JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING

SUSTAINABLE ENERGY ENGINEERING STREAM

TECHNO ECONOMIC ASSESSMENT OF SOLAR PV/WIND / DIESEL GENERATOR HYBRID OFF-GRID POWER SYSTEMS FOR RURAL COMMUNITY

(A CASE STUDY: META ROBI DISTRICT)

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF JIMMA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS OF SCIENCE IN SUSTAINABLE ENERGY ENGINEERING

BY

ROBERA DABA BEDEDA

April, 2018
Jimma, Ethiopia

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BY

ROBERA DABA BEDEDA

ADVISOR: PROF. DR.A.VENKATA RAMAYYA

CO-ADVISOR: DABALA GENATI (MSC)

April, 2018
Jimma, Ethiopia

DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "Techno-economic assessment of solar PV/wind and diesel generator hybrid off-grid power systems for rural community", a case study of Meta Robi district is my original work, has not been presented for a degree in other universities and all the resource of materials used for the thesis have been duly acknowledged.

Robera Daba (Candidate)

Signature________________ Date_______________

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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Co-Advisor: Dabala Genati (Msc)

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Internal Examiner: Nebiyou Bogale (Assistant professor)

Signature________________ Date_______________

EXECUTIVE SUMMARY

Electrification to rural areas, those with no electric access or detached from national grid, is one of the most challenging issues in developing countries like Ethiopia. Due to the recent concerns about the global climatic change and diminishing fuel prices, searching for reliable, environmental friendly and renewable energy sources to satisfy the rising electrical energy demand has become vital.

The main objective of this study was to obtain an optimal suited configuration of hybrid electricity generation system using various renewables/alternative energy sources to meet the village load requirement reliably, economically, continuously and sustainably. The solar potential and wind speed were taken from NASA, the cost of associated hybrid components are collected from different sources and the electric load data was estimated for community and public service's needs. Hybrid Optimization Model for Electric Renewable (HOMER) was used to perform techno-economic analysis to meet the load requirement using solar PV-wind turbine-diesel generator-battery hybrid off-grid configuration. Based on the resources, load, hybrid system and the component cost input data considered and running the simulation HOMER gives optimization, sensitivity and grid comparison results.

The optimization result of the simulation demonstrates that the hybrid configuration (solar PV-wind turbine-diesel generator-battery) that achieves total NPC of $1,506,689 and COE of 0.360$/kWh at a renewable fraction of 0.6 as the best optimal hybrid configuration considering economic and environmental point of view. From environmental stand point of view, the system is characterized with a minimum percentage of carbon dioxide and other GHG emission of about 195,974 kg/year.

The sensitivity analysis examines the consistency of the optimal system under different sensitivity inputs such as load, wind speed, diesel price and PVcapital cost multiplier and it reveals that the multiple hybrid systems (PV-wind-generator-battery) system is more favorable. The grid comparison reveals that hybrid off-grid power generating systems is feasible for electrification of rural community beyond the 3.66 km breakeven grid extension distance.

The selected hybrid configuration system is an excellent solution to guarantee a reliable and affordable electric power supply without interruption of the load for the village of Deleta when compared with grid extension under certain conditions of the high capital cost of grid-extension, sparsely populated and low energy demand of the rural community.

Key words**: **Breakeven grid extension distance**. **Cost of energy, Electrification, Greenhouse gas emission, HOMER and Hybrid configuration

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First of all, I would like to praise and give thanks to the Almighty God who gave me wisdom and strength from the inception until completion of this thesis.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

BGD	Breakeven Grid Extension Distance
CDM	Clean Development Mechanism
CRGE	Climate Resilient Green Economy
COE	Cost of Energy
EEPCo	Ethiopian Electric Power Corporation
EPA	Environment Protection Authority
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GHG	Greenhouse Gas Emission
GoE	Government of Ethiopia
GTP	Gross and Transformation Plan
HID	Human Development Index
HOMER	Hybrid Optimization Model for Electrical Renewable
IPP	Independent Power Producer
LCC	Life Cycle Cost
LPSP	Loss of Power Supply Probability
MoWIE	Ministry of Water, Irrigation and Electricity
NREL	National Renewable Energy Laboratory
NPC	Net Present Cost
SSA	Sub-Sahara Africa
STC	Standard Test Condition
UEAP	Universal Electricity Access Program
UNEP	United Nations Environment Programme

CHAPTER ONE

1. INTRODUCTION

1.1 Background

Achieving universal access to electricity is one of the most important goals set for the energy sector by governments in the developing world **[5].** Electricity alone is not sufficient to spur economic growth, but it is certainly necessary. Access to electricity is particularly crucial to human development, as certain basic activities such as lighting, refrigeration, running household appliances and operating equipment that cannot easily be carried out by other forms of energy. Sustainable provision of electricity can free large amounts of time, labor and promote better health and education. Electrification can make an important contribution toward achieving economic and social objectives. Access to electricity in Ethiopia is one of the lowest by any standard with only 25% of households connected and 53% of electricity coverage of the country is from Ethiopian Electric Power Corporation (EEPCo) in 2014.

Ethiopia is a large, land locked and diverse country located in the Eastern part of Africa between 3° to 15° North and 33° to 48° East. It is the second most populous country in the Sub-Saharan-Africa (SSA) region (estimated 99.4 million in 2015), out of which 80% are rural dwellers. In terms of gross domestic product (GDP) per capita income of USD 669.9, Ethiopia ranks 174 out of 187 according to the HDI 2015 report.

Despite the fact that 80% of the population of Ethiopia live in rural areas, electricity supply from the grid is almost entirely concentrated in urban areas. Among other things, dispersed and very low consumption level of electricity among rural consumers limited grid electricity penetration to rural dweller is less than 2% [**20]**. Based on the hitherto electricity expansion practices, access to electricity does not seem to be the reality of the near future for the greater percentage of the rural communities. However, the recent government's strategy under Universal Electricity Access Program (UEAP) ambitiously increase access to electricity by connecting 5168 new towns and villages to the grid and the country managed to electrify 1700 rural towns and villages per annum. The UEAP does not only aim to increase access, but also aims to raise the level of national per capita consumption of electricity from 28 kWh in 2010 to 128 kWh by the year 2015 **[16].**

Ethiopia, Under UEAP, follows two basic strategies in order to electrify rural area. These are:

- ✓ Grid based large and medium scale power generation and,
- ✓ Small scale renewable energy standalone/ mini-grid technology options.

In rural areas of Ethiopia 70% energy demand for cooking and lighting is from fuel wood. Hence, to access a reliable, affordable, clean and sustainable energy service the government of Ethiopia set a plan to set an energy mix power generation system.

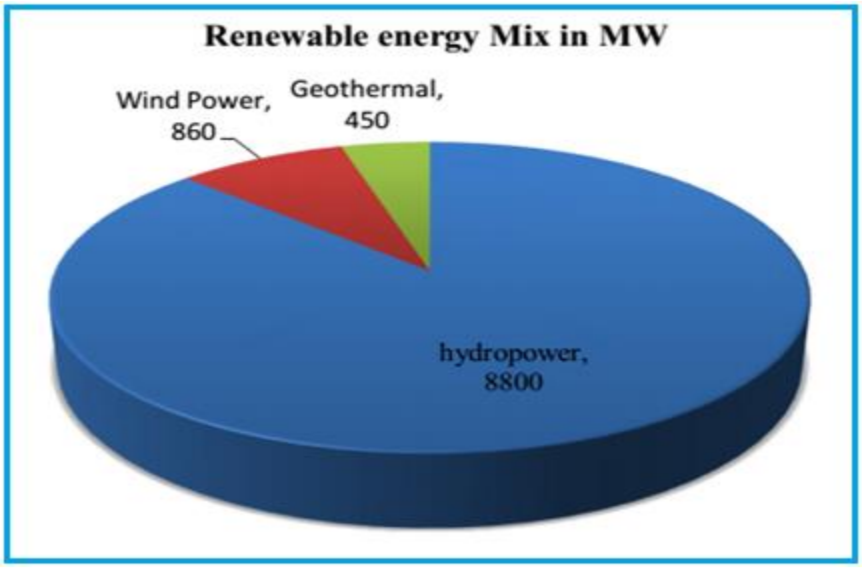
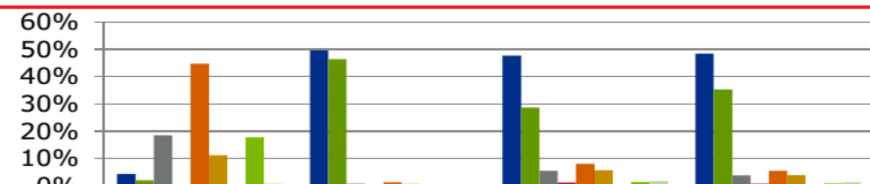


Figure 1. 1: Ethiopia power generation plan from renewable energy in the year 2011-2015 [16]

1.2 Status quo of Rural Electrification in Ethiopia

Currently, in rural areas of Ethiopia energy needs are mostly covered by the use of traditional biomass sources such as fuel wood, agricultural waste for cooking and heating, kerosene for lighting and small battery or thermal generator units for lighting and communication.



	Rural	Large City	Other Towns	Urban (weighted)
Electricity meter shared	4.4%	49.7%	47.7%	48.5%
Electricity meter private	2.0%	46.6%	28.6%	35.3%
Electrical battery	18.5%	0.8%	5.6%	3.8%
Electricity from generator	0.5%	0.2%	1.2%	0.8%
Local kerosene lamp	44.8%	1.3%	8.0%	5.5%
Kerosene light lamp	11.3%	0.7%	5.8%	3.9%
Lantern	0.1%	0.0%	0.0%	0.0%
Firewood	17.7%	0.3%	1.3%	1.0%
Others	0.8%	0.5%	1.7%	1.2%

Figure 1. 2: Energy used for lighting in Ethiopia, 2011 [5]

Decentralized and mostly fossil based energy services used in rural households and communities result in considerable greenhouse gas emissions. As it concerns quite large part of the population and there is strong population increase, electricity needs and consumption are strongly increasing. In combination with the abundance of renewable energy sources available at rural sites in Ethiopia, these emissions contrast with the ambitions of Ethiopia to be a frontrunner in renewable energy and climate policies and practices.

Ethiopia does not have its own oil production; it highly dependent on imported fossil fuels. The country spends nearly all of its export earnings to import petroleum products, putting pressure on foreign exchange reserves. This causes a substantial threat on the economy when there are global oil price hikes. This disrupts security of energy supply where escalating oil prices threaten the country's economy and balance of payment. Availability of fossil energy carriers in rural areas are thus under increasing pressure (both price and availability).

1.3 Current National Policies in Energy Sector

The overall vision of the government of Ethiopia for their energy policy is to ensure access to affordable, clean and modern energy for all citizens and become a renewable energy hub in the Eastern Africa Region by 2025. The mission underlying this vision is to play a significant role for socio-economic development and transformation of the country through provision of sustainable, reliable, affordable and quality energy service for all sectors in an environmentally sound manner. The overarching strategy for this vision is the Climate Resilient Green Economy strategy (CRGE). The CRGE sets the direction to transform Ethiopia to a middle income country through climate resilient growth and reduction of greenhouse gas emissions (GHG). In the focus area of water and energy within the CRGE strategy MoWIE has identified eleven priorities in four dimensions like power generation, energy access, irrigation for agriculture, and water, sanitation and hygiene.

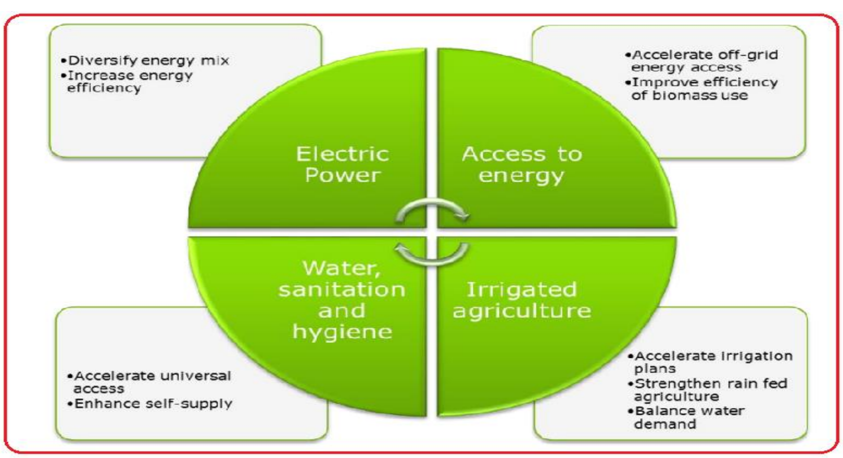


Figure 1. 3: CRGE strategies for water and energy. Source: CRGE (Water and Energy, 2015)

The government policy towards power sector development has been dominated by public managed and public owned utility, leaving little room for concrete private sector interest and participation. The private sector could however play an essential role in accelerated development of the rural energy sector, especially when an enabling environment for this is created by a policy shift at the government.

This policy shift to increasing focus on off-grid solutions and involvement of the private sector will generate interest and commitments towards mini-grids development. This ambition for short term electrification of rural villages is to meet basic energy needs and also stimulate energy use for economic purposes to contribute to overall development of rural livelihoods.

1.4 Bottlenecks to Rural Electrification in Ethiopia

Despite the abundance of natural resources, the difficulties of fossil supply and the absence of modern electricity sources, renewable energy mini-grids have not been widely deployed yet in rural Ethiopia. There are several types of barriers that hamper the deployment of renewable mini-grids. These are:

- ✓ Market uncertainty preventing private and other stakeholder from starting developments: Uncertainties about where large scale grid extension will go, what will happen to mini-grids if the grid reaches the same are, no agreements on tariffs of options for connection to main grid
- ✓ Difficulties with economic feasibility of mini-grids: Very low grid connected electricity prices in Ethiopia, grid extension costs are not recovered in the electricity price, no successful business models demonstrated in Ethiopian context
- ✓ No policy guidance/framework: absence of overall plan and approach, no clear targets on how many or where to develop mini-grids.

To solve the current energy problem, the government of Ethiopia (GoE) has an ambitious of developing its electricity generation portfolios in a manner that includes two major changes compared to the current situation:

- ✓ **Diversification**: Hydro power can deliver electricity at a relatively low cost and essentially without emissions. However, the hydrological conditions vary with dry and wet seasons determining precipitation. According to the ten years master plan, the planned expansion of electricity generation (2015-2025) has three main components: 7,600MW of hydro-power, 5,200MW of wind power, 5200MW of solar power, and 900MW of other power including geothermal.
- ✓ **Independent Power Producer (IPPs)**: A significant share of the capacity expansion (69%) is expected to be produced and managed by IPPs. IPPs planned to produce 3,600MW of solar and wind power.

Even if the country has been made improvement of the energy sector, it is difficult to supply all the remote areas access to modern energy without small energy generation systems. As a result, the aim of this thesis work is to assess the best techno-economic combination of renewable energy resources in a hybrid configuration for the electrification of Deleta village in Meta Robi district

1.5 Statement of the Problem

Developing countries like Ethiopia have serious energy crisis. Satisfying the power demand of the people for the fundamental necessities by itself is in much a bother situation. Hence, governments and peoples started looking towards permanent and never ending sources of energy called renewable sources of energy such as solar and wind energy. The positive aspect of using renewable resources in our country Ethiopia is that they are available in plenty and also pollution free.

Even though Ethiopia is rich in renewable energy sources, majority of the population which live in rural areas depend on biomass for cooking food and lighting **[51].** Due to many reasons most of the villages of the country are not getting electrical energy currently. To connect the rural areas to the grid, high costs and adequate power for the whole country is required. On the other hand there are many bottle neck challenges associated with using the traditional biomass energy, such as the continued depletion of natural forest resources for fire wood has resulted in environmental problem, increasing scarcity and cost of household fuels, particularly fire wood increased stress on women and children who usually are supposed to collect fuel and the cost of petroleum imports has brought worsening impact on Ethiopia's trade balance and foreign exchange availability.

As a result the government of Ethiopia is trying to electrify the rural areas by expending much money to extend the existing national grid even though most of the rural areas are potentially rich in renewable energy resources. Therefore, extending of the central electricity grid to such areas is either financially not viable or practically not feasible as these locations are geographically isolated, sparsely populated and have a very low power demand **[14].** Renewable energy sources can be used as a standalone with minimum cost as compared with the cost required to extend the central grid.

Hybrid off-grid systems are the most widely used and cost effective energy sources for rural electrification where the grid extension is difficult and economically not viable. Such system incorporates a combination of one or several renewable energy sources such as solar and wind energy with convectional diesel generator [**36].** Hence supplying energy to the rural community from hybrid off grid systems will help them by improving their life style as well as reduce deforestation. In addition to this hybrid systems can contribute for the achievement of agricultural lead industrialization **[30].**

1.6 Motivation of the study

The motive of this research is to address access to modern energy for the undeserved rural communities of Deleta village in Meta Robi district in which currently energy needs are covered by the use of traditional biomass sources like fuel wood or agricultural waste for cooking and heating, kerosene and small battery for lighting. Using these types of energy brought health risks (flammability of kerosene, respiratory impacts of fuel wood burning), high costs and absence of constant supply. Moreover, most rural areas in Ethiopia receive an abundant supply of solar, wind and hydro resources throughout the year but due to topographical location most of the remote communities lack access to modern and reliable electricity. Besides recent increase in availability of climate related and donor finance for low carbon and Climate Resilient Green Economy (CRGE) that prioritizes renewables are the main motivating notions for the study.

1.7 Objectives

1.7.1 General Objective

The main objective of this thesis is to find the best combination of renewable energy technologies from the available resources in a given village location that can meet the electricity demand in a reliable and sustainable manner and to analyses whether such hybrid option is a cost-effective solution or not.

1.7.2 Specific Objective

The achievement of the stated main objectives the ability and the accomplishment of the below objectives is required:

- ✓ To estimate and forecast the electrical load for the village
- ✓ To assess the available resources
- ✓ To model electricity generation based on multiple combinations of RETs with the application of HOMER software
- ✓ To select the best options based on the COE generation and then compare these performance indicators to grid extension related costs

1.8 Significance of the study

The significance of the study is to provide comprehensive information on the renewable energy systems mix with convectional diesel generator to electrify the rural community of Deleta village that have no electric access. From this point of view the study could be considered as possible reference solution by utilization of solar and wind energy sources for the electrification of the community of the remote area.

Generally, the result from this study helps;

- ✓ For future renewable energy resources generation plan for the electrification of rural areas that detached from national grid by governments and NGOs.
- ✓ To promote the socio-economic development of the community.
- ✓ To choose the best hybrid energy systems configuration from economic perspectives that can be feasible for the electrification of the community.

1.9 Scope of the Study

The scope of this thesis is limited to determining the best techno-economic combination of renewable energy resources in a hybrid configuration for the electrification of Deleta village in Meta Robi district

1.10 Limitation of the Study

The limitation of this thesis is:

- ✓ Only solar and wind energy are chosen for the analysis due to the no-existence of other renewable energy resources such as biofuels and stream of water flow in the area
- ✓ In this thesis only Homer software was used for modeling and simulation

1.11 Organization of the Thesis

The thesis paper includes seven chapters and seven appendices. These are categorized as follows:

Chapter One: Introduction, over views the rationale of the study. It includes the problem statement, objectives of the study, scope of the study and the significance of the study.

Chapter Two: Literature reviews regarding the related works of the study.

Chapter Three: overall research methodologies. It includes site identification, problem identification and literature survey on hybrid systems applicable for rural community, data collection on solar and wind potential and the cost of the hybrid components and data analysis and feasibility study.

Chapter Four: village load and resource assessment. It includes village load profile, solar and wind resources of Ethiopia and in study area.

Chapter Five: Hybrid systems component characteristics and costs. It includes an over views of hybrid renewable energy systems, typical configurations of renewable energy mix with diesel generators i.e., solar photovoltaic-diesel and wind-diesel, connection systems of the renewable energy with diesel generators,

Chapter Six: Result and discussion

Chapter Seven: Conclusion, recommendation and suggestion for future work

CHAPTER TWO

2. LITERATURE REVIEW

The purpose of literature review is to review some relevant literature on off-grid electricity access using RET, to provide evidence of knowledge gap that justifies the need for this work and to provide support for the methodology used in the study and is a source of information for comparison, triangulation and referencing. Accordingly, the following sub-sections present the relevant reviews.

2.1 Reviews on Renewable Energy Technologies and Hybrid Concepts

Electrical power generation systems consisting of two or more energy sources such as solar and wind or the combination of these with other renewable sources such as hydro, geothermal, biomass or with a convectional diesel generator is called hybrid systems. Hybrid systems also contain storage devices such as batteries or fuel cells. While hybrid energy systems are usually implemented to electrify the community of rural areas those who detached or far away from national grid, they can also operate in parallel with the grid power systems [**52]**.

Nouni et al. **[46]** has used this approach to identify the potential areas for decentralized electricity supply in India. They considered the delivered cost of electricity supply for different load factors and for villages located within a radius of 5-25 km from an existing 11 kV substation for two cases: plain terrain and hilly terrain, where the cost of local distribution tends to be higher. They also considered the cost of supply from decentralized renewable energy options. Considering typical village load data from 1991 Census statistics, they estimated that the average peak load of a remote rural household to be 0.675 kW. Considering the population of villages, they suggested that village's with less than 50 kW peak load could be considered for decentralized electricity supply through renewable energy technologies. The authors then considered the trade-off between grid extension and off-grid supply to find the cost effective electricity supply option for remote villages. While this provides a framework of analysis from the cost of supply perspective, the analysis does not consider the external costs related to fossil fuel use, cost of security of supply, cost of stand-by power for renewable energies.

2.2 Reviews on Hybrid Solar-Wind-Diesel generator Systems

Diesel prices in most remote areas are higher than the usual prices in cities or urban areas, making the energy cost of the hybrid solar-wind-diesel generator system competitive with the energy cost of the diesel generator system. In the hybrid system, the diesel generator is used to minimize the size of the solar-wind systems as well as the cost.

