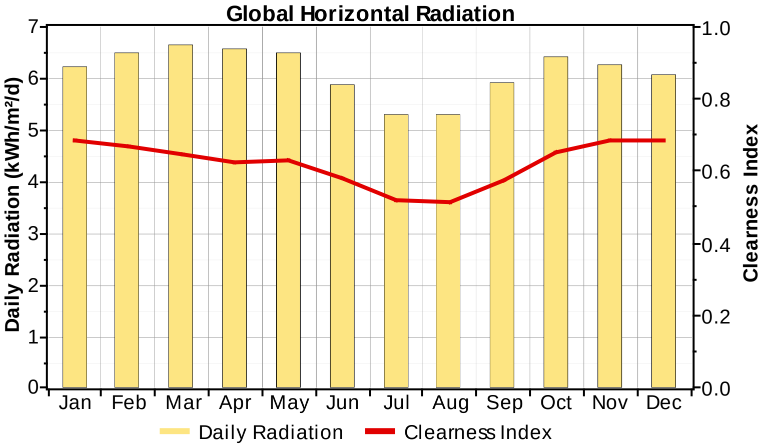

Figure 6.1: Monthly average solar resources

After entering the wind and solar resource data into software, to find the optimum solutions, HOMER is run repeatedly by varying parameters that have a controlling effect over the output.

The parameters that have controlling effect on output are given in table 4.2. In addition to those input parameters, multiple prices of diesel oil and PV modules have been used for sensitivity analysis. The output of the simulation is a list of feasible combinations of PV, wind-turbine, generator, converter, and battery hybrid system set-up. The optimization results are generated in either of two forms; an overall form in which the top-ranked system configurations are listed according to their net present cost (NPC) and in a categorized form where only the least-cost system configuration is considered for each system type. Table 6.1 shows a list of the possible combinations of system components in an overall form while table 6.3 represents optimization results in a categorized form. The tables are generated based on a particular set of inputs selected from the input summary table (table 4.2) and the solar and wind resource data for site.

The diesel price is 1.1$/L and the price of PV has been checked using different sources on the internet and the price ranged from $1.37 to $4.6 per watt [EcoBusinessLinks, 2011], [SolarBuzz, 2011], [Solar Panel Price, 2010]. The solar and wind data inputs are the results of investigation of solar and wind potentials of the site; the diesel price is the current price of diesel in the country and the price of PV is also the current price of PV panels in global market obtained from different websites.

The overall form table is too long to fit in this section, so it has been truncated and only a selected part is shown in table 6.1.

Table 6.1: Categorized optimization results

PV (kW)	G3	Label (kW)	S6CS25P	Converter (kW)	Initial capital (Birr)	Operating cost (Birr/yr)	Total NPC(Birr)	COE (Birr/kWh)	Renewable fraction	Capacity shortage	Diesel (L)	Label (hrs)
12	12	20	32	20	3027376	802199.5	13282245	10.14024	0.85	0.00	10,463	2,701
	12	20	32	20	2476276	943299.5	14534895	11.11385	0.80	0.01	12,716	3,179
12	12	20		20	2498320	1739676	24737171	18.9211	0.71	0.01	23,777	6,202
	12	20		15	1873740	1877157	25870122	19.80286	0.66	0.01	26,009	6,672
12		25	24	10	1508177	2637895	35229306	26.89368	0.17	0.00	37,024	7,493
		25	12	10	758681	2989387	38973020	29.7594	0.00	0.00	43,002	8,463
12		25		10	1111385	3008914	39575501	30.20028	0.16	0.00	42,040	8,669
		25			413325	3078187	39762857	30.36561	0.00	0.00	44,546	8,759

Exchange rate to convert USD to Eth Birr is (1USD=18.37Birr),

Source: commercial Bank of Ethiopia, Feb 10,2013

The following remarkable results can be noted from the table. The most cost effective system, i.e. the system with the lowest net present cost, is the one with PV-wind turbine-generator-battery converter set-up with the generator operating under a load following (LF) strategy (a dispatch strategy whereby the generator operates to produce just enough power to meet the primary load; lower-priority objectives, such as charging the battery bank or serving the primary load, is left to the renewable power sources). For this set-up, the total net present cost (NPC) is 13282244.8 Birr, the cost of energy (COE) is 10.14024/kwh, contribution from renewable resources is 85%, the amount of diesel oil used annually is 10,463 liters and the generator operates for 2701 hours per year.

In this set-up the part that renewable resources contribute to the supply system is quite significant, being 85%. Therefore this setup could be a good choice for implementation. Figure 6.2 shows the monthly average electrical production of this system. Table 6.2 gives some of the main information about the system and the corresponding sizes and quantities of each component shall be indicated accordingly.