Koussa et al. [**29**] presented a sizing model to predict the optimum dimensions of hybrid PV-wind-diesel systems for rural electrification in Algeria. The objective of the optimization parameter is not the production cost but the offered service. They conclude that the major advantage of hybrid system is increased reliability.

Alireza, et al **[1]** has performed a detailed techno-economic analysis of hybrid PV-wind-diesel-battery systems by using HOMER to meet the load demand of off-grid house located in the three remote Colombian settlements. The hybrid systems is economically feasible for diesel fuel price above 1.1$/liter. To select the best optimal configuration systems from economic perspective, total net present cost (NPC), initial capital cost and cost of energy (COE) were selected as the economic indicators. The resulting yearly CO_2 emissions as the environmental index were also determined. The result shows that the combined diesel generator and renewable resources have a very low carbon foot print. In remote area of Puerto Estrella, the emission from hybrid configurations system were about 4262 kgCO_2/year, which 2.6% is from the emissions of diesel based system (162,142 kgCO_2/year). The cost analysis revealed that the combination of solar PV-wind-diesel-battery systems with an initial capital cost of $521,078, NPC of $836,210 and COE of $0.473/kWh were the optimal option for this remote area.

Rehman et al. **[50]** designed a PV/wind/diesel hybrid power systems for a rural area of Saudi Arabia which recently powered by a diesel generator power plant consisting of eight diesel generating sets of 1,120 kW each. The study found a PV-wind-diesel hybrid power system with 35% renewable energy penetration (26% wind and 9% solar PV) to be the feasible system with COE of 0.212$/kWh. The system was able to meet the energy requirements (AC primary load of 17,043.4 MWh/year) of the village with 4.1% energy in excess. The annual contributions of wind, solar PV and diesel generating sets were 4,713.7, 1,653.5 and 11,542.6 MWh respectively. The proposed hybrid power system resulted in avoiding addition of 4,976.8 tons of GHG equivalent of CO_2 gas into the local atmosphere of the village and conversion of 10,824 barrels of fossil fuel annually.

Lau et al. [**31**] analyzed the case of a remote residential area in Malaysia and used HOMER to analyze the economic viability of a hybrid system. The study uses a hypothetical case of 40 households with a peak demand of 2 kW per household. The peak demand is 80 kW and the base demand of around 30 kW is considered in the analysis. Although such high rural demand can be typical for Malaysian conditions, this might not be true for others. The study also does not consider any productive use of electricity.

Givler and Lilienthal [**14**] conducted a case study of Sri Lanka where they identified when a PV-diesel hybrid becomes cost effective compared to a standalone small SHS (50W PV with battery). This study consider an individual household base load of 5W with a peak load of 40W, This study considers an individual household base load of 5 W with a peak of 40 W, leading to a daily average load of 305Wh. Through a large number of simulations, the study found that the

PV-diesel hybrid becomes cost-effective as the demand increases. However, this study only focuses on the basic needs and does not include productive use of energy.

Munuswamy et al. [**42**] compared the COE from fuel cell based electricity generation against the cost of supply from the grid for a rural health center in India applying HOMER simulations. The result shows that beyond a distance of 44 km from the grid, the cost of supply from an off-grid source is cheaper. This work, however, just considered the demand of a rural health center and was not part of any traditional rural electrification programme.

Hafez and Bhattacharya [**21**] analyzed the optimal design and planning of a renewable energy based micro-grid system for a hypothetical rural community where the base load is 600kW and the peak load is 1,183kW with a daily energy requirement of 5,000kWh/day. The study considers solar, wind, hydro and diesel resources for electricity generation. Although the study considers electricity demand over 24 hours, the purely hypothetical nature of the assumptions makes the work unrealistic for many off-grid areas of developing countries.

Table 2. 1: Summary on hybrid power generation technology analysis using HOMER

Technology application	Country/study area	Supply duration/type	Reference
PV/wind hybrid	Ethiopia	Randomized load profile from hypothetical load data	Bekele & Palm [**6**]
PV/diesel hybrid	Malaysia	24h service, but uses a high demand profile for rural area and does not use any productive load	Lau et al. [**31**]
Wind/PV/battery	Bangladesh	Solar and wind hybrid, no productive demand	Nandi & Ghosh [**45**]
PV/diesel/battery	Syri Lanka	Basic needs	Givler & Lilienthal [**14**]
PV/wind/hydro/diesel/battery	Developing country	24h service but unrealistic demand profile for rural area of developing countries	Hafez & Bhattacharya [**21**]
PV/micro hydro/LPG/generator battery	Cameroon	Load based on grid connected used for urban households of Uganda	Nfah et al. [**47**]
Wind/diesel hybrid	Algeria	Limited technology option	Himri [**22**]

2.3 Research Gap

The above review shows the popularity of HOMER as a tool to analyze decentralized electricity supply systems. However, most of the studies do not consider electricity demand in rural areas carefully. Also they did not forecast the load for the study site within the project lifetime. As the optimal system configuration is obtained to meet the demand, demand analysis plays an important role. Most of the studies also focus on a limited level of supply and do not often consider the productive applications of electricity. In addition while technology choices are dependent on local conditions; it is possible to investigate alternative combinations more imaginatively. Finally, the studies also limit their scope to techno-economic analysis and do not consider the business issues related to the work. Therefore, this chapter tries to bridge the above knowledge gaps and presents an application of HOMER by including a pre and post analysis to extend the scope of the work and knowledge base.

CHAPTER THREE

3. RESEARCH METHODOLOGY

The overall research methodology is:

3.1 Site Identification

The specific study area is Deleta village in Meta Robi district.

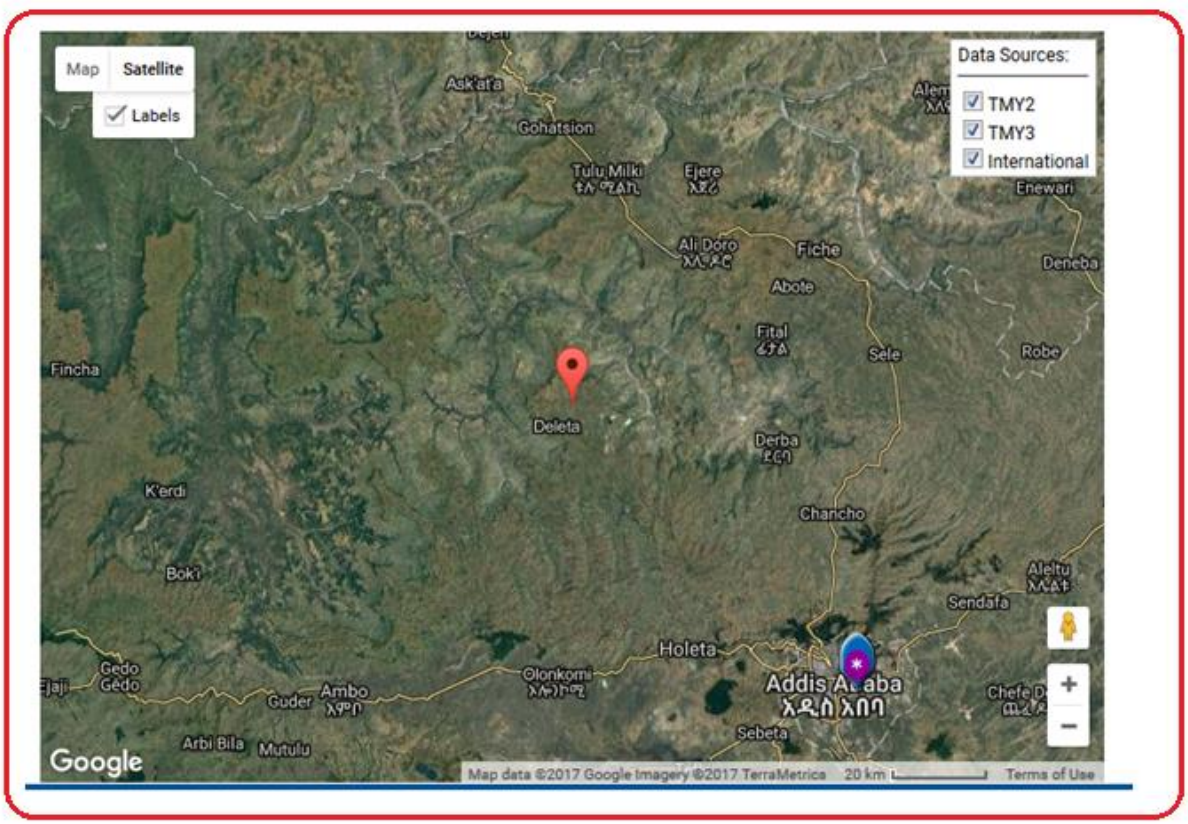


Figure 3. 1: Map of the study area. Source: Google earth

3.1.1 Description of the Study Area

Deleta is the selected off-grid remote rural village for this study. It is a small village found in the Meta Robi district, West Shewa Zone, Oromiya Regional State. The village is located at Latitude of 8° 59' N and Longitude of 38° 8' E and it is about 27 kilometers away from Shino town in North East direction. According to 2007 population and housing census of Ethiopia Deleta village has a total population of 4,770 people out of which 2,500 are male and 2,270 are female and 795 households (Central Statistical Agency). In this remote area, there are primary schools, health extension post, farmers training centers and Keble administration. In spite of having significant renewable energy sources such as solar and wind, the village does not have access to electricity. Different areas have different types of energy sources available for converting into electricity. The best solution to provide electricity to the village is to integrate renewable energy sources (wind and solar) with convectional diesel generator together to electrify the remote village.

3.2 Problem Identification

Problem identification for the specific study area was under taken by direct observation of the site and collecting relevant information regarding the geography, population and the current energy they used and the impact of the traditional energy sources on the health of the community and environment.

3.3 Primary and Secondary Data Collection

Primary data are those collected by the direct participation of the researcher conducting the research. During the field survey, data such as the number of primary schools, farmers training centers, health extension post in the study area are collected.

Relevant secondary data for this thesis are:

- ✓ Solar and wind energy resources potential were taken from NASA.
- ✓ Population size and number of households were taken from Central Statistical Agency
- ✓ The costs, sizes and technical specification of hybrid system components were assessed from different websites.

3.4 Data Analysis and Feasibility Study

Hybrid Optimization Model for Electric Renewable (HOMER) is a micro power design tool used for designing, comparing and evaluating micro power technology options for a wide range of applications such as off-grid village power systems, standalone applications, convectional technologies and emerging technologies (NREL, getting started guide for Homer legacy, version 2.68). It can find the best optimal combination of components that can serve the load at the lowest life cycle cost. HOMER software undertakes this task in three major consecutive steps of simulation, optimization and sensitivity analysis. The detailed data input and analysis in HOMER software is indicated in the Figure 3.3 below.

In the simulation process, energy balance calculation of a designed power systems over the 8760 hours in a year is generated. Results from this stage are used for technical and economic evaluation to determine the feasibility of a system design in meeting the electrical demand under specified conditions and estimate the costs of installing and operating the system over the life time of the project, including initial capital, replacement, operation and maintenance cost and fuel.

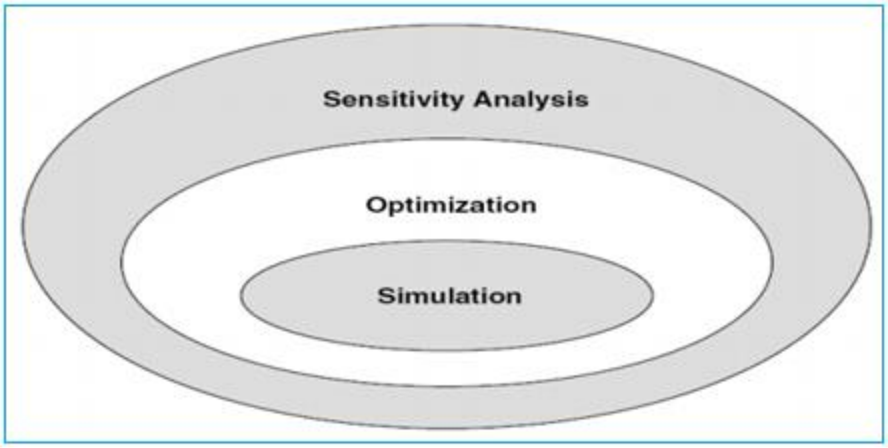


Figure 3. 2: The three consecutive steps of HOMER software [25]

The subsequent optimization stage simulates each of the possible system configurations and displays their list sorted by net present cost and cost of electricity (LCOE) to compare and evaluate the most cost effective option considering factors such as resource availability, load size, fuel price, carbon emissions and renewable fraction. The final sensitivity analysis helps to reveal how sensitive the outputs are to change for sensitivity input variables such as wind speed, solar radiation and fuel prices. Sensitivity analysis results are important in answering the generation questions about technology options to inform planning and policy decisions.

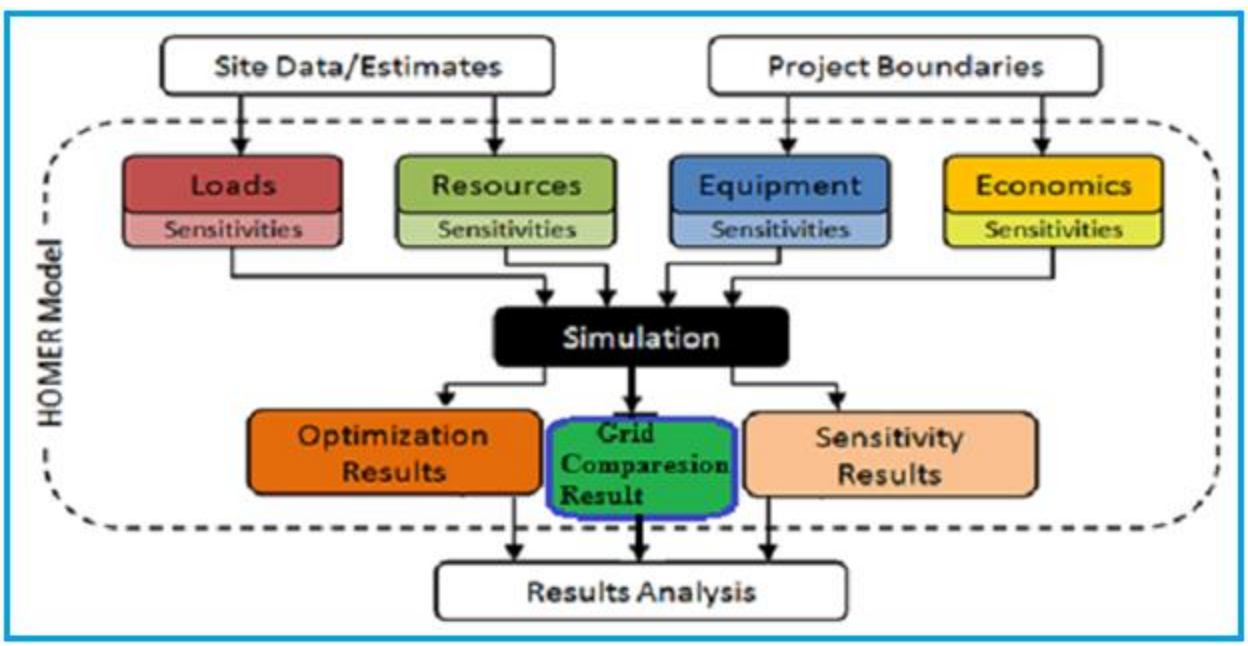


Figure 3. 3: Schematics of data input and analysis in HOMER [25]

CHAPTER FOUR

4. LOAD AND RESOURCES ASSESSMENT

4.1 Village Load Assessment

Electric power is the most versatile type of energy source that can be used to fulfill any kind of energy demand. In remote rural areas the electricity demand is not as high as urban areas. According to Bekele et al**. [6],** the basic electric load in the rural villages of Ethiopia can be categorized as primary and deferrable load. Primary load is the electrical energy demand that the power system designed must serve according to a particular schedule or specified time. On the other hand deferrable load is an electric demand that can be served at a certain period of time. Deferrable met only after the primary load has been satisfied except under special circumstances, the exact timing is not important. It includes activities like water pumping, charging batteries and heating water. It is noteworthy that, since the economy of these communities is based on agriculture, the majority of residents spend most of their time outside their homes for work purposes. At noon, increase in loads can be observed, as some family members usually come home for lunch and other activities. However, maximum load demand takes place at night when the entire families are at home.

In the study area the households are categorized into three classes. These are low class households (310 families), medium class households (275 families) and high class households (210 families). Due to the population and economic growth rate the 650 households of the village definitely increases to a certain figure. Currently, the number of households in the village is approximately 795 households. Energy demand of the village was estimated based on the current number of households. In fact all the communities of the villages have not the same economic status that is some the households are relatively rich and most of them are comparatively poor. For instances majority of the households may not offer the electricity cost if they use electric oven (Enjera Mitad).

4.1.1 Assessment of Household and Community Load of Study Area

In the study area, 795 rural household with average family size of 6, public and commercial centers are considered. By considering the basic necessity of the community primary and deferrable load is estimated for the residents of the village. Primary load contains lighting, radio receiver, TV, refrigerator and DVD player. In addition to these, the community has primary school (1-8 grades), health extension post and farmers training center (FTC). Load estimation for health extension post, farmers training center and Keble administration was taken from UEAP **[3].**

The planned electrical load for low class households are two 11W CFLs operating from 18:00 to 22:00, additionally, for external lighting one 11W CFL is considered, a radio receiver of 10W operating from 12:00-14:00, 20:00-22:00 and a DVD of 25W used from 18:00-22:00 is considered. Middle class households three 11W CFLs operating from 18:00-22:00, additionally, for external lighting two 11W CFLs operating is considered, a radio receiver of 10W operating from 12:00-14:00, 20:00-22:00 and a DVD of 25W used from 18:00-22:00 is considered and a TV set of 65W are to be used in the time 12:00-14:00 and 18:00-24:00 is considered. Similarly, for high class households four CFLs of 11 W rating to be lit from 18:00 to 22:00, additionally, for external lighting two 11W rating CFL operating from 19:00-23:00 is considered, a radio receiver of 10W operating from 12:00-14:00, 20:00-22:00 and a DVD of 25W used from 18:00-22:00 is considered, a TV set of 100W are to be used in the time 12:00-14:00, 18:00-24:00 and a 100 W refrigerator working for 24 hour are considered.

The primary schools that contain 1-8 grades were found in the site of the high household community. It has 13 classes with 60 numbers of students for each. In this primary school teaching and learning process is only exercised only during day time. There are no students who attend the night class due to lack of electricity. But if the school gets electric access there is a chance to enroll students for night class.

Each class room will be installed with four 11 W CFLs (Compact florescent lamps) and a radio receiver. In addition to these six CFLs of 11 W for external lighting operated from (18:00 to 6:00) is considered. The evening classes are conducted from 18:00-21:00 and two radio receivers of 10W operated 6 hours per day (10:00-16:00) are considered for radio lessons of each school. The health extension post is found in the site of low class household community, it have four rooms, one 11W CFL per room and two 11W CFL for external lighting operating for 12hours (18:00-6:00) are considered. A vaccine refrigerator of 100 W working for 24hr and a 10W radio receiver for the office hours that operated for 8 hours per day (10:00-18:00) are a suggested for each health extension post. The diesel driven flour mills of 10 kW was found in the site of high class household community. The operation time from 9:00 to 12:00 and 14:00 to 18:00 is assumed for the diesel drivel flour mill. One 11W CFL for internal and one for external lighting operating from 18:00 to 6:00 is considered for flour mill operation.

The animal clinics also found in the site of middle class household community having two class rooms installed with one 11W CFL operated from 18:00-21:00 per each room and two 11W CFLs for external lighting operating from 18:00-6:00 are considered. A vaccine refrigerator of 100 W working for 24hr and a 10W radio receiver for the office hours that operated for 8 hours per day (10:00-18:00) are also suggested for the animal clinic. The total energy demanded per day for both household and public load are annexed in Appendix 4A.1 and 4A.2 respectively.

Once we have a total electric load demand for a single hour of the day by the households and public service centers, to get the daily load demand requirements of the study area we have to add up all together based on the above groupings.

Table 4. 1: Total power demand of the study site

Time	**Total power consumption [kW]**			
Hours/day	Category of households			Total
	Low class household	Middle class household	High class household	
0:00-1:00	0.122	0.111	21.033	21.266
1:00-2:00	0.122	0.111	21.033	21.266
2:00- 3:00	0.122	0.111	21.033	21.266
3:00-4:00	0.122	0.111	21.033	21.266
4:00-5:00	0.122	0.111	21.033	21.266
5:00-6:00	0.122	1.486	22.083	23.691
6:00-7:00	0.1	1.475	22.05	23.625
7:00-8:00	0.1	0.1	21	21.2
8:00-9:00	0.1	0.1	21	21.2
9:00-10:00	0.1	0.1	21	21.2
10:00-11:00	0.11	0.11	21.04	21.26
11:00-12:00	0.11	0.11	21.04	21.26
12:00-13:00	3.21	20.735	44.14	68.085
13:00-14:00	3.21	20.735	44.14	68.085
14:00-15:00	0.11	0.11	21.04	21.26
15:00-16:00	0.11	0.11	21.04	21.26
16:00-17:00	0.11	0.11	21	21.22
17:00-18:00	0.11	0.11	21	21.22
18:00-19:00	14.824	33.958	57.095	105.877
19:00-20:00	18.234	40.008	61.715	119.957
20:00-21:00	21.334	42.758	63.815	127.907
21:00-22:00	21.334	42.758	63.243	127.335
22:00-23:00	3.62	24.058	46.653	74.331
23:00-0:00	0.166	17.986	42.033	60.185

The average daily energy demand of the study area is about 1096kWh/day and the yearly energy demand for the study area can be calculated as follow:

$$\text{Annual average energy deamnd} = 1096\ \text{kWh/day} * 30\text{days/month} * 12\text{month/year}$$

$$\text{Annual average energy deamnd} = 394{,}560\ \text{kWh/year}$$

4.1.2 Village Load Profile

In the study area the load requirement is for domestic (electrical home appliances), public service centers such as primary schools, health clinic, farmers training centers, Keble administration and deferrable load. A load profile the study site is illustrated in Figure 4.1 based on the utility's 2016/2017 electric demand data entered into HOMER with a random day to day variability of 15% and time to time variability of 20%. The power system serves for 24 hours per day and the hourly load consumption shifts throughout the day with peak demand of 229 kW, average load of 45.2 kW, average energy consumption of 1085 kWh/day and load factor of 64.1%.