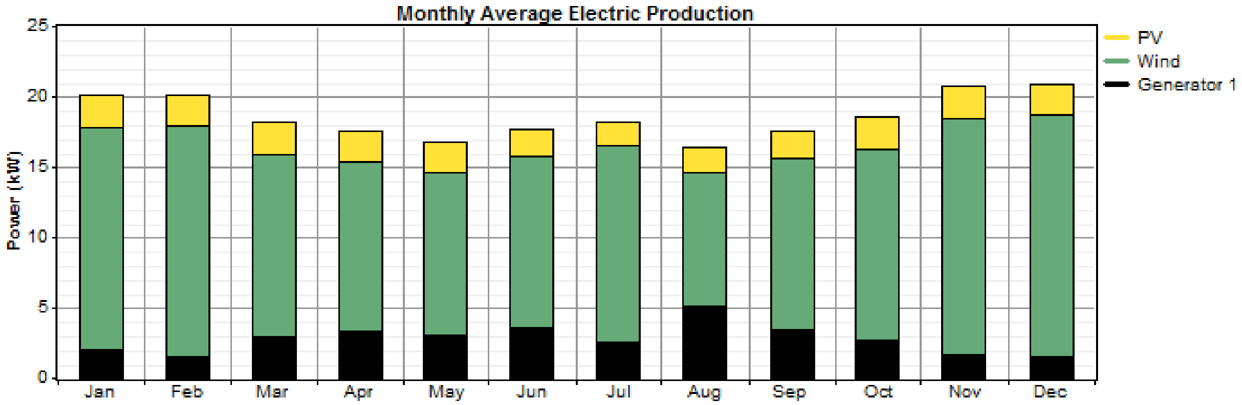

Figure 6.2: Monthly Average Electric Production of the selected hybrid system

Table 6:2 System report for the 91 % renewable resource contribution

System architecture		**Sensitivity case**		**Annual Electric Production(kwh/yr)**			**Annual Electric consumption (kWh/yr)**			**Emissions**	
PV Array	12 kW			PV Array	18,199	11%	AC primary load	101,804	100%	Carbon dioxide	27,553
Wind turbine	12 Generic 3kW			Wind turbine	119,775	74%	Coast summary			Carbon monoxide	68
Gen1	20 kW	Solar data-average	5.13	Gen1	24,566	15%	Total net present cost	13282244.8 Birr		Unburned hydrocarbons	7.53
Battery	32 Surrette 6CS25P	Wind data average	7.275	Total	162,540	100%	Levelized cost of energy	10.14024/kwh		Particulate matter	5.13
Converter	20 kW	Diesel	$1.1	Excess	46,233	kWh/yr	Operating	802199.53/yr		Sulfur dioxide	55.3

		price-		Electricity			Cost			
Inverter	20kw			Unmet load	135	kWh/yr			Nitrogen oxides	607
Rectifier	20kw			Capacity shortage	508	kWh/yr				
Dispatch strategy	Load Following			Renewable fraction	0.849					
Exchange rate to convert USD to Eth Birr is (1USD=18.37Birr), Source: commercial Bank Of Ethiopia, Feb 10,2013										

Table 6.3: Net Present Costs

Component	Capital (Birr)	Replacement (Birr)	O&M (Birr)	Fuel (Birr)	Salvage (Birr)	Total (Birr)
PV	551100	0	0	0	0	551100
Generic 3kW	1322640	0	281795.8	0	0	1604436
Generator 1	330660	444921.4	6342775	2702741.4	-48055.9	9773024
Surrette 6CS25P	529056	393595.6	150285	0	-112994	959942.7
Converter	293920	122638.1	0	0	-22833.9	393742.6
System	3027376	961155.1	6774856	2702741.4	-183884	13282245

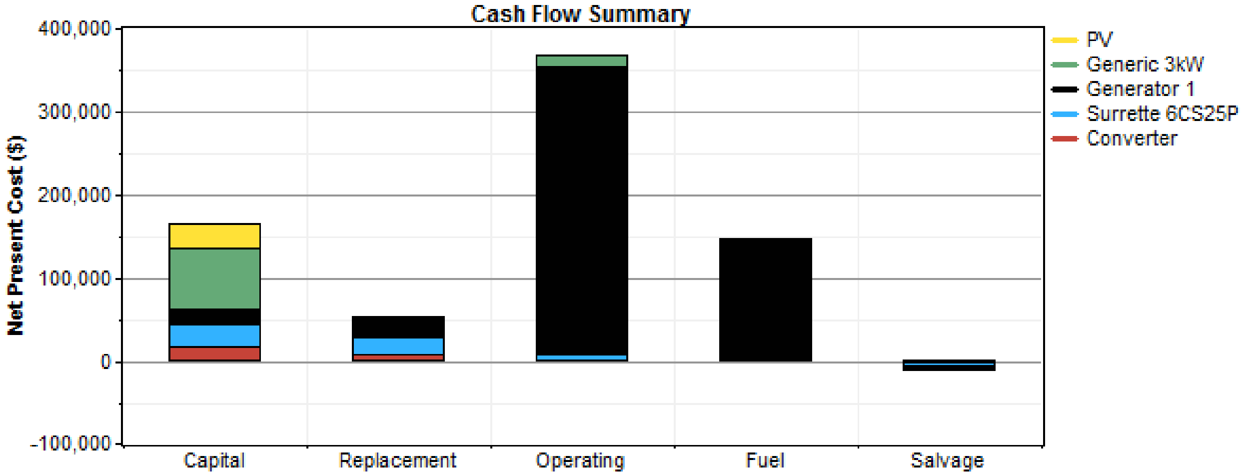

Figure 6.3: Cash flow summary of the selected hybrid system

The second most cost effective system which comprises Wind-Gen-Battery-Converter set-up is the system in the 2rd row. For this set-up the contribution made by renewable resources is 80 %, which is less than the earlier set-up by 5 %. Nonetheless, the NPC has increased to $ 791,230 and the COE to 0.605 $/kWh. This could also be a good choice if there is a motive for utilizing the available wind energy, which would, however, be at the cost of a 26.3 % increase in the total NPC. Once again the monthly average electric production for this set-up is shown in figure 21 and table 6.4 gives the most important information about this set-up.

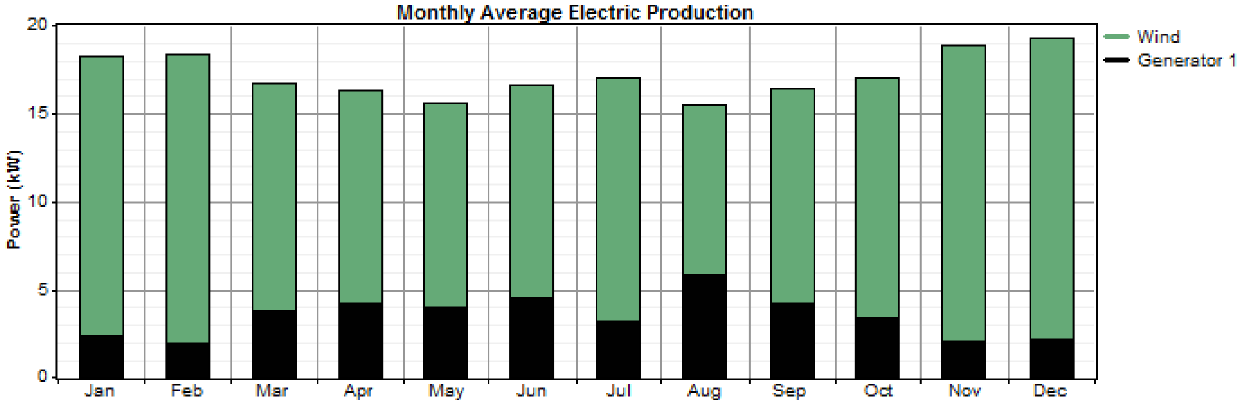

Figure 6.4: Monthly Average Electric Production of this setup

In general we can see in the list numerous feasible setups with different levels of penetration into the renewable resources; the selection, however, depends on whether the initial cost is the principal concern or the benefits gained from utilizing the renewable resources.

As in the previous case for optimum solution the model was run repeatedly using different types, sizes, capacities and numbers of wind turbines, PV panels, diesel generators, batteries and converters; etc. The sensitivity analysis has been also done by varying important parameters such as: diesel oil price and cost of PV panels.

6.2 Sensitivity Analysis

Sensitivity analysis was also carried out and for a fixed average wind speed of 8.24 m/s (measured at 10 meters) and average solar radiation of 6.13 kWh/m2/day an increase in diesel price will increase the Net present cost of the system. In the figure, the net present cost of the most cost-effective set-up for a particular set of diesel and PV prices is also included.

In the above figures it can be seen that the wind plays big role in supplying energy to the concerned enterprises. At this point, it must be known that this is not only due to more availability of wind potential than solar energy potential, but also it is because of wind turbine used. The wind turbine used in the design of the system is one with small cut-in wind speed, 2m/s, and also have small capital cost when compared to majority of turbines in the market. Let’s see effects of varying diesel prices as follows:

6.2.1 Net present cost sensitive to diesel price

The sensitivity of net present cost to different diesel price scenario is shown below in figure 6.4 and shows a considerable range of diesel price. The following table indicates simulation results for different cases:

Table 6.4: Comparison of net present cost, energy cost and green house gas emission diesel-only option with hybrid system

Components	Net present cost(Birr)	Cost of energy(Birr/kWh)	Diesel consumed per year(L)	CO2 emission per year
Diesel only	39762857	30.36561	44,546	117,304
Wind/PV/Diesel/Battery	13282245	10.14024	10,463	27,553
Wind/Diesel/Battery	14534895	11.11385	12,716	33,486
PV/Diesel/Battery	35229306	30.20028	42,040	110,706

From the above table we can plot a graph showing the effect of increasing diesel price on net present cost of each scenario:

Table 6.5: sensitivity of net present cost to diesel price

Diesel prices	Net present cost (Birr)	
	Diesel only	Hybrid system
$1.1	39762857	13282245
$1.2	40808937	13527944
$1.3	41854998	13773642

The corresponding figure representation will be shown below:

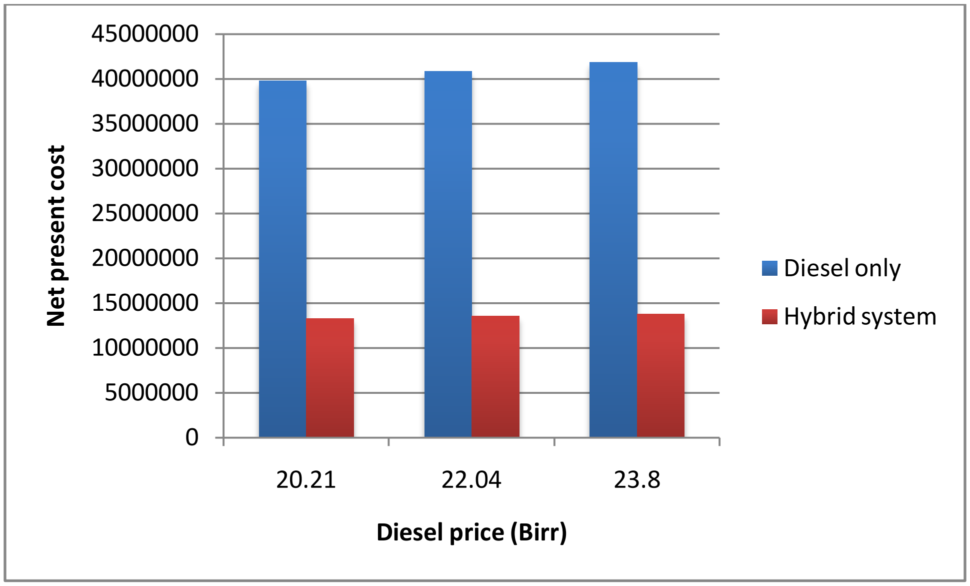

Figure 6.5: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different diesel price

From the graph above we can understand that the hybrid NPC is almost constant since the diesel price is not totally meaningful change on the system throughout project life time.