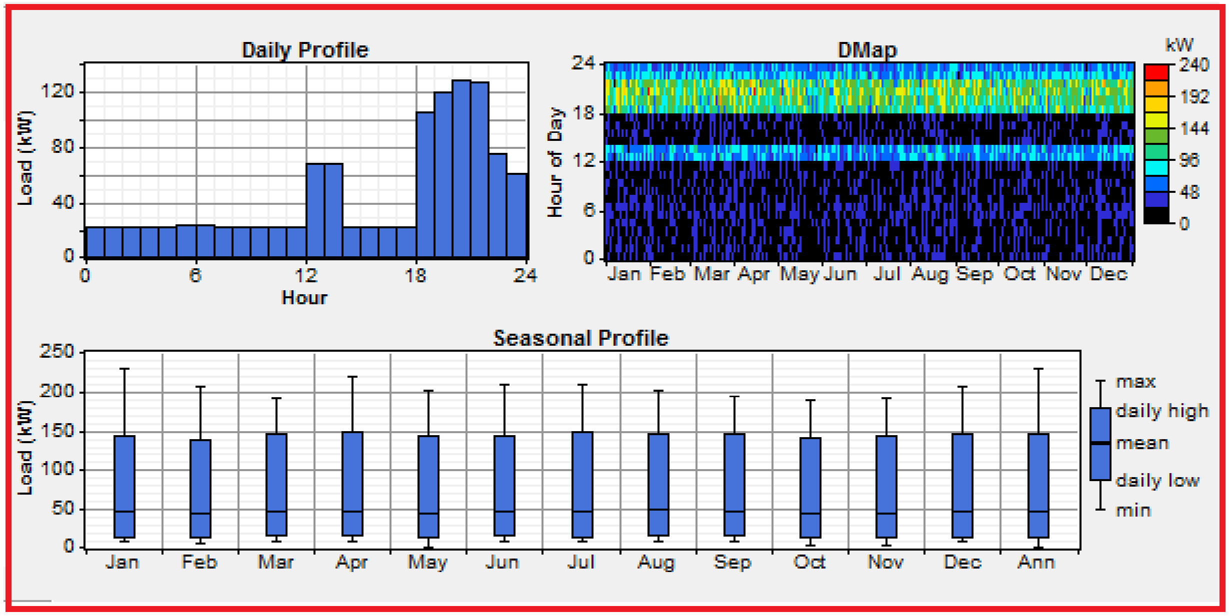


Figure 4. 1: Load profile of the study area

4.1.3 Deferrable Load Estimation

Water pumping system is required for households, schools and health centers. A minimum of 100L of water per day per family and 2400L/day for health center and school is suggested **[6]**. To accomplish this, 5 pumps operating 2.58hours/day for low class household, 4 pumps operating 3.8hours/day for middle class households and 3 pumps operating 5.8hours/day for high class households with a nominal flow rate of 0.617 metric cubes per hour, head of 10-100m and nominal head of 70m are to be installed to supply water for the community. For public service centers such as health center and schools is about 2,400l/day. To accomplish these 3 pumps of 320W (with a capacity of 10l/m) is assumed for both primary schools and health center. For each household class a water storage capacity of four days is suggested with a storage capacity of 21.7kWh (low class households), 18.33kWh (medium class households) and 13.13kWh (high class households). For health center and school water storage capacity of four days is suggested requiring a storage capacity of 3.6kWh. For animal clinic 1200L/day water is suggested. To accomplish this one 320 pump operating 2 hours per day is considered, water storage capacity of two days for animal clinic is suggested with storage capacity of 1.28kWh. 15% load decrease for June and September while 30% for July and August are assumed **[6].**

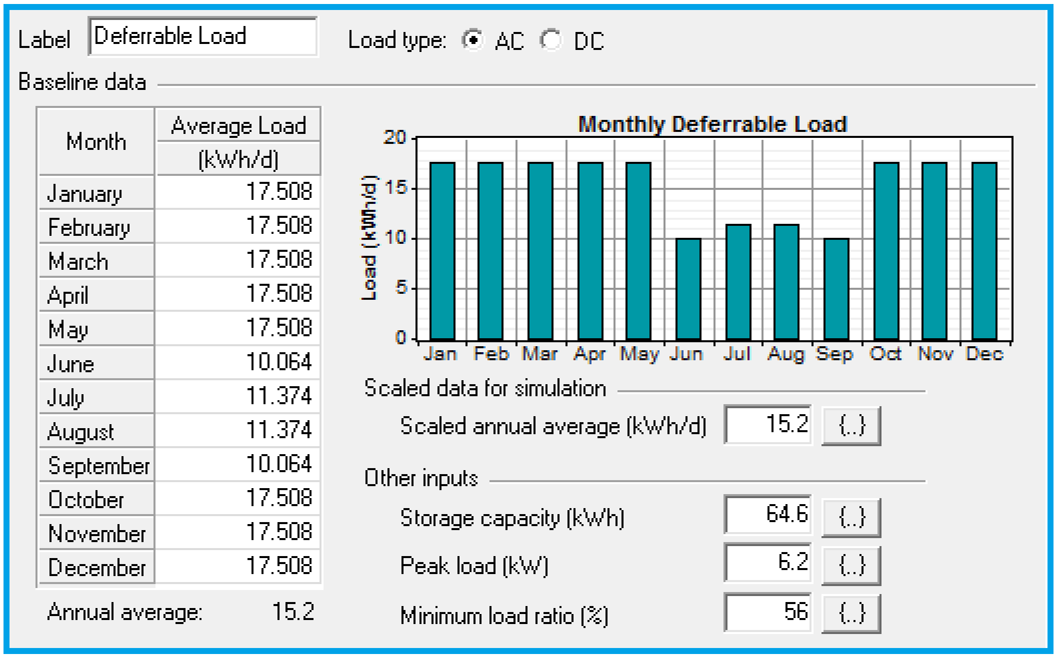


Figure 4. 2: Deferrable load profile of the study area

4.1.4 Electricity Demand Forecasting

One of the primary tasks of an electric utility is to accurately predict load demand requirements at all times, especially for long term. Accurate models for electric power load forecasting are essential to the operation and planning of a utility company. Hence knowing the load behavior in advance is very important in planning, analysis and operation of power systems to maintain an interrupted, reliable, secure and economic energy providing. Load forecast are extremely important in electric generation, transmission, distribution and markets **[9].**

In this study an end use approach is used to forecast a load growth of a remote area supplied through hybrid power system. This methodology implies the current energy demand of the community is first estimated based on customers end device energy consumption and the energy demand is projected throughout the project life time based on the household growth due to the population growth rate and the penetration of them to the system. An end use approach method is given by **[10].**

$$E_i = E_o + S * (H_i - H_o) * E \qquad (4.1)$$

Where,

E_i = The i[th] year annual average energy demand in kWh/day

E = Annual average energy consumption in kWh/day/household

S = Customer penetration rate

E_o = The annual average electricity demand in kWh/day, in 2016

H_o = The number of household on which E_o is estimate, 2016 base year

H_i = The number of household in the i^{th} year

4.1.5 Population and Energy Demand

Population growth has strong ties with energy demand. As population increases, the total energy consumption will increase. The end use approach in this thesis work considered the number of households and household growth, because electricity demands satisfied and supplied for households not for individual population. According to the World Bank, 2013 report the average rural population growth rate of Ethiopia is about 1.9%. The figure is assumed constant throughout the project life time and used to determine the population of the study area in the next 25 year. The population size of the study area in 2016 with 6 occupants per house hold is about 4,770 (795HH). This population figure is projected by an annual growth rate of 1.9% until the end of the forecasted period and converted to total number of household using a given number of occupants per household. The following formula is used for population growth forecasting **[3].**

$$P_n = P_o\left(1+\frac{r}{100}\right)^n \qquad (4.2)$$

Where, P_n = population at the n^{th} year, P_o = current population, r = annual population growth rate in %

4.1.6 Customer penetration

Customer penetration indicates the number of newly growing households that are connected to the system annual to be electrified. Assuming 85% of them is electrified annually and taking this constant up to the project forecasted horizon.

4.1.7 Average Electricity Consumption

The average primary and deferrable load consumption estimated for the study site is 1085kWh/day and 15kWh/day respectively. This is taken as the demand in the first year of the forecasted period 2016. The average primary energy consumption per household is 1.36 and deferrable load energy consumption per household is 0.02. Assuming annual energy consumption (primary+ deferrable) per household is constant throughout the forecasted time horizon. Population growth and load forecasted is annexed in the Appendix 4A.3.

4.2 Renewable Energy Resource Potential in Ethiopia

There is a huge resource potential in Ethiopia, which if utilized could minimize the present energy crisis prevailing in the country and enhance the process of rural electrification. Economic growth in recent years has been partially enabled and driven by its renewable energy generation, with a doubling of Ethiopia's renewable generation capacity to 2.36GW from 2008 to 2015 and up to 10GW including projects currently under commission (power Africa, 2016). 86% of Ethiopia's current generation is from hydropower, with approximately 8% of its source from other renewables (wind and geothermal). This capacity nevertheless represents only a fraction of potential renewable capacity as an estimated 45GW of hydropower and 60GW of renewable power is available **[13].**

4.2.1 Wind Energy Potential in Ethiopia

Ethiopia has significant wind energy potential, estimated at 1,350GW. Resources are concentrated in the Somali region, with over 1,000GW of potential, mean wind speed of over 7m/s and pockets of areas with greater than 10m/s**.** Afar, Oromiya and the Southern Nations also have average wind speeds greater than 6.5m/s which is the minimum level required for wind power projects [**13].** Western regions such as Gambella and Benshangul-Gumuz average less than 4m/s. Only 324MW have been developed by 2016.

4.2.2 Wind Resource Assessment of the Study Area

In the study area since there is no meteorological stations, to determine the wind energy potential of the site the 10 year monthly average wind data were taken from NASA.

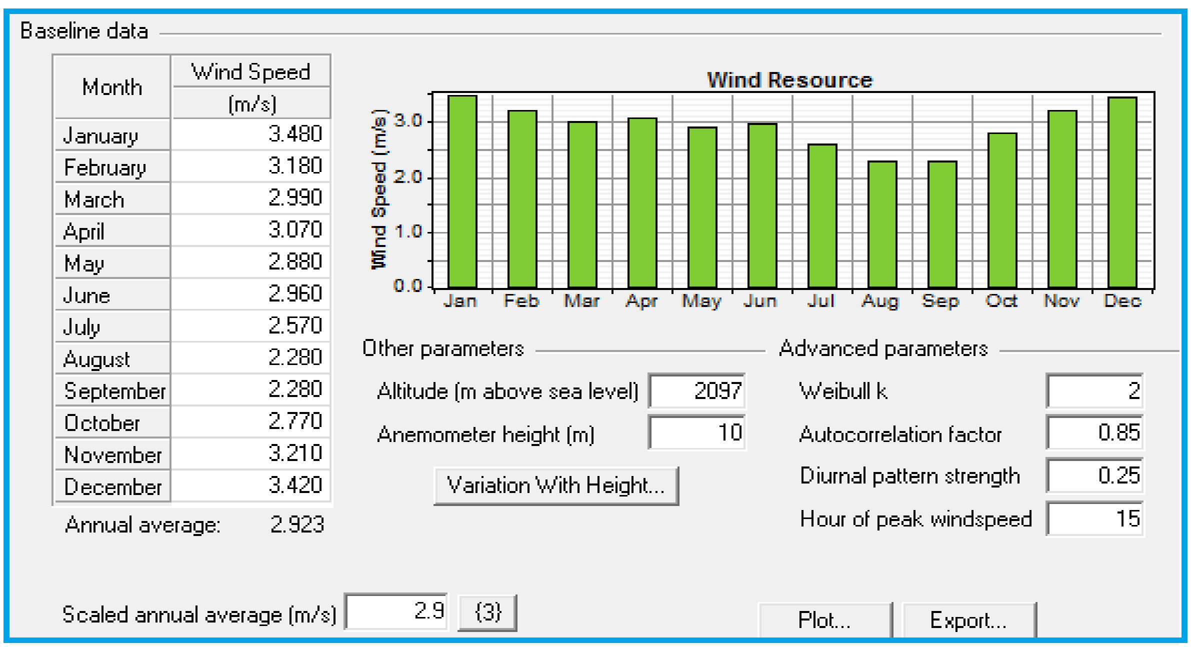


Figure 4. 3: Wind energy resource data of the study area

As it can be seen from Figure 4.3, the monthly average wind speed of the study site has maximum value in the month of January with a value of 3.48m/s. The minimum wind speed occurs in the month of August and September with 2.28m/s. January and December are the month with maximum average wind speed of 3.48 and 3.42m/s respectively. The average wind speeds of the other months are in between of the maximum and minimum values. For the study area the annual and monthly average wind speed is categorized in the first wind class. Therefore it is sufficient for hybrid off-grid electric power generation for the study community.

4.2.3 Statistical Wind Speed Distribution Analysis

Meteorological records typically provide average wind speeds which do not directly provide a reliable indication of average power output because of this nonlinear relationship between wind speed and output. However, the statistical properties of wind can be used to estimate the expected output of a wind generator [**41**].

The Weibull distribution provides the most general model of wind speed variation but when the Weibull shape factor which controls the evolution of the distribution from an exponential form to a bell curve is set to 2, it simplifies to a Rayleigh distribution. This shape factor is appropriate for a wind turbine that is employed for a rural mini-grid because it is intermediate between a mainly exponential function applicable to sheltered situations given by shape factor 1 and a bell curve distribution given by shape factor 3, which is more applicable to locations such as offshore with a sustained high average speed. Weibull distribution can be characterized by the two functions **[41].**

1. The probability density function
2. The cumulative distribution function

The probability density function f (V) indicates the fraction of time (or probability) for which the wind is at a given velocity V. It is given by **[36].**

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{K-1} e^{-\left(V/C\right)^{K}} \qquad (4.3)$$

Where, $k > 1, v \geq 0, c > 0$

Here, k is the weibull shape factor and c is scale factor. The cumulative distribution function of the velocity (v) gives us the fraction of time (or probability) that the wind velocity is equal or lower than V. Thus the cumulative distribution F (V) is the integral of the probability density function **[36].**

$$F(v) = \int_{0}^{\alpha} f(v)\,dv = 1 - e^{-\left(V/C\right)^{K}} \qquad (4.4)$$

Under the weibull distribution the main factors determining the uniformity of the wind is the shape factor k and uniformity of wind increases with the shape factor k. The shape factor can vary from 1 to 4. The values are known from experience and multiple observations of sites where wind speed measurements have been taken. The wind types are categorized as island, coastal and trade wind (off-shore) sites **[36].**

Table 4. 2: Typical shape factor values [35]

Types of winds	Shape factor (k)
Trade winds and Island	3.0-4.0
Coastal winds	2.5-3.5
Inland winds	1.5-2.5

When weibull shape factor k is not known, use k =2 for inland sites, 3 for coastal sites and 4 for island sites and trade wind regimes.

The probability density plotted against the wind speed and frequency is +shown in Figure 4.4.

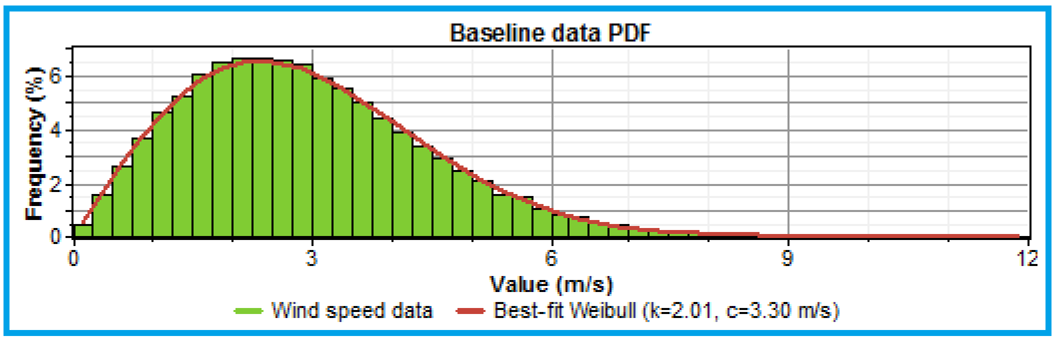


Figure 4. 4: Probability density plot between wind speed and frequency

The weibull distribution can vary from site to site both in its shape and median value. The two parameters that govern the shape of weibull distribution curve are the scale parameter and shape parameter. At higher value of scale parameter, the distribution is spread over a wider range and the probability average wind velocity has a higher value. At higher shape parameter between 2 and 3 the distribution is more skewed towards higher wind velocities, while it is between 1 and 2 the distribution is skewed towards lower velocities indicating a higher probability of lower wind velocities. As it can be seen from the graph the study site has a mean wind speed of 3.3 m/s and shape factor of 2.

Average wind velocity following weibull distribution is given by the following equation [**38].**

$$V_m = \int_0^\infty Vf(v)\, dv \tag{4.5}$$

Substituting equation 4.5 into equation 4.6

$$V_m = \int_0^\infty V\frac{k}{c}\left(\frac{V}{c}\right)^{K-1} e^{-(V/c)^K}\, dv \tag{4.6}$$

Equation 4.6 can be arranged in the form of

$$V_m = k\int_0^\infty \left(\frac{V}{C}\right)^k e^{-(V/C)^K}\, dv \qquad (4.7)$$

Taking

$$x = \left(\frac{v}{c}\right)^k,\ dV = \frac{c}{k}x^{\left(1/k - 1\right)}dx$$

Substituting for dV in equation 4.7

$$V_m = c\int_0^\infty e^{-x}x^{1/k}\, dx \qquad (4.8)$$

The standard gamma function can be

$$\Gamma n = \int_0^\infty e^{-x}x^{n-1}\, dx \qquad (4.9)$$

$$V_m = C\Gamma\left(1 + \frac{1}{K}\right) \qquad (4.10)$$

Taking k =2 in equation 4.10

$$V_m = C\Gamma\left(\frac{3}{2}\right) \qquad (4.11)$$

Evaluating the above equation and rearranging,

$$C = \frac{2}{\sqrt{\pi}}V_m \qquad (4.12)$$

V_m = average wind speed at 10m height which is 2.9 and the scale factor $C = 3.3$ m/s

4.2.4 Site specific wind speeds

As the scale and shape parameters have been determined, two meaningful wind speeds for wind energy estimation are very useful to wind energy investors. These are called the most probable (VF_{max}) and maximum energy carrying (VE_{max}) wind speeds. The most probable wind speed provides the most frequently occurring wind speed for a given wind probability distribution. The most probable wind speed can be calculated using the Weibull shape and scale parameters **[44].**

Under weibull approach probability density function can be expressed as follow **[36].**

$$f(V) = \frac{k}{c^k} V^{k-1} e^{-\left(V/c\right)} \tag{4.13}$$

For the most frequent wind velocity,

$$f'(v) = 0$$

$$\frac{k}{c^k} V^{k-1} e^{-\left(V/c\right)} \left[-\frac{k}{c^k} V^{2(k-1)} + (k-1)V^{(k-2)}\right] = 0 \tag{4.14}$$

Solving the above expression for V,

$$V = c\left(\frac{k-1}{k}\right)^{1/k} \tag{4.15}$$

$f'(v) > 0$, in the interval $\left[0, c\left(\frac{k-1}{k}\right)^{1/k}\right]$ and $f'(v) < 0$ in the interval $\left[c\left(\frac{k-1}{k}\right)^{1/k}, \infty\right]$

This implies that f(V) is maximum at V, therefore the most frequent wind speed in the regime is given by

$$VF_{max} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{4.16}$$

The velocity contributing maximum energy to the regime is given by **[43]**

$$VE_{max} = \frac{c(k+2)^{1/k}}{k^{1/k}} \tag{4.17}$$

4.2.5 Variation of Wind Speed with Heights

Depending on the size of the wind turbine envisaged for a given project, it may be desirable to adjust wind speeds from historic data, which are likely to be collected at about 10 m above ground level, to give wind speeds at the actual hub height (i.e., height of the center of rotation of the turbine). Wind speed rises with height, following approximately a power law **[27].**

$$\frac{V}{V_r} = \left(\frac{Z}{Z_r}\right)^{\alpha} \tag{4.18}$$

Where, V is the wind speed at required height Z, V_r is the wind speed at the reference height Z_r and α is an exponent which depends on the roughness of the terrain. The most frequently adopted value being 0.14 which is widely assumed for application to low surfaces and well exposed sites.

Table 4. 3: Typical shear exponents for different types of terrains

Terrain description	Shear exponent
Smooth, hard ground, lake or ocean	0.1
Short grass on untilled ground	0.14
Level country with high grass root	0.16
Tall row crops, hedges, a few trees	0.2
Many trees and occasional buildings	0.22-0.24
Wooded country-small towns and suburbs	0.28-3.0
Urban areas with tall buildings	0.4

4.2.6 Weibull Parameter Extrapolation

If the wind distribution is desired at some height other than the anemometer level, a Weibull C and k (values known at one height) should be extrapolated to another desired height. The Weibull distribution values C_{10} and k_{10} determined at 10 meters height above the ground level can be adjusted by the following relation **[41].**

$$C_z = C_{10} * (z/z_{10})^n \tag{4.19}$$

$$k_z = \frac{k_{10}}{1 - 0.00881\ln(z/z_{10})} \tag{4.20}$$

Where, z and z_{10} are in meters and the power law exponent n is given by

$$n = [0.37 - 0.00881\ln(C_{10})] \tag{4.21}$$

4.2.7 Wind Power Density Estimation of the study Site

Assessing the energy available in the wind regime prevailing at a site is one of the preliminary steps for wind energy project. Wind energy density and the available energy in the regime over a period are the yardsticks for evaluating the energy potential. The average wind power density for each month is calculated using actual probability density distribution for the specified month [**36].**

$$WP_D = \sum_{i=1}^{n} \frac{1}{2} \rho \, V_{mi}{}^3 \, f(vi) \tag{4.22}$$

Where, the subscript m stands for the month and n is the number of records for the specified month.