Though the optimum system configuration changes under different diesel price assumptions, the hybrid system remains most economically feasible solution than the existing arrangements (diesel-only), under all scenarios considered.

From sensitivity analysis, it is observed that for a diesel price of less than $1.1/L Wind/Generator/Battery/Converter systems is favorable while for diesel price higher than $1.1/L Wind/PV/Generator/Battery/Converter system is favorable .

Table 6.6: sensitivity of net present cost to solar radiation

Solar radiation ($kWh/m^2/d$)	**Net present cost(Birr)**	
	Diesel only	Hybrid system
4.5	39792855	13496715
5.13	39762857	13282245
6	39762857	13032578

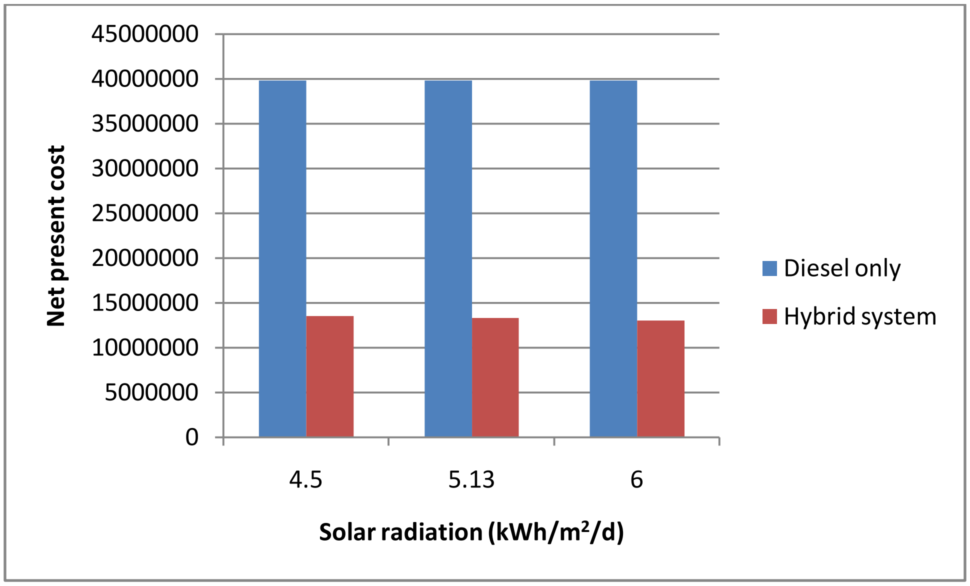

Figure 6.6: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different solar radiation.

Table 6.7: Sensitivity of net present cost to wind speed

Wind speed (m/s)	**Net present cost (Birr)**	
Wind Speed	Diesel only	Hybrid system
6	39762857	17157635
7.28	39762857	13282245
8	39762857	9008170

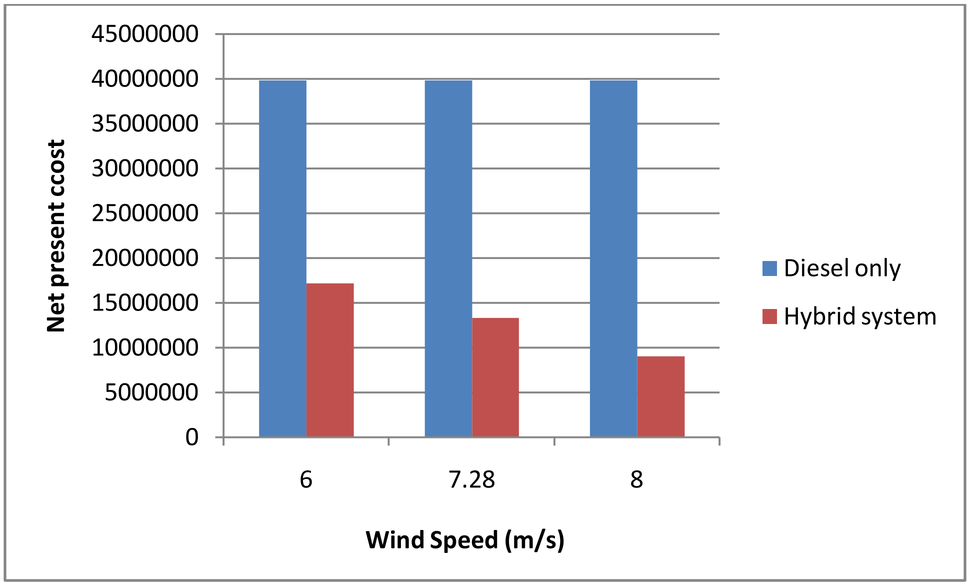

Figure 6.7: Net present cost (NPC) of optimized hybrid vs. diesel scenarios only under different wind speed

From the **Figure 6.6** and **Figure 6.7** above we can understand that as the wind speed and solar radiation increases the net present cost of the hybrid system will become decreases.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

A hybrid power generation system which comprises of PV arrays, wind turbines and diesel generator with battery banks and power conditioning units has been discussed in this thesis to achieve a cost effective system configuration which is supposed to supply electricity to model MSEs working on wood and metal products where electricity from the main grid has not reached yet. Before the design of the hybrid system was started, the wind energy and solar energy potentials of the area under study had been studied. Then, based on these potentials, a design of a standalone electric power supply system for a model community has been conducted.