The average wind power density using weibull probability distribution is calculated as follows **[36]**

$$WP_D = \frac{1}{2}\rho C^3 \Gamma\left(1+\frac{3}{K}\right) \quad (4.23)$$

For k =2

$$C = \frac{2}{\sqrt{\pi}} V_m \quad (4.24)$$

V_m = average wind speed at 10m height which is 2.9 m/s

Γ is the gamma function and given as

$$\Gamma n = \int_0^\infty e^{-x} x^{n-1} dx \quad (4.25)$$

For shape parameter (k=2)

$$\Gamma\left(1+\frac{3}{2}\right) = \frac{3}{2} x \frac{\sqrt{\pi}}{2} = 3\frac{\sqrt{\pi}}{4} \quad (4.26)$$

Therefore wind power density for each month can be calculated by using the following equation.

$$WP_D = \frac{1}{2}\rho x\, C^3 x \frac{3\sqrt{\pi}}{4} \quad (4.27)$$

The density of air varies with elevation but assuming that it is constant and taken as 1.225kg/m^3.

Table 4. 4: Wind power potential of the study area

Month	Monthly average wind speed at 10m, m/s	Scale Factor (c) (m/s)	Wind power density (W/m^2)
Jan	3.48	3.93	49.4
Feb	3.18	3.58	37.3
Mar	2.99	3.37	31.2
Apr	3.07	3.46	33.7
May	2.88	3.25	27.9
June	2.96	3.34	30.3
July	2.57	2.89	19.6
Aug	2.28	2.57	13.8
Sep	2.28	2.57	13.8
Oct	2.77	3.13	24.9
Nov	3.21	3.62	38.6
Dec	3.42	3.86	46.8
Average	2.92	3.3	30.6

The wind power density of the study area specified in Table 4.4 is not constant; it varies from month to month. The minimum wind power density occurs in the month of September and August with 13.8W/m^2. January and December are the month with maximum power density of 49.4 and 46.8 W/m^2 respectively. The power densities of the other months are in between of the maximum and minimum values. For the study area the annual and monthly average wind speed, as well as the power density distribution are categorized in the first wind class. Therefore it is sufficient for hybrid off-grid electric power generation for the study area.

Table 4. 5: Wind class categories by wind speed and power density

Wind Class	At 10 m height		At 30 m height		At 50 m height	
	Wind power density (W/m^2)	Speed(m/s)	Wind power density (W/m^2)	Speed(m/s)	Wind power density (W/m^2)	Speed(m/s)
1	0-100	0.4-4	0-160	0-5.1	0-200	0-5.6
2	100-150	4.4-5.1	160-240	5.1-5.9	200-300	5.6-6.4
3	150-200	5.2-5.6	240-320	5.9-6.5	300-400	6.4-7.0
4	200-250	5.6-6.0	320-400	6.5-7.0	400-500	7.0-7.5
5	250-300	6.0-6.4	400-480	7.0-7.4	500-600	7.5-8.0
6	300-350	6.4-7.0	480-640	7.4-8.2	600-800	8.0-8.8
7	350-400	7.0-9.4	640-1600	8.2-11.0	800-2000	8.8-11.9

Source: united States, DOE

4.2.8 Wind Turbine Siting

The most challenging work of using wind turbine for wind energy extraction is searching the appropriate place. If located too close to the homes it creates noise. If it is too far away then the cost of cables should not be overlooked from economic pint of view **[39].** Looking at nature itself is usually an excellent guide to finding a suitable wind turbine site. The inclination of trees and bushes can reveals about the prevailing wind direction of the regime. However, the best guide is the Meteorological data in terms of wind rose calculated for 20-25 years. But in our country Ethiopia such data are rarely available. Therefore, Looking at nature itself is usually an excellent guide to finding a suitable wind turbine site. In addition to this the site to be selected should be free from nearby obstacles and the infrastructures such as road must also be taken into account.

4.1.1 Solar Energy Resource Potential of Ethiopia

Ethiopia's exploitable solar resource is estimated at 5.5 kWh/m^2/day or just over 2,000 kWh/m^2 annually compared to 2,015 kWh/m^2 in South Africa and California (Soda, Mines Paristech and Gesto Energia,1990-2004). The annual average daily radiation in Ethiopia reaching the ground is estimated to be 5.5$kwh/m^2/day$ which varies from a minimum of 4.5$kwh/m^2/day$ in July to a maximum value of 6.5$kwh/m^2/day$ in February and March and the country's annual total solar energy reserve is 2.199 Million TWh/annum [**13**]. The higher potential is mainly found in the central and northern parts of Ethiopia (Tigray, Oromiya and Ahmara regions) and the Somali region, where irradiation can exceed 2,450kWh/m^2. However, even in lower potential regions there are sufficient resources to develop grid and off-grid solar projects including the mini-grids.

4.1.2 Solar Resource Assessment of the Study Area

To use the solar photovoltaic as a power generation option, the solar resource data is important for simulation. In the study area there is no weather station and also it is far away from the next weather station where ground measurements of solar radiation performed. Therefore, the solar radiation data of the study area was taken from NASA surface meteorology at 8.59° N latitudes and at 38.8° E longitudes. The 22 years monthly average solar radiation was 5.81kWh/ m^2/day.

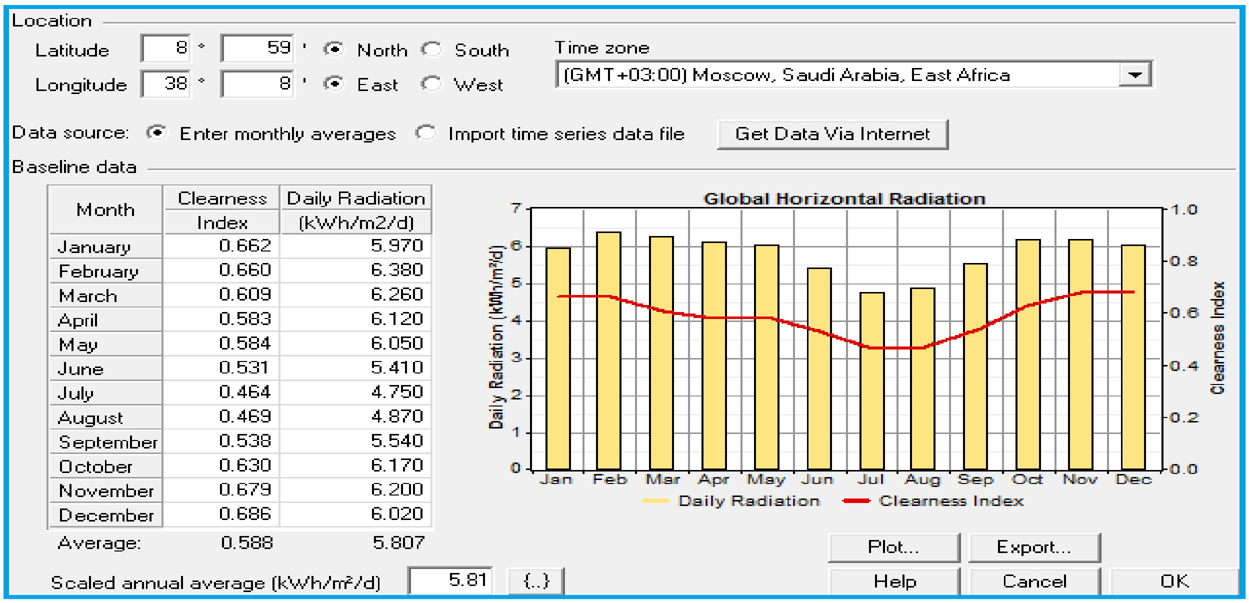


Figure 4. 5: Solar energy resource of the study area

As it can be seen from Figure 4.5 the daily solar radiation of the study site has maximum value in the month of February with a value of 6.38Wh/ m^2/day. Since July and August are the months of the rainy season of the site, the intensity of solar radiation is found to be 5.8kWh/ m^2/day and this value indicates the area has good solar potential for the implementation of photovoltaic systems to give electric power for the community.

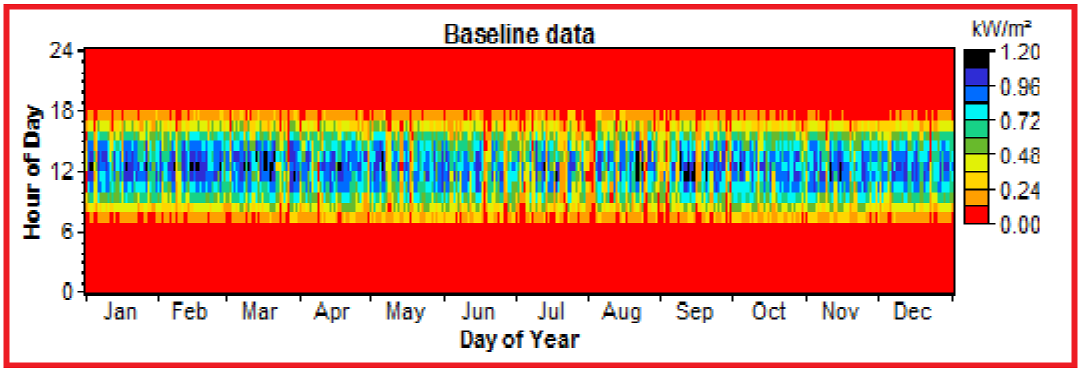


Figure 4. 6: Data map of daily solar radiation pattern

As the data map of the diurnal solar radiation shows the highest solar radiation is occurred approximately from 9:00 to 16:00 hours. The daily variation of solar radiation is from middle of May till the month of August and June, July and August the month of rainy season.

4.1.3 Sequences of Activities to Determine the Power Output of PV Arrays

Steps to calculate approximately the power output of photovoltaic array are as follows:

1. Determine the solar radiation at the horizontal surface based on the day of the year and the site latitude and then establish a clearness index.
2. The clearness index is used to calculate the direct, diffuse and random components of the radiation on a horizontal surface.
3. The total radiation is then calculated from the direct, diffuse and random values obtained
4. Finally, the radiation on the surface of panel is determined. It requires monthly average values of solar radiation on the horizontal surface of a specific site location.

4.1.4 Determination of Solar Time and Equation of Time

There is a difference between real time and solar time. For a given point on the earth's surface in the Northern/Southern hemisphere, solar noon in defined as the time of the day when the sun appears due South/North. Solar time is the time of day measured from solar noon. Solar time coincides with real time only at certain times of the year; examples when the earth is at perigee or apogee of its orbit. At other times, real and solar time may differ by as much as ± 15 minutes. The difference between local solar time and local standard time (corrected for longitude) is called equation of time (EOT) **[23].**

$$\mathrm{EOT} = 9.87\sin(2\beta) - 7.53\cos(\beta) - 1.5\sin(\beta)\ (\mathrm{Minutes}) \quad (4.28)$$

$$\beta = \frac{360(\mathrm{N} - 81)}{364} \quad (4.29)$$

Where, N = days of the year

$$\text{Solar time} = \text{Standard time} + 4 * (L_{st} - L_{loc}) + \mathrm{EOT} \quad (4.30)$$

Where,

L_{st} = standard meridian for the local time zone(degrees)

L_{loc} = Longitude of the location (degrees)

4.1.5 Determination of Solar Angles

Solar angles are the angles obtained from the sun earth geometry. These angles are responsible for the radiation that falls on the earth surface including PV module.

Latitude (ϕ): It is the radial line joining the given location to the center of the earth with its projection of the equatorial plane. The latitude indicates how far north or south location is from the equator. By convection, latitude is measured positive for the northern hemisphere.

Declination angles (δ): It is the angle made by the line joining the centers of the sun and the earth with its projection on the equatorial plane. It happens because the earth rotates about an axis, this varies from a maximum value of +23.45° on June 21 to a minimum value of -23.45°on December 21, zero on the two equinox days of March 21 and September 21 [**12**].

$$\delta = 23.45\sin\left(360\frac{284 + N}{365}\right) \quad (4.31)$$

Where, N = days of the year, the number of days ranged from 1 to 365.

Hour Angle (ω): It is the angle measured in the earth's equatorial plane between the projections of the distance to the center of the earth and the projection of a line from the center of the sun to the center of the earth. It is an angular measure of time and is equivalent to 15° per hour, measured from noon based on the local solar time or local apparent time being positive in the morning and negative in the afternoon.

$$\omega = \left(\frac{360°}{T_{day}}\right) * ST \quad (4.32)$$

Where, ω is the sunset hour in degrees, T_{day} = Length of the day in second and ST = standard time

Collector Slope (β): It is the angle made by the plane surface with horizontal taken to be positive for surfaces sloping towards the south and vice versa. In this work the value of beta is taken as 8.59 degrees.

Zenith angle (θ_z): It is the complementary angle of sun's altitude angle between the sun's rays and a line perpendicular to the horizontal plane through the point that is the angle between the beam from the sun and the vertical.

Azimuth Angle (γ_s): It is the the solar angle in degrees along the horizontal east-west of north. By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west

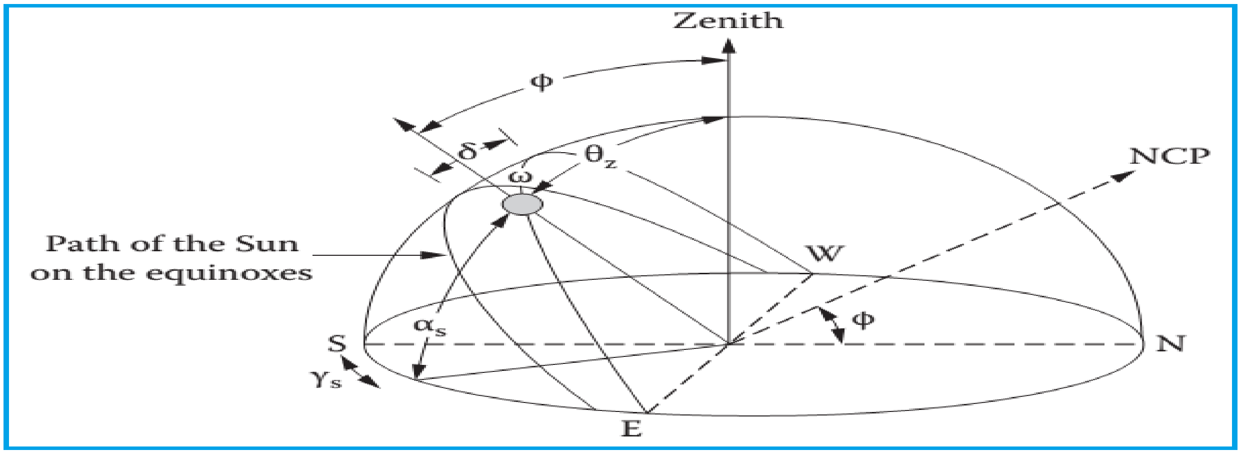


Figure 4. 7: Position of the Sun in the sky relative to the solar angles [57]

4.1.6 Extraterrestrial solar radiation

It states that the amount of solar radiation arriving at the top of the atmosphere over a particular point on the earth's surface. To determine the extraterrestrial normal radiation, defined as the amount of solar radiation striking a surface normal (perpendicular) to the sun's rays at the top of the earth's atmosphere the following equation is used **[57].**

$$G_{extra} = I_o \left[1 + 0.033 \cos\left(\frac{360 * n}{365}\right)\right] \quad (4.33)$$

Where, I_o is the solar constant, $1367\ W/m^2$ and n is the number of days

4.1.7 Determination of Global solar Radiation on Titled Surface

Global solar radiation is the total solar radiation that reaches the earth's surface. The global solar radiation on a tilt surface consists of three components **[26]**, namely, direct solar radiation, G_B diffuse solar radiation, G_D and reflected solar radiation G_R.

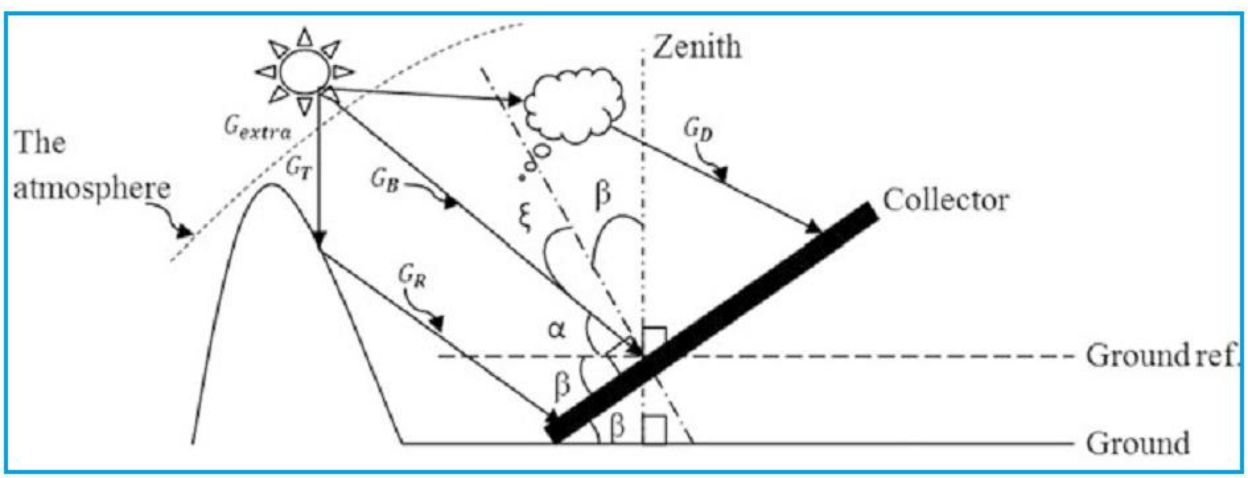


Figure 4. 8: Solar radiation components on a tilt surface [26]

The global radiation which falls on a tilt surface is given by [**26**].

$$G_T = G_B + G_D + G_R \quad (4.34)$$

4.1.8 Estimation of solar radiation

The sizing of PV system for electricity generation depends mainly on the solar radiation since the produced power depends on its value. Since the solar radiation reaching the earth's surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential.

4.1.9 Prediction of Monthly Average Daily Global Radiation on a Horizontal Surface

The first empirical correlation using the idea of employing sunshine hours for the estimation of global solar radiation was proposed by Angstrom. Later it was modified by Prescott and Page. The simplest model used to estimate monthly average daily solar radiation on horizontal surface is the well-known Angstrom equation [**12**].

$$H = H_o\left[a + \frac{n}{N_s}b\right] \quad (4.35)$$

Where

H = monthly average daily global solar radiation (MJ/m^2)
H_o = monthly average daily extraterrestrial solar radiation (MJ/m^2)
$a\&b$ = Angstrom's correlation parameter
n = monthly average daily hours of sunshine from sunshine recorder
N_s = monthly average of the maximum possible hours of sunshine

The correlation parameter can be calculated using the following expression

$$a = -0.309 + 0.539\ \text{Cos}\phi - 0.0693E_o + 0.290\left(\frac{n}{N_s}\right)$$

$$b = 1.527 - 1.027\ \text{Cos}\phi + 0.0926E_o - 0.359\left(\frac{n}{N_s}\right)$$

Where

E_o = Altitude of a site in kilometers

δ = Declination angle for the average day in the month

ϕ = Latitude of the site

The total radiation incident on a horizontal surface can be given by Klein relationship

$$H_o = \frac{24x3600G_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360N_s}{365}\right)\right]\left[\cos(\phi)\cos(\delta)\sin(\omega_s) + \left(\frac{\pi\omega_s}{180}\right)\sin(\phi)\sin(\delta)\right]$$

The solar day length (N_s) is calculated by using **[25].**

$$N_s = \frac{2}{15}(\omega_s) \tag{4.36}$$

$$\omega_s = \cos^{-1}\big(-\tan(\phi)\tan(\delta)\big) \tag{4.37}$$

4.1.10 Prediction of Monthly Average Daily Diffuse Radiation on a Horizontal Surface

The monthly average daily diffuse radiation on a horizontal surface can be determined from the monthly average daily global radiation on a horizontal surface and the number of bright sunshine hours [**12**].

$$\frac{H_d}{H} = 0.931 - 0.814\left(\frac{n}{N_s}\right) \tag{4.38}$$

4.1.11 Prediction of Monthly Average Hourly Global Radiation on a Horizontal Surface

The monthly average hourly global radiation on a horizontal surface can be given by the following equations [**12**].

$$\frac{I}{H} = \frac{\pi}{24}(a + b\cos\phi) * \frac{\cos\phi - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \tag{4.39}$$

Where,

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60)$$

4.1.12 Prediction of Monthly Average Hourly Diffuse Radiation on a Horizontal Surface

The monthly average hourly diffuse radiation on a horizontal surface can be given by the following equations [**12**].

$$\frac{I_d}{H_d} = \frac{\pi}{24} * \frac{\cos\phi - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \tag{4.40}$$

CHAPTER FIVE

5. HYBRID SYSTEMS COMPONENTS CHARACTERISTICS, COSTS AND MODELING WITH HOMER

5.1 Hybrid Power Generation Systems

Hybrid power generation system is an alternate solution for electrification of remote rural areas where the grid extension is difficult and not economical. Such system incorporates energy producing components that provide a constant flow of uninterrupted power. This is a combination of different renewable energy resources such as solar photovoltaic modules and wind turbine and diesel generator as a backup.