The study of the renewable potentials of the site is based on the recently recorded data (2003-2008) obtained from the Ethiopian Meteorological Agency.

Regarding solar energy potential there is no accurately recorded solar radiation database in the country, instead only sunshine hour data was available. Therefore, empirical formulas which are able to incorporate the available sunshine hour data and provide the required solar radiation data were used to determine the potential of the site. The results obtained from empirical formulas were also cross-checked against satellite data obtained from other sources such as NASA and SWERA [NASA, 2010], [SWERA, 2011]. The analysis of the renewable energy resources data has been carried out by HOMER software. From the results, the wind energy potential of the site is found to be considerable, although it may not be sufficient for a large independent wind farm; it is viable option if incorporated into other energy conversion systems such as PV, diesel generator and battery. The results also confirmed the availability of huge utilizable wind energy at the site.

The results obtained from the software give numerous alternatives of feasible hybrid systems with different levels of renewable resources penetration which their choice is restricted by changing the net present cost of each set up. The COE of the feasible setups in this study is high compared to the current global electricity tariff and the tariff in the country. However, considering the shortage of electricity in the country (<20% coverage) and absence of electricity usage in rural areas (<2% coverage), this cost should not be taken as a decisive factor. At current costs, central grid power is the least expensive option but will not be available to most rural households.

A wind-solar cell hybrid energy system would be cost effective if there is reduction in component cost by installation of many of this hybrid system in a farm thereby lowering the investment cost per kilowatts. Its availability, sustainability and environmental friendliness make it a desirable source of energy supply.

The model developed is fairly general and may be adequate for preliminary results for energy consumption cost for household and industrial sector willing to adopt renewable energy sources.

Instead other issues such as the role of a standalone hybrid system in protecting the environment from degradation, the improvement of life of people living in rural area, development of clean energy, the future situation regarding fossil fuel sources, and its contribution to the reduction of pollutant emissions into the environment should be taken in to account. Taking these issues into account the free solar and wind energy of the country should be utilized to improve the quality of life of the MSEs living in rural areas.

Based on the simulation program results previously presented, the following conclusions can be demonstrated:

AS a result of analyzing wind, PV, diesel with a storage battery bank hybrid system to supply a load, a combination of them with wind as a main source, with limited operation of diesel generator (2,701 hour/year) forms the optimum case with a COE equals to 10.14024 Birr/kWh.

- Using wind as a standalone system to supply load is not economical or practical choice because of low availability of wind during different times in a year (months from September to December have low average wind speeds). Higher rating is required for the wind turbine required to supply a load with a certain power, also higher battery capacity (higher autonomy days) are required to supply this load.

- Using PV as a standalone system to supply the load isn't also economical or practical one. Different times through a year have low solar isolation especially during winter months (Months December, January, and February).
- Using diesel generator only to supply the load requires many units to supply this load, more fuel, so more CO2 is produced, also more maintenance and operational costs is needed. The COE is high; it is 30.36561 Birr/kWh. Amount of CO2 produced is about 117,304/year, it is too high compared with the hybrid (27,553/yr).

- A wind-solar cell hybrid energy system would be cost effective if there is reduction in component cost by installation of many of this hybrid system in a farm thereby lowering the investment cost per kilowatts. Its availability, sustainability and environmental friendliness make it a desirable source of energy supply.
- Though the optimum system configuration changes under different diesel price assumptions, the hybrid system remains most economically feasible solution than the existing arrangements (diesel-only), under all scenarios considered.
- The model developed is fairly general and may be adequate for preliminary results for energy consumption cost for MSEs willing to adopt renewable energy sources. Therefore the most economical scenario is using wind-PV –Diesel Generator-Battery hybrid system as stated before.

7.2 Recommendations

The following recommendations are made out of this research; some of them are directed to the researchers while the others are directed to decision makers.

- Ethiopia has a huge potential of renewable energy resources which can be used for rural electrification through the off-grid system. There are, however, many challenges like low purchasing power of the rural community, unfavorable conditions towards the utilization of renewable energies, absence of awareness how to use these resources, etc.

Thus, the author of this work recommends that the government, non-governmental organizations and the private sectors should make combined efforts to overcome these challenges by using more flexible approaches to improve the current poor status of rural electrification in Ethiopia.

- The implementation for this hybrid system as a pilot system in country can be done if a subsidy is available for this project, this will make it possible for more research, study and analysis.
- As far as the environmental aspects are concerned, this kind of hybrid systems have to be wide spread in order to cover the energy demands of rural MSEs, and in that way to help reduce the green house gases and the pollution of the environment. This is an important point to be taken into consideration
- Similar solar and wind energy potentials assessment can be conducted for other sites in the country (as Adama).

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APPENDIXES

Appendix A: Friction Coefficient α of Various Terrains [Patel, 2006]

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

Appendix B: Various value of shape factor:

Types of wind	Shape factor
Inland winds	1.5 to 2.5
Coastal winds	2.5 to 3.5
Trade winds	3 to 4

Appendix C: Adama wind speed at different height (m/s)

Month	2 meters (2003 - 2007)	10 meters (2006-2008)	40 meters (2007)	Power generated at 10 m (kWh)
January	2.4	9.2	10.5	351.0
February	2.5	9.6	9.5	435.2

March	2.0	7.8	10.8	300.4
April	2.0	7.5	7.0	271.1
May	1.9	7.3	7.7	178.6
June	2.0	7.5	7.8	216.2
July	2.2	8.2	7.1	290.4
August	1.7	6.6	6.0	257.3
September	2.0	7.5	7.9	216.7
October	2.1	8.1	10.4	296.1
November	2.6	9.9	11.1	309.9
December	2.7	10.2	11.0	393.8
Average	2.2	8.3	8.9	293

Appendix D: System Report - HOMER

Sensitivity case

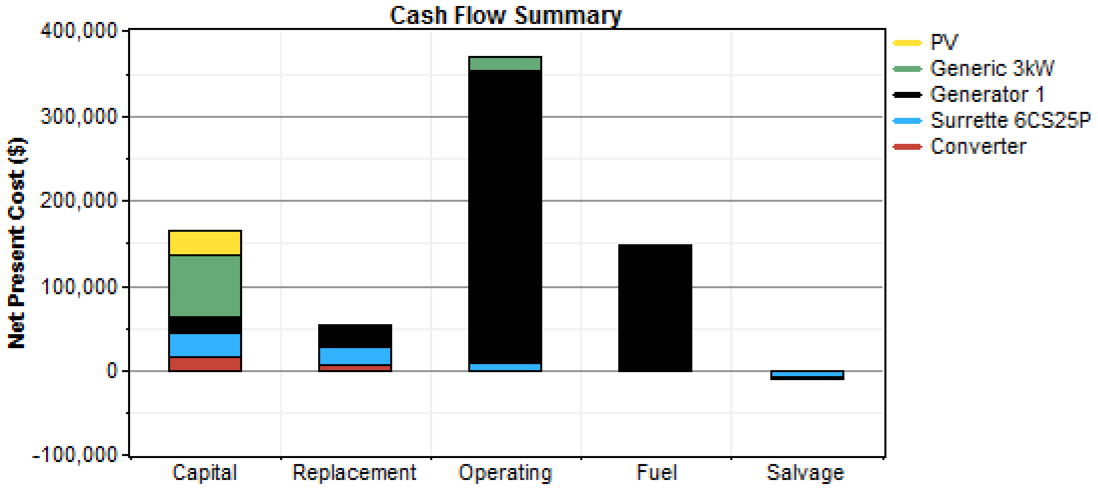
Solar Data Scaled Average:	5.13	kWh/m²/d
Wind Data Scaled Average:	7.28	m/s
Diesel Price:	1.1(18.37)	$(birr)/L

System architecture

PV Array	12 kW
Wind turbine	12 Generic 3kW
Generator 1	20 kW
Battery	32 Surrette 6CS25P
Inverter	20 kW
Rectifier	20 kW
Dispatch strategy	Load Following

Cost summary

Total net present cost	$ 723,040 (13282245 birr)
Levelized cost of energy	$ 0.552 (10.14024birr) /kWh
Operating cost	$ 43,669 (802199.5 birr)/yr

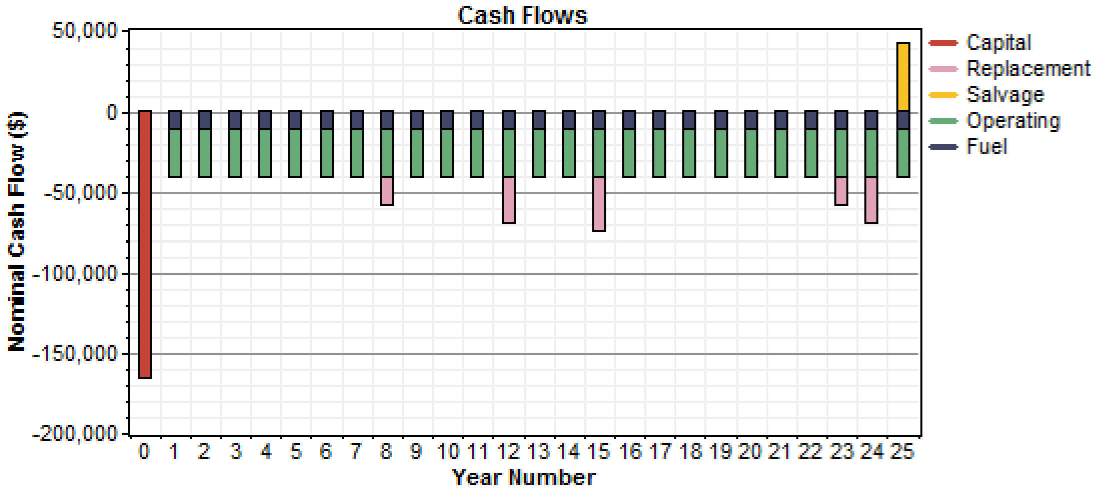


Net Present Costs

Component	Capital (Birr)	Replacement (Birr)	O&M (Birr)	Fuel (Birr)	Salvage (Birr)	Total (Birr)
PV	551100	0	0	0	0	551100
Generic 3kW	1322640	0	281795.8	0	0	1604436
Generator 1	330660	444921.4	6342775	2702741.4	-48055.9	9773024
Surrette 6CS25P	529056	393595.6	150285	0	-112994	959942.7
Converter	293920	122638.1	0	0	-22833.9	393742.6
System	3027376	961155.1	6774856	2702741.4	-183884	13282245