One of the main problems of renewable energy, in particular of solar and wind is the strong variability of the resources. Indeed, solar radiation is available only during the day and both solar and wind resources vary according to the weather and seasonal conditions. For these reasons, when off-grid loads require supply continuity, large energy storage capacity could be necessary if a single technology is used and power systems need to be oversized in order to produce an excess of electricity for storage. As a consequence, the cost of the system can considerably increase. Moreover, in some cases a single source does not provide enough energy to meet the load's requirements. In most of these cases, the implementation of hybrid systems can provide competitive advantages. As a matter of facts, hybrid systems are able to produce electricity even at times when one of the used resources is unavailable.

5.2 Types of hybrid system configuration

5.2.1 Solar photovoltaic/diesel or wind/diesel

Solar photovoltaic or wind coupled with a diesel gen-set is one of the most common and simple configurations. SPV or wind provides most of the electricity, while the gen-set balances the production when fluctuations of renewable resources occur. In general, the presence of a fully dis-patchable power system makes storage optional. Nevertheless, batteries are often included in the system: in this case batteries meet short-term fluctuations, and the diesel generator takes care of the long-term fluctuations **[2].** Typically, this kind of system is used for generation capacities up to 100 kW when quality power cannot be delivered by the intermittent sources alone **[7].**

5.2.2 Photovoltaic and wind

If the site conditions are favorable, a system combining two renewable sources such as solar and wind is more reliable than a system using a single resource **[8].** Clearly, the performance of such systems strongly depends on local weather variations, and an accurate assessment of both solar and wind resources during the year is mandatory.

The system requires battery storage, inverter and charge regulator **[8]:**

- ✓ If electricity demand is lower than wind turbine production, the excess electricity form wind turbine and PV is stored;
- ✓ If load demand is higher, the PV array cover the excess load;
- ✓ If load demand is higher than the power supplied from both renewable systems, additional energy is taken from the storage.

5.2.3 Hybrid System Connection Schemes

Depending on the kind of voltage system and the bus that interconnect the sources, there are three types of hybrid system connection schemes. AC bus line, DC bus line, or mixed bus line are the most frequently used in remote areas **[51].**

1. **AC bus line**: all generating units are connected to an AC bus line for power transmission. PV arrays need a DC/AC converter, while technologies generating alternate current such as wind and gen-set are allowed for direct coupling. Regarding the battery bank, the energy supply is controlled by a bidirectional inverter. AC coupled system is more flexible, easily expandable and it offer a flexibility for extension when necessary. Due to the above functionality this type of connection system has been selected for this work.

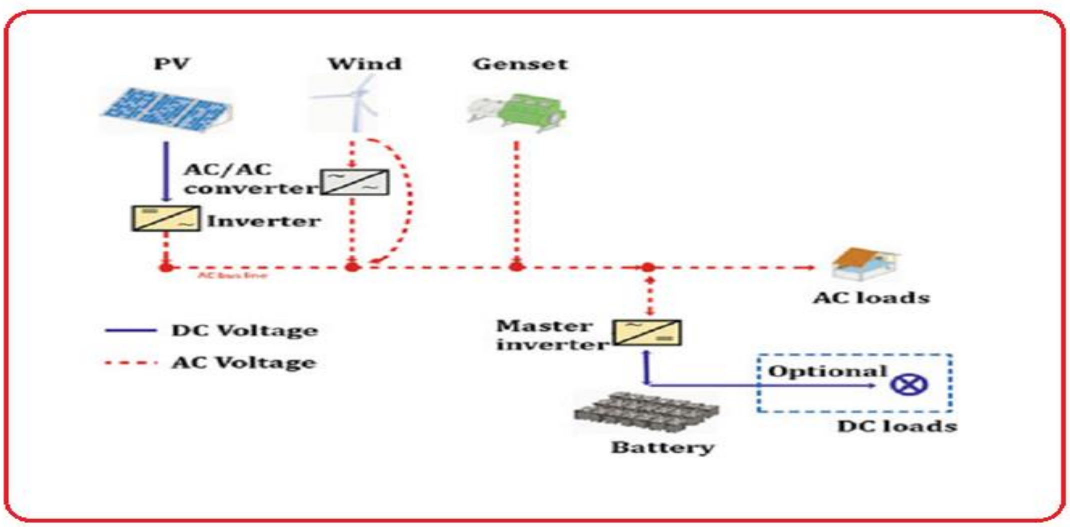


Figure 5. 1: AC bus line hybrid system [51]

2. **DC bus line:** in this case all the technologies generating alternate current need AC/DC converter. This means that the PV generating source is equipped with charging controller and AC generating sources with rectifier this means that the power generated by wind and diesel generator are first rectified and then converted back to AC bus line which

reduces the efficiency of energy conversion due to several power processing stages. Due to this reason these connection scheme have not been selected for this work.

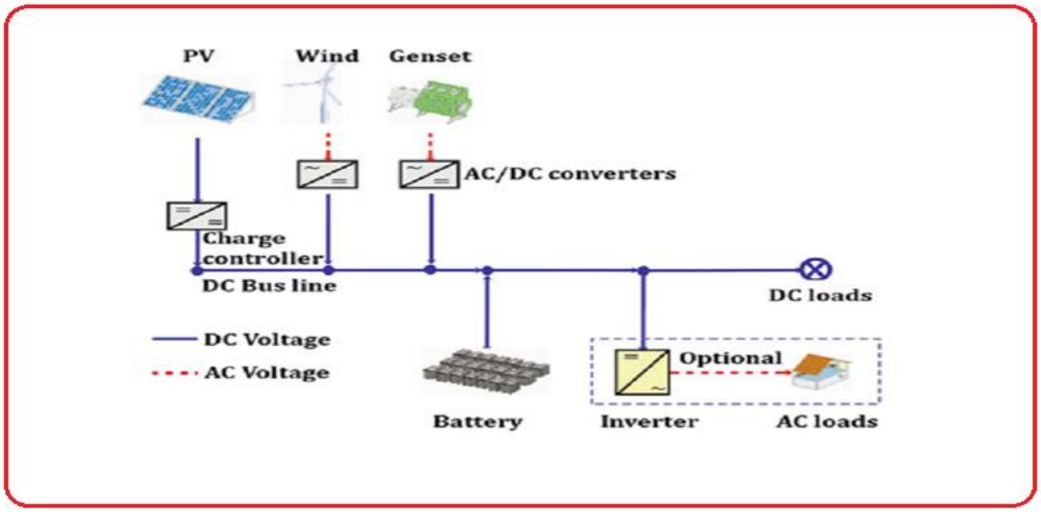


Figure 5. 2: DC bus line hybrid system [51]

3. **Mixed bus line**: DC and AC generating units are connected to the DC or AC line. This system uses a bidirectional master inverter to link the DC bus and AC bus. In this the efficiency of the generator can be maximized due to the capability of the inverter operation parallel with the AC bus line. Therefore, these connection schemes have not been selected due to its two buses and to ignore the danger which may be generated due to the failure of the bidirectional master inverter.

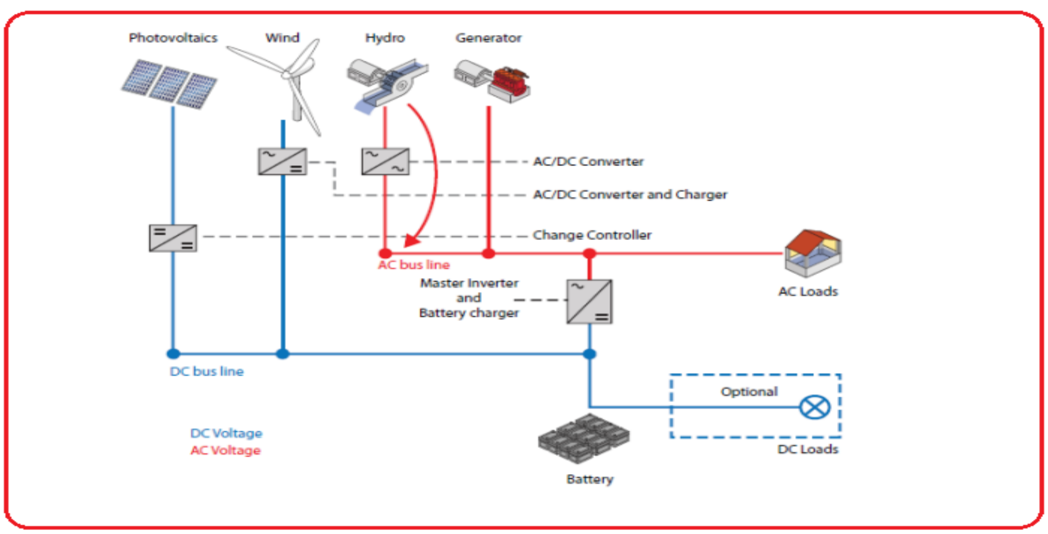


Figure 5. 3: AC/DC bus line hybrid system [51]

5.3 Hybrid System Components Characteristics

Hybrid energy system model in Homer comprises of five primary components which includes PV system, wind turbine, diesel generators, converter and storage batteries.

5.3.1 Photovoltaic (PV) Cells, Panels and Arrays

A PV cell is a semiconductor device that can convert solar energy into DC electricity through the photovoltaic effect. The PV generated electricity is 'silent', low in maintenance and does not need fuel or oil supplies. However, PV energy is only available when enough radiation is accessible.

A PV panel consists of several connected PV cells. The power rating of a panel is specified at standard test conditions (STC) which include a defined cell junction temperature, usually 25℃ and irradiance of 1000 W/m^2 and is the maximum power output in this state expressed in peak watt (W_P) also it depends on its cell area and efficiency. PV panels are available in wide variety of ratings, in some cases up to 300 W_P each are manufactured. Also developments are under way to produce alternating current panels by including an inverter into the panel setup to enable easy and modular AC bus connection **[24].**

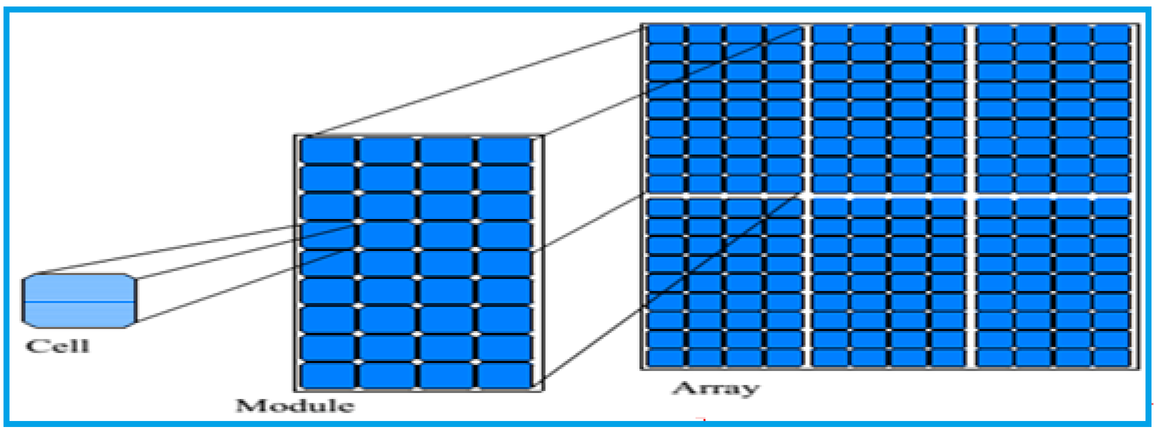


Figure 5. 4: Photovoltaic cells, modules and arrays [24]

If higher voltages are required from a single module voltage and current, modules must be connected into arrays. Series connection results in higher voltages, while parallel connections results in higher currents. When modules are connected in series, it is desirable to have each modules maximum power production occur at the same current. But when they are connected in parallel, it is desirable to have each modules maximum power production occur at the same voltage**.**

5.3.2 Photovoltaic Performance Characteristics

The electrical performance characteristics of PV cell is generally represented by the currents versus voltage (I-V), power versus voltage (P-V), efficiency versus irradiance (E-I) and efficiency versus temperature (E-T) curves). The figure below depicts the electrical characteristics curve of a generic poly crystal 60Wp PV module. Those curves shows the variation of current, voltage, power and efficiency of the modules when cell resistance, solar irradiance and cell temperature varies. In the I-V characteristics curve the point at which the voltage is zero is called the short circuit current. This is the current we would measure with output terminal shorted. On the other hand the point at which current is zero is called as an open circuit voltage. This is the voltage we would measure with output terminal open. Somewhere in the middle of the two regions, the curve has a knee point. The power output of PV cell/module can be obtained from the PV cell or module current and terminal voltage from different operating conditions of the module. The following relation is used to calculate the output of the photovoltaic array [**40**].

$$P_{PV} = \gamma_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)\left(1 + \alpha_P\left(T_C - T_{C,STC}\right)\right) \tag{5.1}$$

γ_{PV} = rated capacity of the PV array, meaning its power output under standard test conditions [kW].

f_{PV} = PV derating factor (%). HOMER exercises this factor to the output power PV array to take into account some factors which lower the output in real conditions.

α_P = tempearature coefficient of power (%/°C)

$G_{T,STC}$ = incident radiation at standard test conditions ($1kW/m^2$)

T_C = cell temperature(°C)

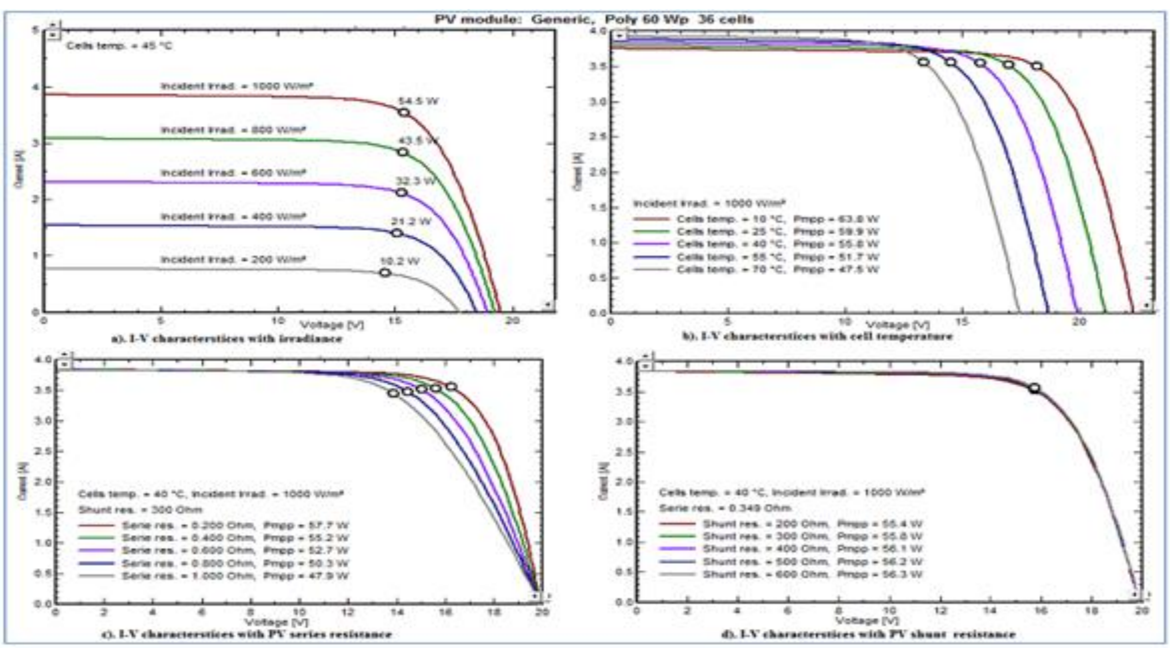


Figure 5. 5: I-V curve of generic 60Wp poly crystal PV module [48]

Photovoltaic manufacturers rate the power output of their PV modules at a standard test conditions (STC), meaning a radiation of $1kW/m^2$, a cell temperature of 25℃ and no wind. Standard test conditions do not reflected typical operating conditions, since full sun temperatures tend to be much higher than 25℃. The temperature coefficient of power indicates how strongly the PV array power output depends on the cell temperature, meaning the surface temperature of the PV array. It is a negative number because power output decreases with increasing temperature. Manufacturers of PV modules usually provide this coefficient in their product brochures, often labeled either coefficient as power temperature coefficient in %/℃. Also PV power output increases with increase of solar irradiance reached on the PV surface **[40].**

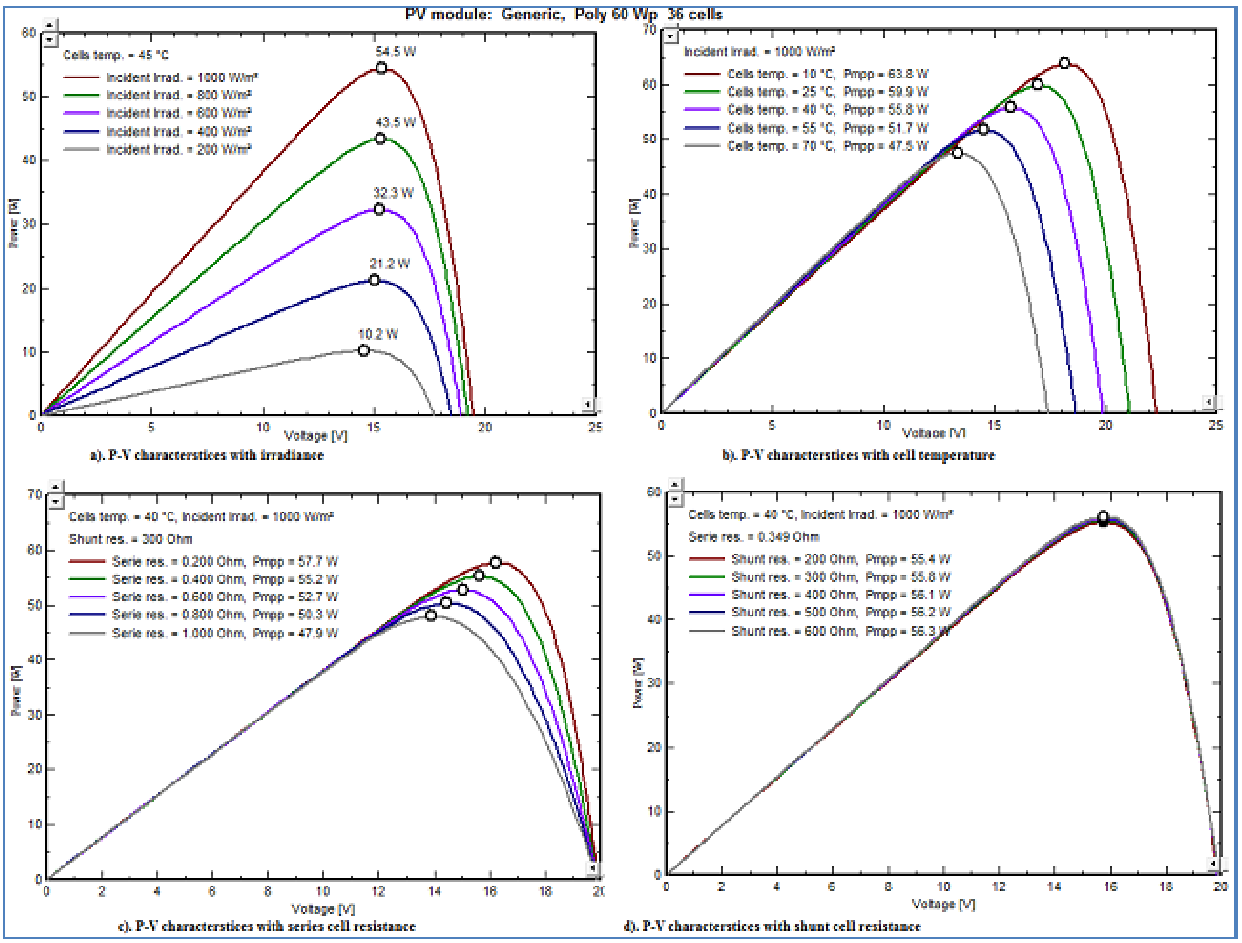


Figure 5. 6: P-V curve of generic 60Wp poly crystal PV module [48]

The photovoltaic cell temperature is the temperature of the surface of the PV array. During the night it is the same as the ambient temperature, but in full sun the cell temperature can exceed the ambient temperature by 30℃ or more [**40**]. The design of a PV power supply system should account the effect of PV cell temperature on PV power output. In photovoltaic based hybrid electric power supply system HOMER will calculate the cell temperature in each time step and use that in calculating the power output of the PV array. An energy balance for the PV array is given by the following equation **[48].**

$$\tau\alpha G_T = \eta_C G_T + U_L(T_C - T_a) \qquad (5.2)$$

Where,

τ = The solar transmittance of the cover in percentage

α = The solar absorptance (%)

G_T = The solar radiation striking the array (kW/m^2)

η_C = The electrical efficiency of array in percentage

U_L = Heat transfer coefficient (kW/m^2 °C)

T_C = The temperature of the cell (°C)

T_a = The ambient temperature(°C)

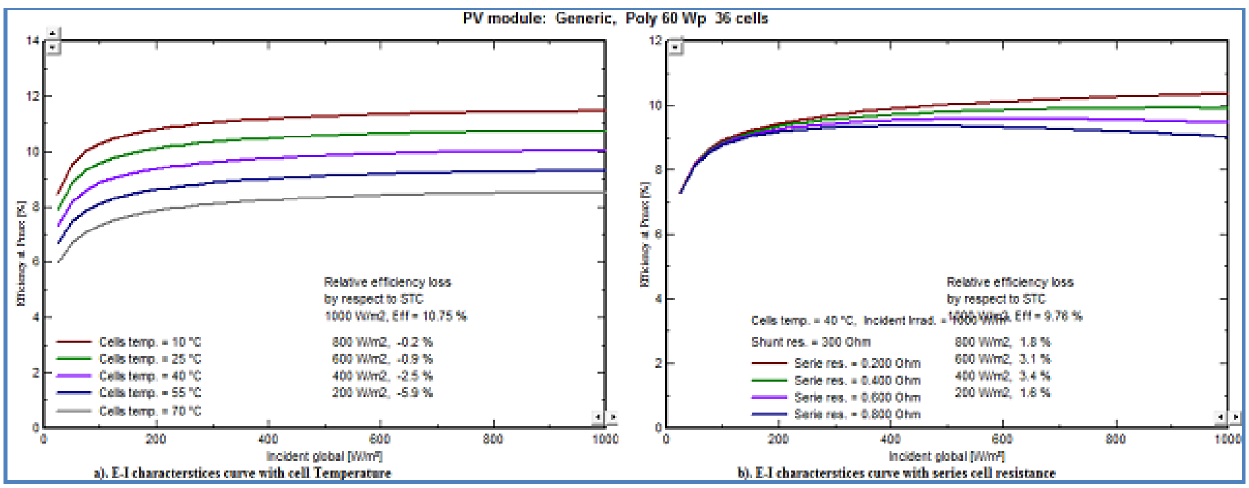


Figure 5. 7: E-I curve of generic 60Wp poly crystal PV module [48]

The above equation (5.2) states that a balance exists between the solar energy absorbed by the PV array and the electrical output plus the heat transfer to the surroundings. Solving for the cell temperature the following equation (5.3) is obtained.

$$T_C = T_a + G_T\left(\frac{\tau\alpha}{U_L}\right)\left(1 - \frac{\eta_C}{\tau\alpha}\right) \qquad (5.3)$$

It is difficult to measure the value of $\tau\alpha/U_L$ directly, so instead manufacturer report the nominal operating cell temperature (NOCT) which is defined as the cell temperature that results at an incident radiation of $0.8\ kW/m^2$, an ambient temperature of 20°C and no load operating, meaning ($\eta_C = 0$).

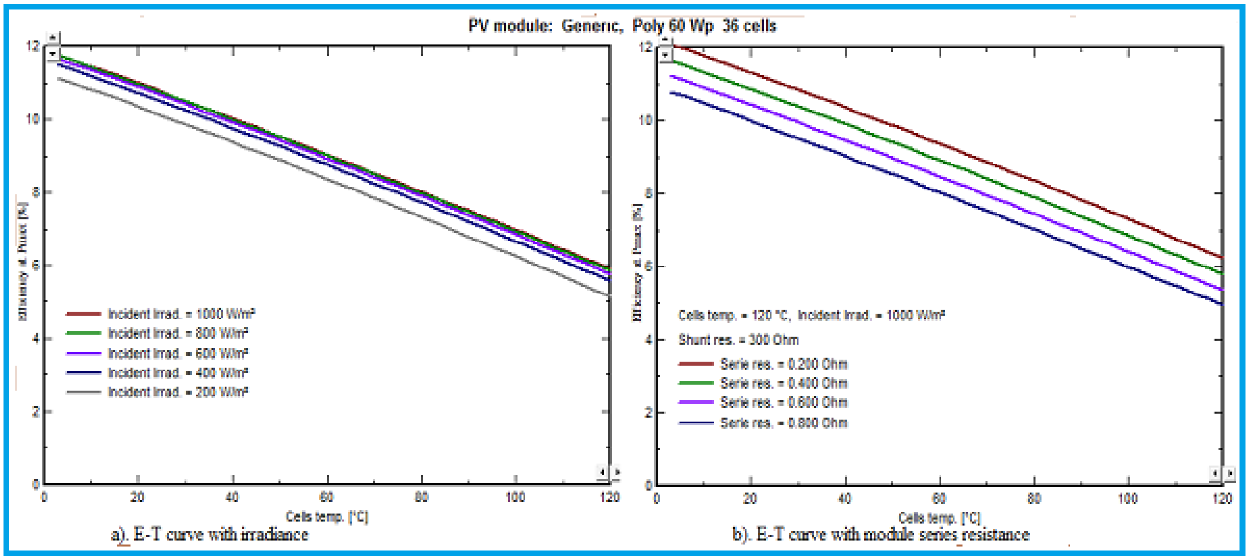


Figure 5. 8: E-T curve of generic 60Wp poly crystal PV module [48]

By substituting the equation of (5.3) into the above equation (5.2) and solve for $\tau\alpha/U_L$ to get the following equation (5.4) [**12**].

$$\tau\alpha/U_L = \frac{T_{C,NOCT} - T_a}{G_{T,NOCT}} \tag{5.4}$$

Where,

$T_{C,NOCT}$ = The nominal operating cell temperature (℃)

$G_{T,NOCT}$ = The radiation of solar with NOCT ($0.8\ kW/m^2$)

T_a = The ambient temperature for NOTC (20 ℃)

Assuming the ratio of $\tau\alpha/U_L$ is constant and substituting in to the cell temperatures, the following equation can be obtained.

$$T_C = T_a + G_T\left(\frac{T_{C,NOCT} - T_a}{G_{T,NOCT}}\right)\left(1 - \frac{\eta_C}{\tau\alpha}\right) \tag{5.5}$$

5.3.3 Photovoltaic Cost

Photovoltaic solar panel cost has been reduced dramatically in the past ten years and it is assumed to continue its down slope of the future. The cost of solar panel is variable that actually depends on the time, place and the solar panel installation. The cost of an investment in a PV system is driven mostly by the initial up-front investment or capital expenditure. Additional costs encountered during a system's lifetime are comparatively low. According to the National

Renewable Energy Laboratory the Photovoltaic costs for different sectors are presented in Table 5.1 below.

Table 5. 1: Photovoltaic system cost benchmarks

Sector	Residential PV	Commercial PV	Utility-Scale PV, Fixed-Tilt
Quarter 2016 benchmarks in 2016 $/Wdc	$2.93	$2.13	$1.42
Quarter 2016 benchmarks in 2017 $/Wdc	$2.98	$2.17	$1.45
Quarter 2017 benchmarks in 2017 $/Wdc	$2.80	$1.85	$1.03

5.3.4 Wind Turbine Types and Blade Aerodynamics

Wind turbines are the machines that transfer the kinetic energy of the wind into useful mechanical power. If the mechanical energy is directly used for pumping water or grinding stones, the machine is called a wind mill. If the mechanical energy is converted to electricity the machine is called a wind generator. Depending on the position of the rotor axis, wind turbines are classified as either vertical-axis or horizontal axis.

The horizontal axis turbine, HAWT is the most common type of turbine and it can be categorized into two different types: the up wind turbine which has the rotor facing the wind. In these machines the wind meets the rotor first and then leaves from the direction in which the nacelle is located and the downwind machines that have the rotor placed on the leeward side of the tower; this means the nacelle comes first in the path of the wind and then the blades. In HAWT the rotor axis lies horizontally parallel to the air flow. The blades sweep a circular plane normal to the air flow situated upwind (in front of the tower) or downwind (behind the tower). The main advantage of HAWTs is the good aerodynamic efficiency and versatility of applications. The main disadvantage is that the tower must support the rotor and all gearing and also electrical generator standing on top of it, the necessity of yawing to face the wind is also their disadvantage [**38**].

Modern wind turbine is the sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. The sizes of them can be range from a few watts (small wind turbines) to several watts (large wind turbines). Most of today’s commercial machines are horizontal axis wind turbine with three bladed rotors. Wind turbine single source systems tend to produce highly variable and therefore unreliable power supply due to the irregularity of wind speeds. If they combine with other sources in form of hybrid systems the produced energy can become more regular improving the system performance and cost effectiveness. The wind turbine types and their configuration as well as the cross section view a wind turbine is illustrated in Figure 5.9 and Figure 5.10 respectively.

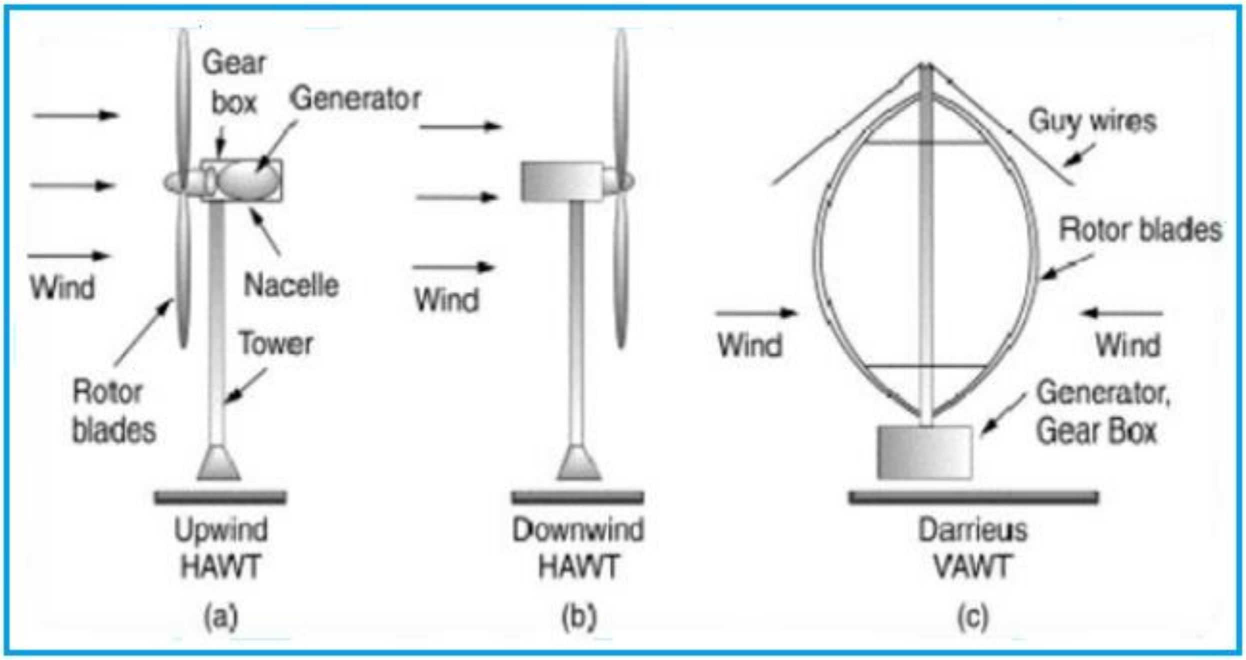


Figure 5. 9: Wind turbine types and their configuration [38]

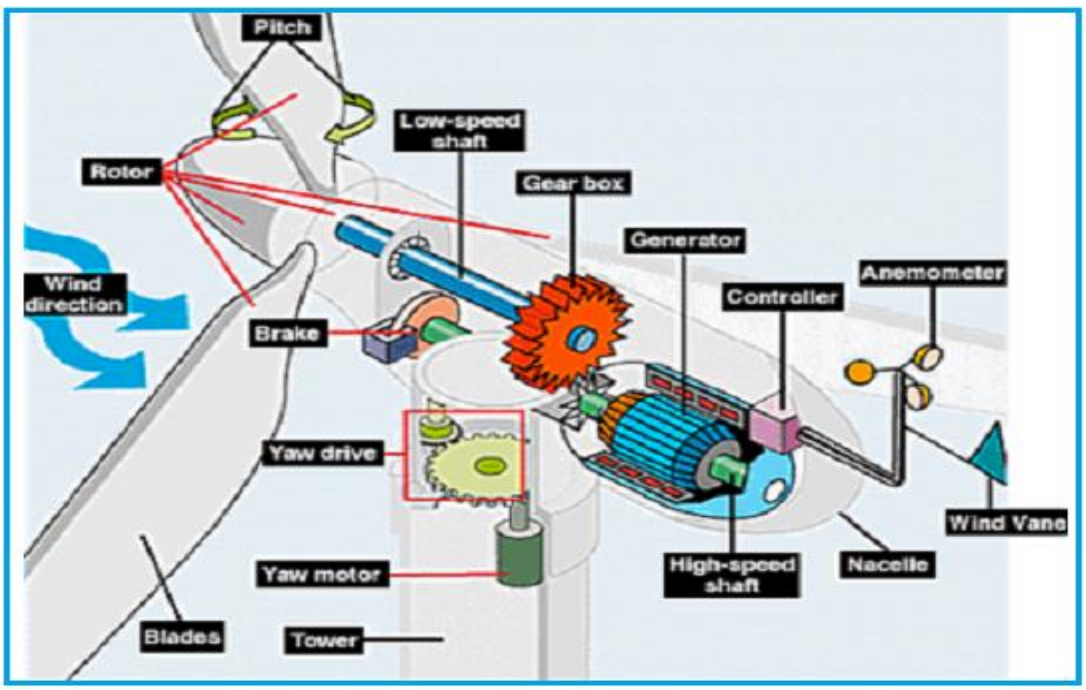


Figure 5. 10: Cut view of wind turbine [38]

Blades: These are the main components that capture the kinetic energy of the wind and help the turbine rotate.

Brake: It is the mechanical speed reducer that prevents the generator speed from increasing above the maximum value. Even though the pitch for the blades can be helpful for speed reduction, the brakes have a faster response than that of the pitch control. The low speed shaft is connected to a gearbox with a high turn ratio that provides faster rotating speed to the generator during low wind speed conditions.

Gearbox: It is the component that allows the wind turbine shaft to be coupled to the generator shaft.

Generator: It is the mechanical to electrical energy conversion unit of the system that is driven by the mechanical power of the turbine. The electrical output of the generator is connected to the grid or load through power electronic converters.

High-speed shaft: It drives the generator without a gearbox and it is essentially a gearbox with a turn ratio that is smaller than that of the low speed shaft. It is effective during high-wind-speed conditions.

Tower: It supports the body of the turbine and the other components.

5.3.5 Wind Turbine Generators

Wind turbine generators are different from other generating units in that the input power to the generator shaft is taken from the wind turbine rotor which fluctuates greatly in terms of mechanical power. The transmission system consists of the rotor shaft with bearing, brakes, an optional gear box as well as a generator and optional clutches. There are two types of generator, synchronous and asynchronous. Synchronous generators are more expensive compared to asynchronous (induction) generators. Six pole asynchronous generators are the most commonly used types [**54**]. This is applicable only for large wind turbine technology. The design principle of small wind turbines is different from the large wind turbines. The main purpose of small wind turbine is to produce power frequently over short periods. It is important that small wind turbines generates in weak winds and responds quickly when strong winds occur. The rapid starting of the rotor before the generator cuts in is a further requirement [**37**]. Small wind turbines often have direct drive generators (without a gearbox) and give out direct current. Their blades could be aero-elastic types and usually need the vane to point into the wind.

5.3.6 Wind Turbine Efficiency and Power Curve

The theoretical limit of power extraction from wind was derived by German aerodynamicist Albert Betz. Betz law [**55**] states that 0.59 or less of kinetic energy in the wind can be transformed to mechanical energy using a wind turbine. In practice wind turbines rotors deliver less than Betz limit. The factors that affect the efficiency of a turbine are the turbine rotor, transmission and the generator. Normally, the turbine rotors have efficiency between 40% to 50%. Gear box and generator efficiencies can be estimated to be around 80% to 90%. This efficiency is not constant, it varies with wind speeds.

5.3.7 Mechanism of Wind Power Control

With regard to the power control mechanism, the power regulation mechanisms must be implemented is such a way that power output is limited close to the rated value as wind turbines have their highest efficiency at the wind speed they are designed for. There are three commonly used wind power control mechanisms [**54**]. These are:

1. **Stall control**: Using stalling regulation the aerodynamic design principle is to increase the angle at which the relative wind strikes the blades (angle of attack) and to reduce the induced lifting force at the moment the wind speed becomes too high. This happens because of turbulence created on the side of the rotor blade which is not facing the wind. Stall controlled wind turbines have their rotor blades bolted onto the hub at a fixed angle.
2. **Pitch control**: This is usually hydraulically operated. An electronic controller which depends on the output power sends a signal to the blade pitch mechanism so as to turn the rotor blades out of the wind to the exact degree required and to keep the rotor blades at the optimum angle for maximized output at all wind speeds. In this the rotor blades are rotated around their longitudinal axis [**54**].
3. **Active stall regulation**: With this the machine is usually programmed to pitch the blades much like a pitch controlled machine at low wind speeds so as to get a reasonably large torque at low wind speeds. If the generator is about to be loaded, then the machine also pitches its blades to increase the angle of attack of the rotor blades forcing the blades to go into a deeper stall thus wasting the excess energy in the wind [**54**]. In this control mechanism the machine can be run almost exactly at rated power at all high wind speeds.

5.3.8 Wind Turbine Costs

The capital cost associated to the wind energy system includes the cost of turbine, tower, inverter, wiring, painting, anti-corrosion packages and the installation cost. The European Commission, in its road map, assumes that onshore wind energy cost €948/kW in 2007. It assumes that costs will drop to €826/kW in 2020 and €788/kW in 2030. The long term cost curve may still apply for a situation where there is a better balance between demand and supply for wind turbines than at the present time.

The Fuhrlander wind turbine with a rated power of 30kW at rated wind speed of 12m/s and hub height of 50 m is used in HOMER with component cost of US$972/kW for initial capital cost, $952/kW for replacement cost and operation and maintenance cost is taken to be 7% of an initial capital cost and the projected life time is 25 years. Detailed technical specification and capital cost of on shore and off shore wind turbine according to EWEA is annexed in Appendix 5A.1 and 5A.2 respectively.

5.3.9 Back-up Components

The low reliability of PV-wind hybrid systems is a major barrier for market development of such renewable systems. Therefore, diesel generators have been widely employed along with renewable sources to increase the reliability of such systems. The initial capital cost of diesel generator is relatively small when compared to PV cost and wind turbine cost. The big problem with this is that, the operation and maintenance cost is very high because it requires a continuous supply of fuel and frequent maintenance and inspection of the engine throughout its operating life. For the hybrid system simulation 44kVA of Cummins diesel generator with US$700/kW for initial capital cost, US$500/kW for replacement cost and US$0.5/hour is considered. Diesel price was determined according to the Ethiopian diesel price in August 2017, which is $ 0.7/L or ETB 16/L based on the exchange rate on the 28 of August, 2017. Technical specification 20kVA Cummins diesel generator is annexed in Appendix 5A.3.

5.3.10 Energy Storage Battery Bank

Now a day's energy storage system has taken a huge part in case of power generation including hybrid power systems. It makes the system much more reliable and efficient. Batteries are used, whenever power deficit occur; it helps to transfer the stored energy to the system and In case of excess energy supply from resources, the system will store the surplus energy in the storable form of energy. The four main characteristics of batteries are:

a. **Battery Capacity**: It is the amount of energy the battery can store. Temperature, rate of discharge, battery age and battery type determines the amount of energy extracted from a fully charged battery.

The three main ratings to specify the capacity of a battery are:

1. Ampere-hour (Ah): It is the amount of current at which the battery can discharge their stored energy over a fixed interval of time.
2. Reserve capacity: This refers the length of time in minutes when the battery can manage to produce a specified level of discharge.
3. KWh capacity: The amount of energy required to charge a depleted battery (not fully discharged batteries).

b. **Battery voltage**: is that of fully charged battery. It depends up on the number of cells and voltage per cell.

c. **Cycle depth**: Fully discharging batteries can cause an adverse effect regarding to the life of the battery. Deep cycle batteries can discharge up to 15%-20% of their capacity. This gives a depth of discharge (DOD) of 85%-90%.

d. **Autonomy**: This refers the ratio of restorable energy capacity to the maximum power discharge. It indicates the maximum amount of time in which the system can extract its energy.

For the simulation, battery voltage rating of 6V has been chosen for simulation with two batteries per string at an initial capital cost, replacement cost and operation and maintenance cost for one unit battery considered as $833, $555 and 15$/year respectively **[4].** A converter is an electronic power device that is required in a hybrid system to maintain the energy flow between AC and DC electrical components. It has an inverter and a rectifier to do the conversion from DC to AC and inverter of AC to DC. The capital cost and replacement cost of US$730/kW and 10% of operation and maintenance cost is considered for the simulation. Converter cost, size and technical parameter is annexed in Appendix 5A.4. Hybrid system components cost, size and technical parameter for HOMER input is summarized in the Table 5.2.

Table 5. 2: Hybrid system components cost, size and technical parameter for Homer input

Systems Parameter	PV systems	Fuhrlander 30kW WT	Diesel generator	Battery	Converter
Size (kW)	1	30	10	1156Ah	1
Capital cost($)	1340	29,160	7000	833	730
Replacement cost($)	1340	28,560	5000	555	730
O&M cost($/yr)	20	51	0.5$/h	1 battery = $13	80
Size considered (kW)	30,50,120,250,300	-	22,44,53,88, 250,300	-	50,100,150,200, 250,300
Quantity considered	-	4,6,10,11,12,13,14,15,18,24, 36	-	0,50,100,150,200,250,300, 500	-
Life time	25 year	25 year	15000hr	1156Ah	15

5.4 Hybrid System Components Modeling

HOMER hybrid model requires several inputs which basically describe the technology option, component costs, component specification and resource availability. Renewable resources available at a location can differ considerably from site to site and it is a vital aspect in developing the hybrid system. Hybrid power generation systems modeled in HOMER by using load, resources and component size, cost and technical parameter is shown in Figure 5.11. The wind turbine and diesel generator are connected to AC bus while PV and battery need DC bus and a converter.