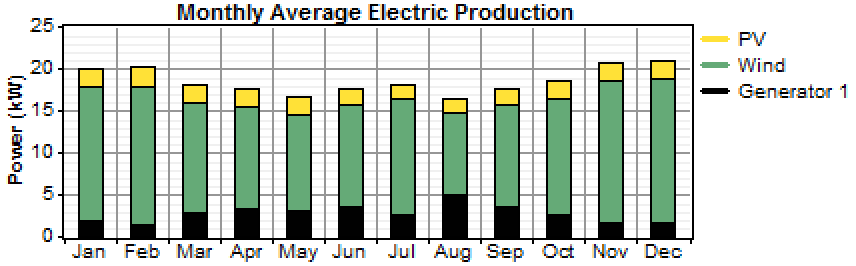
Annualized Costs

Component	**Capital** (Birr/yr)	**Replacement** ($Birr/yr)	**O&M** (Birr/yr)	**Fuel** (Birr/yr)	**Salvage** (Birr/yr)	**Total** (Birr/yr)
PV	0	0	0	0	0	43114.39
Generic 3kW	1010.35	0	22044	0	0	125503.8
Generator 1	25864.96	34811.15	496173.7	211420.3	-3765.85	764504.3
Surrette 6CS25P	41387.61	30788.12	11756.8	0	-8835.97	75096.56
Converter	22999.24	9589.14	0	0	-1781.89	30806.49
System	236826.04	75188.41	529974.5	211420.3	-14383.7	1039026



Electrical

Component	Production (kWh/yr)	Fraction
PV array	18,199	11%
Wind turbines	119,775	74%
Generator 1	24,566	15%
Total	162,540	100%



Load	Consumption (kWh/yr)	Fraction
AC primary load	102,429	100%
Total	102,429	100%

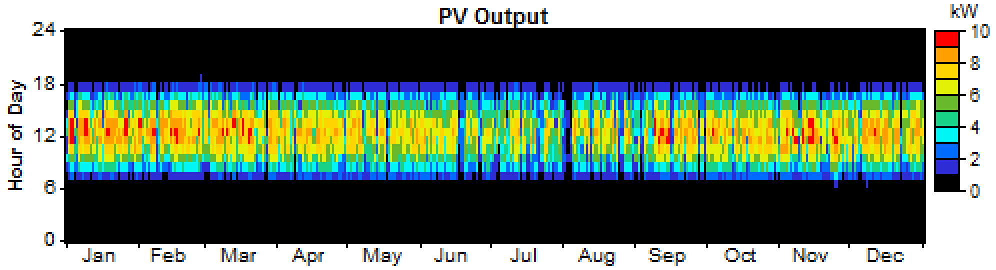
Quantity	Value	Units
Excess electricity	46,233	kWh/yr
Unmet load	135	kWh/yr
Capacity shortage	508	kWh/yr
Renewable fraction	0.849	

PV

Quantity	Value	Units
Rated capacity	12.0	kW
Mean output	2.08	kW
Mean output	49.9	kWh/d
Capacity factor	17.3	%

Total production	18,199	kWh/yr

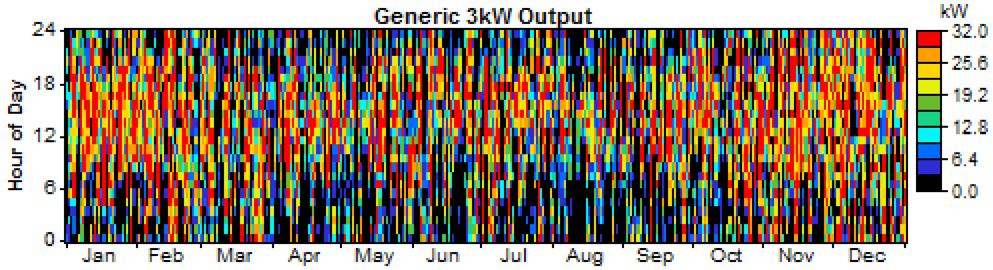
Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	9.62	kW
PV penetration	17.7	%
Hours of operation	4,456	hr/yr
Levelized cost	0.129(2.36973)	$(birr)/kWh



DC Wind Turbine: Generic 3kW

Variable	Value	Units
Total rated capacity	36.0	kW
Mean output	13.7	kW
Capacity factor	38.0	%
Total production	119,775	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	31.2	kW
Wind penetration	117	%
Hours of operation	7,998	hr/yr
Levelized cost	0.0570	$/kWh



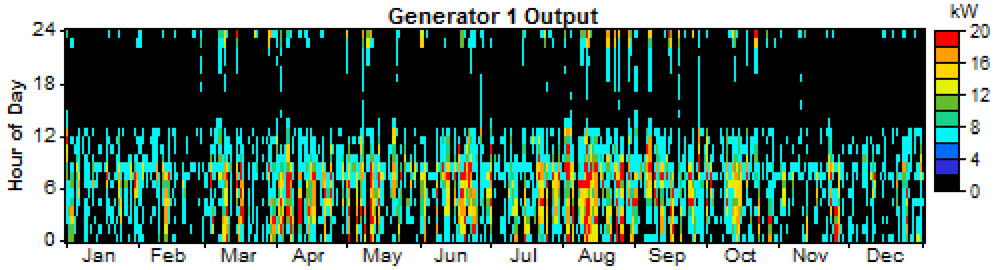
Generator 1

Quantity	Value	Units
Hours of operation	2,701	hr/yr
Number of starts	683	starts/yr
Operational life	7.40	yr
Capacity factor	14.0	%
Fixed generation cost	12.7	$/hr
Marginal generation cost	0.275	$/kWhyr

Quantity	Value	Units

Electrical production	24,566	kWh/yr
Mean electrical output	9.10	kW
Min. electrical output	6.00	kW
Max. electrical output	20.0	kW

Quantity	**Value**	**Units**
Fuel consumption	10,463	L/yr
Specific fuel consumption	0.426	L/kWh
Fuel energy input	102,956	kWh/yr
Mean electrical efficiency	23.9	%

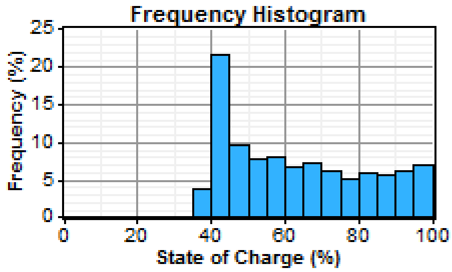


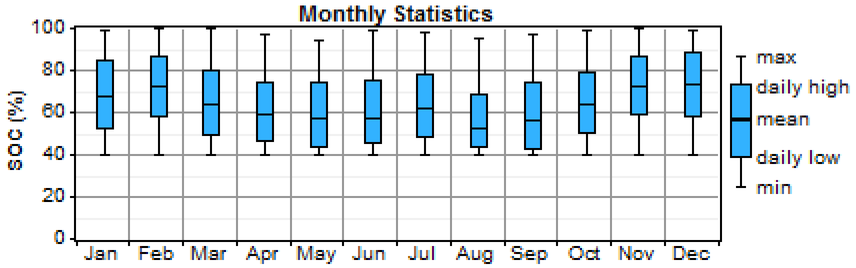
Battery

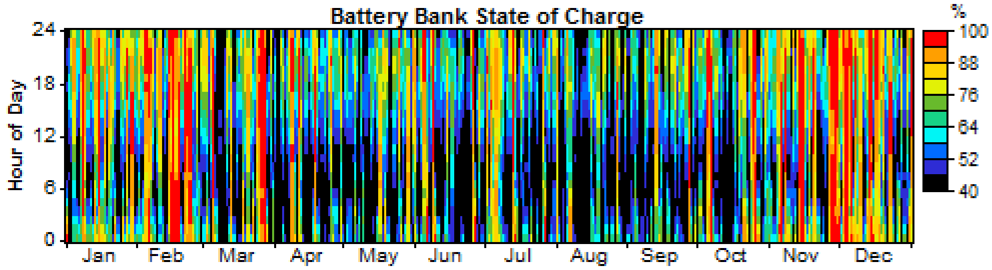
Quantity	**Value**
String size	1
Strings in parallel	32
Batteries	32
Bus voltage (V)	6

Quantity	**Value**	**Units**
Nominal capacity	222	kWh
Usable nominal capacity	133	kWh
Autonomy	11.4	hr
Lifetime throughput	308,646	kWh
Battery wear cost	0.104(1.91048)	$(birr)/kWh
Average energy cost	0.000	$(birr)/kWh

Quantity	**Value**	**Units**
Energy in	26,151	kWh/yr
Energy out	20,938	kWh/yr
Storage depletion	18.2	kWh/yr
Losses	5,195	kWh/yr
Annual throughput	23,409	kWh/yr
Expected life	12.0	yr



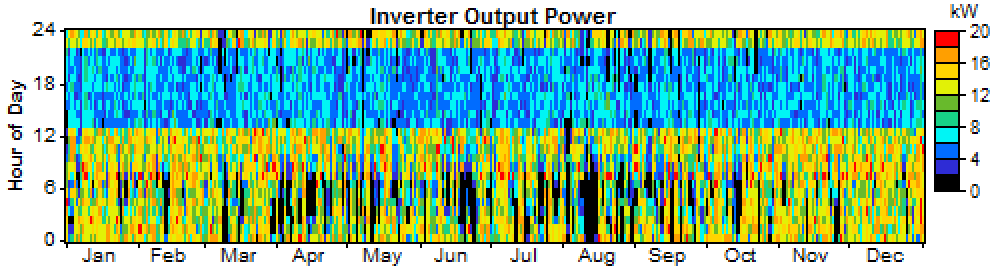


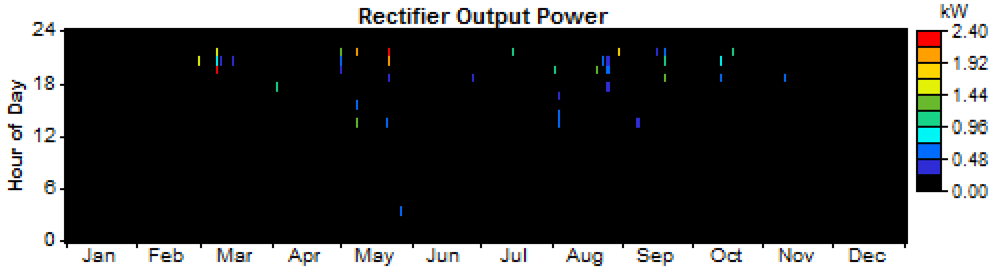


Converter

Quantity	Inverter	Rectifier	Units
Capacity	20.0	20.0	kW
Mean output	8.9	0.0	kW
Minimum output	0.0	0.0	kW
Maximum output	20.0	2.3	kW
Capacity factor	44.5	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	8,575	45	hrs/yr
Energy in	86,566	43	kWh/yr
Energy out	77,910	36	kWh/yr
Losses	8,656	6	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	27,553
Carbon monoxide	68
Unburned hydocarbons	7.53
Particulate matter	5.13
Sulfur dioxide	55.3
Nitrogen oxides	607