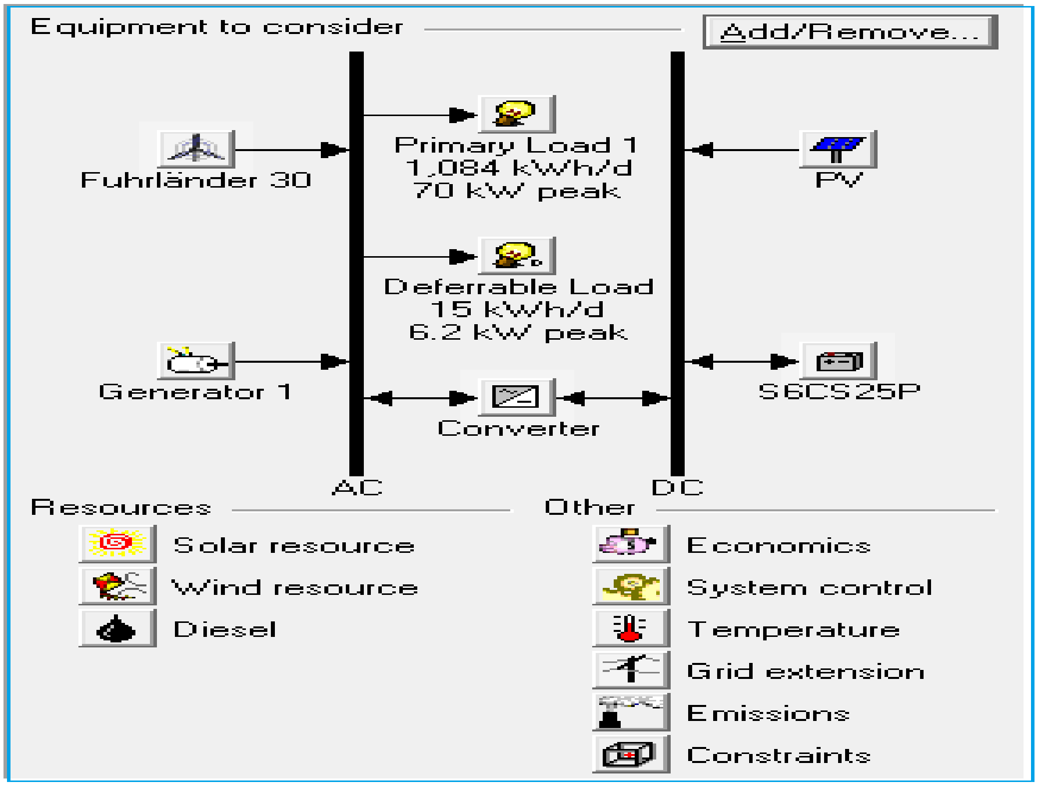


Figure 5. 11: HOMER schematic of hybrid power system modeling

The double headed arrow indicated into the batteries and converters have the following meanings. The converter changes the excessive available power from AC to DC load to charge the batteries after fully meeting the load demand of the system. When the output of the hybrid system is not enough to meet the load, the battery discharges the DC load to the system via the converter to AC power loads.

5.5 System Operational Control and Strategies

HOMER software simulates each system using both LF (load following) and CC (cycle charging) dispatch strategy and will select the optimal strategy for each system. In LF strategy, the generators will only produce enough power to meet the load demand when operational. Meanwhile for CC strategy, the generators will operate at full capacity and the excess power will be used to charge the battery bank.

Additionally, the system allows multiple generators to operate simultaneously and the generators must have a higher capacity than the peak load demand. The operating reserve as a percent of hourly load is set to 10% and as a percent of solar power output and wind power output is set to 25% and 50% respectively. The operating reserve is the surplus of operating capacity that ensures the reliability of electricity supply if there is a sudden variation of load or renewable power output.

5.6 Comparison of Hybrid Off-grid Systems with Grid Extension

In this study grid comparison was done to compare the cost of grid extension with the cost of standalone system configuration. Breakeven grid extension distance is the distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system. Homer calculates the breakeven grid extension distance by using equation 5.6 [**46**].

$$D_{grid} = \frac{C_{NPC}.\,CRF(i, R_{proj}) - C_{power}.\,L_{tot}}{C_{cap}CRF(i, R_{proj}) + C_{OM}} \quad (5.6)$$

Where, C_{NPC} = total net present cost of standalone ($), CRF = capital recovery factor, i = Interest rate (%), R_{proj} = project life time (yrs.), L_{tot} = total primary and deferrable load (kWh/yr), C_{power} = cost of power from the grid ($/kWh), C_{cap} = capital cost of grid extension ($), C_{OM} = operation and maintenance cost of grid extension ($/kW/yr)

According to the report [**46**], the average cost of grid extension in remote rural areas varies from $8,000 to $10,000 for every kilometer and rapidly increases up to $22,000/km for extremely difficult terrains. Rural electrification is almost seven to ten times more expensive than that in urban areas. In this work a $12,500 for every kilometer or 337,500 birr and the operation and maintenance cost of the system considered was 2% of the capital cost which is $250 or 6750 birr, whereas the grid power price $/kWh in 2017 is 0.044 or 1.19 birr/kWh (EEPCo). The grid extension capital cost for the study site is presented in the Table 5.3.

Table 5. 3: Grid extension cost

Study Area	Grid voltage level	Distance from national grid (km)	Unit capital cost ($/km)	O& M cost ($/km/yr)	Total capital cost of grid extension ($/km)	Grid power price ($/kwh)
Deleta village	33kV	27	12,500	6,750	337,500	0.044

5.7 Economic Feasibility Analysis

The concept of LCC is used for cost analysis of the proposed hybrid configuration. The life cycle cost of a component consists of procurement cost and operation and maintenance cost. Some costs involved in the procurement and operation of a component are incurred at the time of an acquisition (includes costs of purchasing equipment and their installation) and other costs are incurred at later times (includes costs of fuel if exists, operation and maintenance). LCC accounts for all costs associated with a system over its life time, taking into account the time value of money. Two phenomena affect the value of money over time [**19**].

These are:

1. **Inflation Rate**: Is a measure of the decline in value of money. The inflation rate for any item need not necessarily follow the general inflation rate.
2. **Discount Rate**: It relates the amount of interest that can be earned on the principal that is saved. In LCC analysis the discount rate reflects the present value of a future payment and may also indicate the interest rate the bank takes on a loan.

The principal HOMER's economic output indicators are the operating cost, total net present cost (NPC), the levelized cost of energy (COE) and the initial capital cost. NPC analysis is an appropriate gauge or scale for the purpose of economic comparison of different energy system classification and configuration since NPC balances widely divergent cost characteristics of renewable and non-renewables sources as well it also explores and summarizes all the relevant associated costs that occur within the life time of the project **[58].**

The annualized capital cost of each component is given as follow **[35]**

$$C_{acap} = C_{cap} * CRF \tag{5.7}$$

Where, CRF is the capital recovery factor **[55]**

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5.8}$$

Where, N and i are the system lifetime, and the annual real interest rate.

The total net present cost of each configuration can be calculated as follows **[18]**

$$NPC(\$) = \frac{TAC}{CRF} \tag{5.9}$$

$$TAC = C_{acap} + \sum_{i=1}^{n} C_{OM,j} + C_f + \sum_{i=1}^{n} C_{R,i} \tag{5.10}$$

Where, n is the number of all the devices in the system, $C_{OM,j}$ is the annual operation and maintenance (O&M) cost for the i^{th} component of the system, C_f is total annual fuel cost and CR_i is the annualized replacement cost for the i^{th} component of the system.

The LCOE is the ratio of the total annualized cost of the system to the annual electricity delivered by the system.

$$LCOE = \frac{TAC}{Q_t} \tag{5.11}$$

Where, Q_t is the electricity generated by the systems (kWh)

CHAPTER SIX

6. RESULT AND DISCUSSION

6.1 Simulation Results

The optimal hybrid power generating system is the one which can supply power demand for the community at the lowest price or the systems which have the lowest total net present cost (NPC), while supplying the electricity at the required level of availability. Examining each feasible system configuration allows for economic and technical merit evaluation including the COE and renewable energy fraction. Other system operational characteristics such as annual electric power production, annual electric load served, fuel consumption, excess electricity, capacity shortage, unmet electric load and emission can be also evaluated.

Table 6. 1: Overall categorized simulation result

Primary Load 1 (kWh/d) 1,085 | Wind Speed (m/s) 2.9 | Diesel Price ($/L) 0.7 | PV Capital Multiplier 1

Double click on a system below for simulation results.

PV (kW)	FL30	Gen (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen (hrs)
120		44		50	CC	$ 273,100	104,308	$ 1,386,562	0.340	0.30	0.18	101,157	8,732
120		44		50	LF	$ 273,100	104,308	$ 1,386,562	0.340	0.30	0.18	101,157	8,732
50		44		50	CC	$ 179,300	113,411	$ 1,389,937	0.343	0.13	0.20	114,250	8,753
50		44		50	LF	$ 179,300	113,411	$ 1,389,937	0.343	0.13	0.20	114,250	8,753
250		44		50	CC	$ 447,300	90,028	$ 1,408,328	0.344	0.51	0.17	86,495	7,583
250		44		50	LF	$ 447,300	90,028	$ 1,408,328	0.344	0.51	0.17	86,495	7,583
300		44		100	CC	$ 550,800	81,560	$ 1,421,432	0.348	0.57	0.17	78,481	6,522
300		44		100	LF	$ 550,800	81,560	$ 1,421,432	0.348	0.57	0.17	78,481	6,522
300		44		50	CC	$ 514,300	85,724	$ 1,429,389	0.350	0.56	0.17	82,627	7,128
300		44		50	LF	$ 514,300	85,724	$ 1,429,389	0.350	0.56	0.17	82,627	7,128
	6	44			CC	$ 250,760	110,588	$ 1,431,265	0.347	0.18	0.18	111,340	8,753
	6	44			LF	$ 250,760	110,588	$ 1,431,265	0.347	0.18	0.18	111,340	8,753
120		44		100	CC	$ 309,600	105,299	$ 1,433,646	0.351	0.30	0.18	101,157	8,732
120		44		100	LF	$ 309,600	105,299	$ 1,433,646	0.351	0.30	0.18	101,157	8,732
50		44		100	CC	$ 215,800	114,402	$ 1,437,021	0.354	0.13	0.20	114,250	8,753
50		44		100	LF	$ 215,800	114,402	$ 1,437,021	0.354	0.13	0.20	114,250	8,753
250		44	100	100	LF	$ 567,100	82,009	$ 1,442,525	0.351	0.54	0.14	74,857	6,413
250		44		100	CC	$ 483,800	90,101	$ 1,445,605	0.354	0.51	0.17	85,756	7,475
250		44		100	LF	$ 483,800	90,101	$ 1,445,605	0.354	0.51	0.17	85,756	7,475
50	4	44		50	CC	$ 295,940	107,856	$ 1,447,282	0.348	0.24	0.16	106,023	8,753
50	4	44		50	LF	$ 295,940	107,856	$ 1,447,282	0.348	0.24	0.16	106,023	8,753
30	4	44		50	CC	$ 269,140	110,528	$ 1,448,999	0.350	0.19	0.17	109,897	8,753
30	4	44		50	LF	$ 269,140	110,528	$ 1,448,999	0.350	0.19	0.17	109,897	8,753
250		44	100	50	LF	$ 530,600	86,187	$ 1,450,631	0.353	0.53	0.14	79,017	7,020
250		44	100	100	CC	$ 567,100	83,285	$ 1,456,145	0.349	0.53	0.11	77,598	6,240

Table 6. 2: Categorized simulation result

Primary Load 1 (kWh/d) 1,085 Wind Speed (m/s) 2.9 Diesel Price ($/L) 0.7 PV Capital Multiplier 1

Double click on a system below for simulation results.

PV (kW)	FL30	Gen (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen (hrs)
120		44		50	CC	$ 273,100	104,308	$ 1,386,562	0.340	0.30	0.18	101,157	8,732
	6	44			CC	$ 250,760	110,588	$ 1,431,265	0.347	0.18	0.18	111,340	8,753
250		44	100	100	LF	$ 567,100	82,009	$ 1,442,525	0.351	0.54	0.14	74,857	6,413
50	4	44		50	CC	$ 295,940	107,856	$ 1,447,282	0.348	0.24	0.16	106,023	8,753
250	4	44	100	50	LF	$ 647,240	80,512	$ 1,506,689	0.360	0.60	0.12	72,467	6,673
	4	44	100	50	LF	$ 312,240	117,582	$ 1,567,398	0.384	0.12	0.20	115,076	8,753
300	24		700	50	CC	$ 1,766,440	28,136	$ 2,066,787	0.531	1.00	0.20		
600			1200	100	CC	$ 1,921,600	45,947	$ 2,412,073	0.637	1.00	0.19		
	54		1700	250	CC	$ 3,218,240	67,919	$ 3,943,256	1.018	1.00	0.20		

6.2 Optimization Results

Looking at the overall and categorized simulation result illustrated in the Table 6.1 and 6.2 the first, third, fourth and fifth column cases are compared based on the total NPC, COE, operating cost over the life cycle of the system and other operational characteristics such as annual electric power production, annual electric load served, fuel consumption, excess electricity, capacity shortage, unmet electric load and emission.

1. PV-generator hybrid system

From the simulation result presented in Table 6.2, PV/diesel generator that excludes both Wind turbine and battery is the most cost effective hybrid power generation system for Deleta village with total net present cost (NPC) of $1,386,562, cost of energy (COE) 0.34 $/kWh (9.18 ETB/kWh). The amount of diesel used annually is 101,156 liters and the generator operates for 8,732 hours per year. The advantage of this solution is that the total net present cost and COE is the lowest, but renewable resource contributed is low 30%.

The optimum hybrid power generation systems architecture is shown in Figure 6.1 with total annual energy production of 30% PV array and 70% diesel generator. In this case diesel generator operates at full output power to serve the primary load and any surplus electrical production goes toward the lower priority objectives. The excess annual electricity production, unmet electric load and capacity shortage will stand at 3.3%, 14.1% and 18.2% respectively. The COE from these optimum hybrid power generation systems is more expensive than the national grid (0.273 $/kWh) currently the consumer can pay. The detail of the optimized PV/diesel generator systems regarding the annual electricity production, annual electricity consumption and emission from the system is presented in Table 6.3.

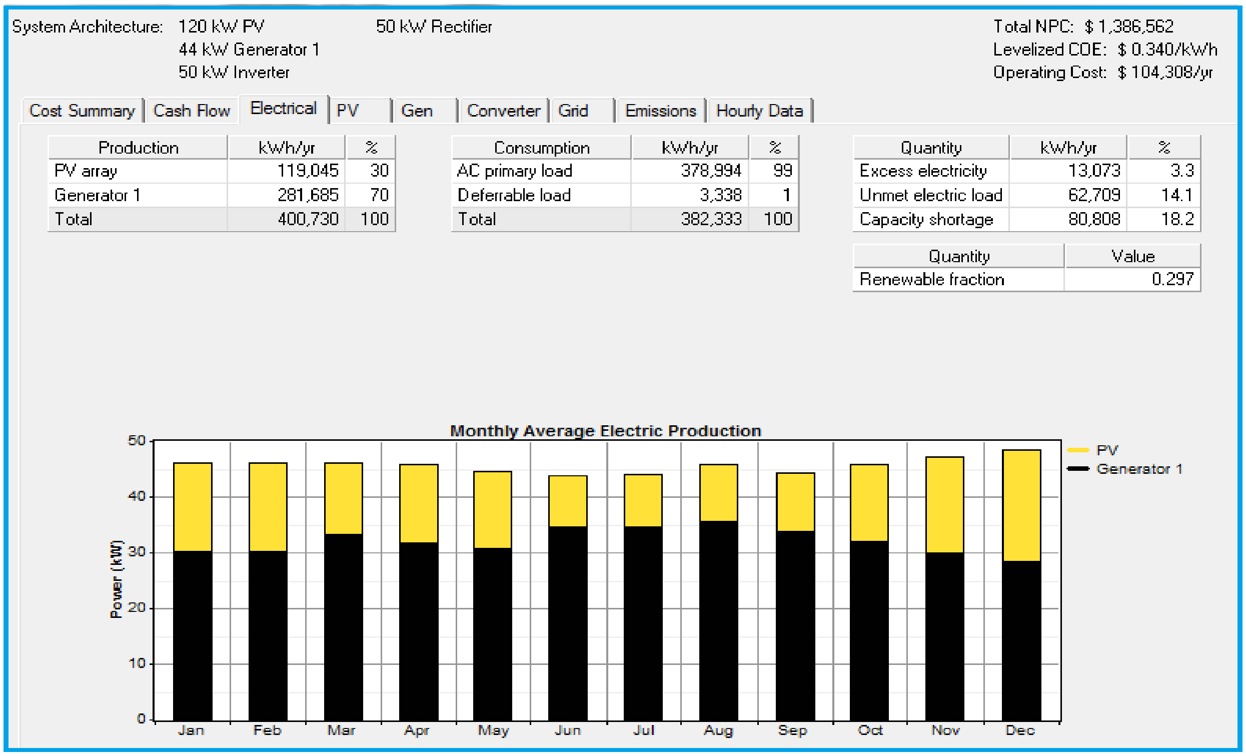


Figure 6. 1: Optimized PV/ diesel generator system at 30%RF

Table 6. 3: Summary of optimum hybrid system for 30% RF

System Architecture		Annual electricity production (kWh/yr)		Annual electricity consumption (kWh/yr)		Emission (kg/yr)	
PV	120kW	PV array	119,045	AC primary load	378,994	Carbon dioxide	266,380
Diesel generator	44kW	Diesel generator	281,685	Deferrable load	3,338	Carbon monoxide	658
				Total	382,333		
Converter	50kW			**Cost summary**		Unburned hydrocarbons	72.8
Dispatch strategy	CC	**Total**	400,730	capital cost	$273,100	Particulate matter	49.6
		Excess electricity	13,073	Operating cost	104,308$/yr		
		Unmet load	62,709	Total NPC	$1,386,562	Sulfur dioxide	535
		Capacity shortage	80,808	LCOE	0.34$/kWh	Nitrogen oxides	5,867

2. PV-generator-battery hybrid system

In view of the third simulation result, the most cost effective system is the PV/generator/battery setup, with the generator operating with a load following (LF) strategy (a dispatch strategy whereby the generator operates to produce only enough power to meet the primary load; lower priority objectives such as battery charging or serving the deferrable load is left to renewable power sources). For the optimum hybrid system architecture presented Figure 6.2, the total net present cost (NPC) is $1,442,525, cost of energy (COE) is 0.351 $/kWh and the renewable resource contributed is 54%. The amount of diesel used annually is 74,857 liters and the generators operate for 6,413 hours per year. The power percentage share for the system is 54% PV array and 46% diesel generator

Excess annual electricity production, unmet electric load and capacity shortage will stand at 12.9%, 10.9% and 14% respectively. The COE from these optimum hybrid power generation systems is more expensive than the national grid (0.273 $/kWh) currently the consumer can pay. The detail of the optimized PV/diesel generator/battery systems regarding the annual electricity production, annual electricity consumption and emission from the system is presented in Table 6.4.

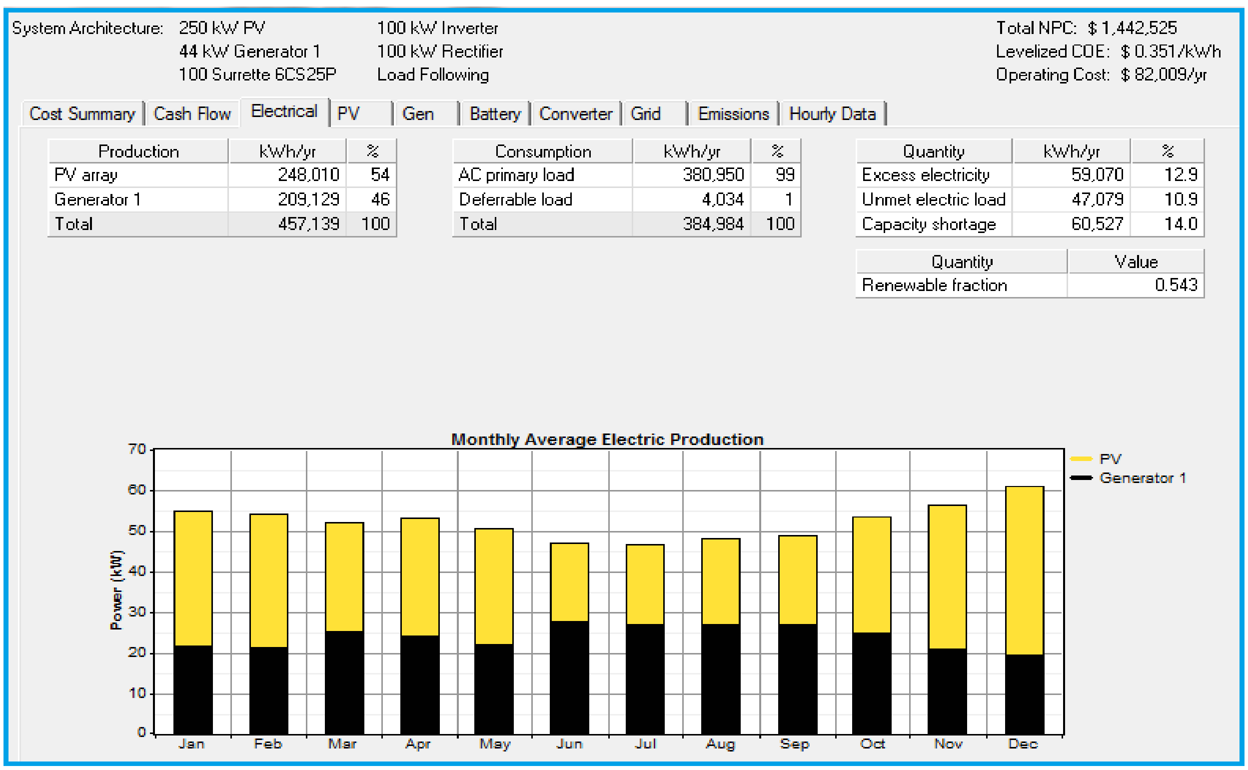


Figure 6. 2: Optimized PV/ diesel generator/battery system at 54%RF

Table 6. 4: Summary of optimum hybrid system for 54% RF

System Architecture		Annual electricity production (kWh/yr)		Annual electricity consumption (kWh/yr)		Emission (kg/yr)	
PV	250kW	PV array	248,010	AC primary load	380,950	Carbon dioxide	197,124
Diesel generator	44kW	Diesel generator	209,129	Deferrable load	4,034	Carbon monoxide	487
				Total	**392,001**		
Battery	100 batteries			**Cost summary**		Unburned hydrocarbons	53.9
Converter	100kW	**Total**	457,139	capital cost (CI)	$567,100	Particulate matter	36.7
Dispatch strategy	LF	Excess electricity	59,070	Operating cost	82,009$/yr		
		Unmet load	47,079	Total NPC	$1,442,525	Sulfur dioxide	396
		Capacity shortage	60,527	LCOE	0.351$/kWh	Nitrogen oxides	4,342

3. PV-wind-generator hybrid system

As it is seen from the systems setup, the fourth most cost effective system is the PV/wind turbine/diesel generator setup, with the generator operates at full output power to serve the primary load and any surplus electrical production goes toward the lower priority objectives). For the optimum hybrid systems presented in Figure 6.3, the total net present cost (NPC) is $1,447,282, cost of energy (COE) 0.348 $/kWh and renewable fraction contributed is 24%.

The amount of diesel used annually is 106,023 liters and the generator operates for 8,753 hours per year. The power percentage share for the system is 13% PV array, 12% wind and 76% diesel generator. Excess annual electricity production, unmet electric load and capacity shortage will stand at 1.2%, 10.5% and 15.6% respectively. The COE from these optimum hybrid power generation systems is more expensive than the national grid (0.273 $/kWh) currently the consumer can pay. The detail of the optimized PV//wind/diesel generator systems regarding the annual electricity production, annual electricity consumption and emission from the system is presented in Table 6.5.

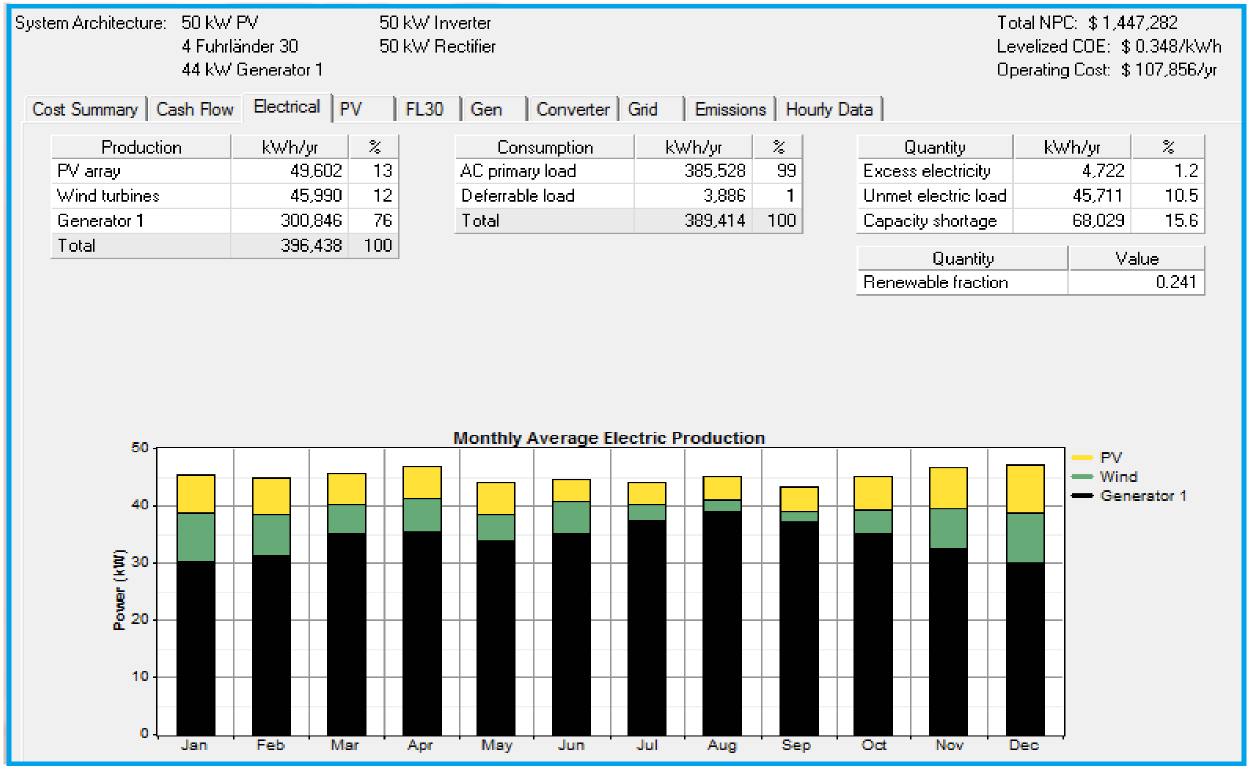


Figure 6. 3: Optimized PV/wind/ diesel generator system at 24%RF

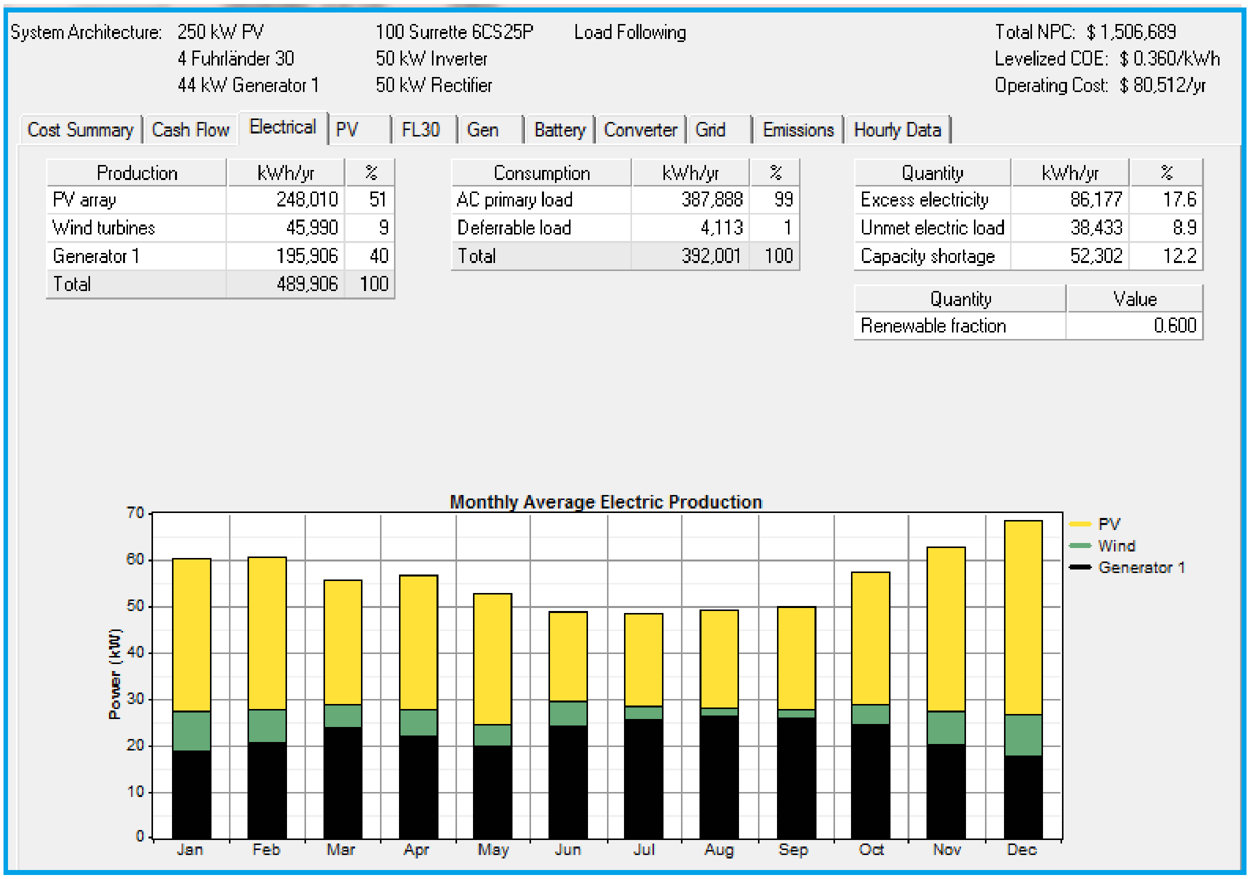
Table 6. 5: Summary of optimum hybrid system for 24% RF

System Architecture		Annual electricity production (kWh/yr)		Annual electricity consumption (kWh/yr)		Emission (kg/yr)	
PV	50kW	PV array	49,602	AC primary load	385,528	Carbon dioxide	279,194
Wind Turbine	4(30kW)	Wind turbine	45,990	Deferrable load	3,886	Carbon monoxide	689
				Total	**389,414**		
Diesel generator	44kW	Diesel generator	300,846	**Cost summary**		Unburned hydrocarbons	76.3
Converter	50kW	**Total**	**396,438**	capital cost	$295,940	Particulate matter	52
Dispatch strategy	CC	Excess electricity	4,722	Operating cost	107,856$/yr		
		Unmet load	45,711	Total NPC	$1,447,282	Sulfur dioxide	561
		Capacity shortage	68,029	LCOE	0.348$/kWh	Nitrogen oxides	6,149

4. PV-wind-generator-battery hybrid system

The fifth optimal hybrid configuration system from the simulation result presented in Table 6.2 is the PV/wind/diesel generator/battery hybrid power generation with total net present cost (NPC) of $1,506,689, COE 0.36 $/kWh and renewable fraction of 60%. The amount of diesel used annually is 72,467 liters and the generator operates for 6,673 hours per year. The optimum hybrid power generation systems architecture is shown in Figure 6.4 with total annual energy production of 51% PV array, 9% wind turbine and 40% diesel generator. In this case a load following (LF) strategy is feasible (a dispatch strategy whereby the generator operates to produce only enough power to meet the primary load; lower priority objectives such as battery charging or serving the deferrable load is left to renewable power sources).

Excess annual electricity production, unmet electric load and capacity shortage will stand at 17.6%, 8.9% and 12.2% respectively. The COE from these optimum hybrid power generation systems is also more expensive than the national grid (0.273 $/kWh) currently the consumer can pay.



Production	kWh/yr	%
PV array	248,010	51
Wind turbines	45,990	9
Generator 1	195,906	40
Total	489,906	100

Consumption	kWh/yr	%
AC primary load	387,888	99
Deferrable load	4,113	1
Total	392,001	100

Quantity	kWh/yr	%
Excess electricity	86,177	17.6
Unmet electric load	38,433	8.9
Capacity shortage	52,302	12.2

Quantity	Value
Renewable fraction	0.600

Figure 6. 4: Optimized PV/wind/diesel generator/ battery system at 60%RF

As it is seen from the Figure 6.4 the electrical power generated by hybrid system is strongly depends on the nature of the energy sources. The power generated by solar photovoltaic depends on the time of the day and the strength of the solar radiation while the energy from the wind turbine depends on the availability of wind speed. Wind resource is intermittent in nature and it has a great impact on the output from the wind turbine. As it can be seen from the categorized optimization result illustrated in Table 6.2, there are renewables resources achieving renewable fraction 100% and provide electric power excluding diesel generator. Renewables solar PV and wind are intermittent in nature; therefore, to supply continuous electric power a diesel generator is mandatory.

In summary, one clear deduction from the optimal hybrid system illustrated in Table 6.2 is that it will not impossible to supply continuous electrical power for the Deleta village only depending on renewable energy resources as the convectional diesel generator is always required in any configuration systems to meet the energy demand. Diesel generator is needed for quality service when the renewable energy technologies are low and unable to meet the required energy demand, but it can be minimized from 70% to 40% by employing more renewables as in the fifth option that makes use of all the renewable resources with the less pollutant emissions and negligible difference of 0.02$/kWh COE.

Table 6. 6: Summary of optimum hybrid system for 60% RF

System Architecture		Annual electricity production (kWh/yr)		Annual electricity consumption (kWh/yr)		Emission (kg/yr)	
PV	250kW	PV array	248,010	AC primary load	387,888	Carbon dioxide	190,829
Wind Turbine	4(30kW)	Wind turbine	45,990	Deferrable load	4,113	Carbon monoxide	471
				Total	392,001		
Diesel generator	44kW	Diesel generator	195,906	**Cost summary**		Unburned hydrocarbons	52.2
Battery	100 batteries	**Total**	489,906	capital cost (CI)	$647,240	Particulate matter	35.5
Converter	50kW	Excess electricity	86,177	Operating cost	80,512$/yr		
Dispatch strategy	LF	Unmet load	38,433	Total NPC	$1,506,689	Sulfur dioxide	383
		Capacity shortage	52,302	LCOE	0.36$/kWh	Nitrogen oxides	4,203

6.3 Sensitivity Results Analysis

6.3.1 Robustness of Optimization Results

Robustness of the optimizations can be examined by the consistency of the optimal system type as the sensitivity inputs change. The potential variations of wind speed, PV capital cost,diesel prices and electricy demand. In this study the fuel price increased in a range from the current price 0.7$/L or 18.9Birr/L until 1$/L or 27birr/L and the load considered is the forecasted primary load of 3674kWh/day, wind speed resource considered is 2.9 m/s, 2 m/s and 3.5 m/s, while the cost of PV capital considered are 0.4, 0.6, 0.8,1 and 1.2. Diesel prices are expected to increase and the current technological development would lead to decrease PV prices, as well as more utilization of new electrical devices would increase the future loads.

6.3.2 Sensitivity and Precision of Net present Cost (NPC) and Levelized Cost of Energy (LCOE) for the Optimal PV/diesel system

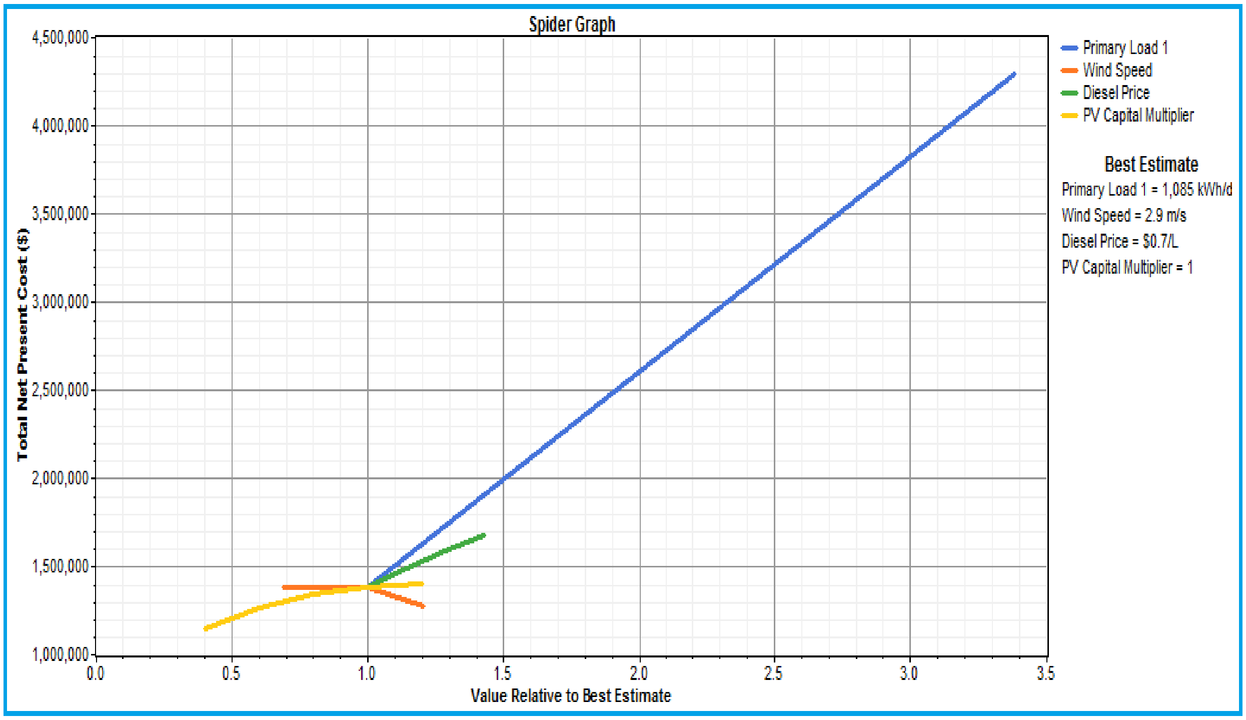


Figure 6. 5: Sensitivity of NPC for the optimal PV/diesel/hybrid system

The sensitivity of NPC results for the optimal system with best estimate values of primary load = 1,085kWh/day, diesel price = $0.7/Liters, wind speed =2.9 m/s and PV capital cost multiplier =1 is illustrated in Figure 6.5. From Figure 6.5, the origin of the graph lines is at the meeting point where the sensitivity inputs shown by the graph lines are equal to the best estimate values shown by the unity value relative to the best estimate on the horizontal axis. At this point, the total net present cost (NPC) $1,375,000 on the vertical axis is equal to the predicted value that shown on the categorized simulation result illustrated in Table 6.2.

Each of the graph lines shows how the NPC changes as the sensitivity input varies relative to its best estimate value by factors above unity to the right and below unity to the left.

The following observation can be made from the above Figure 6.5:

- ✓ when the load would increase by a factor of up to 3.4 relative to the base line estimate of 1,085kWh/day as shown by the sky blue line, the NPC of optimized system would change to $4,375,000 (i.e., uncertainty of 33% in energy demand presents 68% uncertainty in NPC of the optimal hybrid system. With higher load, a larger system is required which increases the system life cycle costs.
- ✓ When PV capital cost would vary up to 1.2 (allowing a maximum uncertainty of 20% in the PV initial costs) relative to the best estimate of $1340/kW as shown by the yellow line, the optimized NPC would increase to $1,400,500 (i.e., a 20% uncertainty in PV capital cost would make the NPC to increase by 2%.
- ✓ When diesel price would vary up to 1.4 relative to the best estimate of $0.7/Liters as shown by green line (allowing up to 40% uncertainty in the diesel fuel price) the optimized NPC would increase up to $1,700,000 (i.e., the diesel fuel uncertainty presents up to 19% uncertainty in the NPC of the optimal hybrid system.

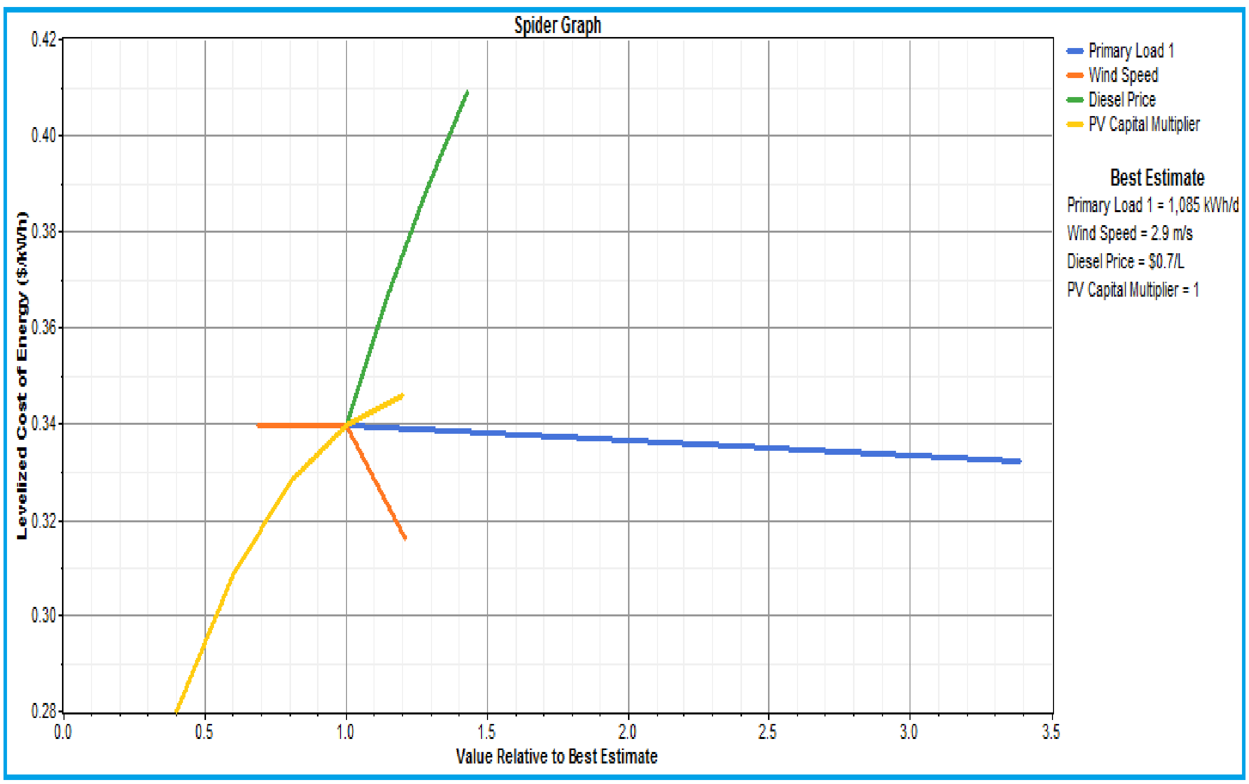


Figure 6. 6: Sensitivity of LCOE for the optimal PV/diesel/hybrid system

The sensitivity of LCOE results for the optimal system with best estimate values of primary load = 1,085kWh/day, diesel price = $0.7/Liters, wind speed =2.9 m/s and PV capital cost multiplier =1 is illustrated in Figure 6.6.

From the above Figure 6.6:

- ✓ When the load would increase by a factor of up to 3.4 relative to the base line estimate of 1,085kWh/day as shown by the sky blue line, the optimized system would have a lower LCOE of $ 0.33/kWh (i.e., a 33% uncertainty in load demand presents an uncertainty of 3% in the LCOE).
- ✓ When PV capital cost would vary up to 1.2 relative to the best estimate of $1340/kW as shown by the yellow line, the LCOE of the optimized hybrid system would increase up to $ 0.345/kWh i.e., a 20% uncertainty in PV capital cost presents a 1.4% uncertainty in LCOE)
- ✓ When the wind speed would vary up to 1.2 relative to the best estimate of 2.9 m/s as shown by red line, the LCOE of the optimized hybrid system would decreased up to $ 0.315/kWh i.e., a 20% uncertainty in wind speed presents a 7% uncertainty in LCOE)
- ✓ When diesel price would vary up to 1.4 relative to the best estimate of $0.7/Liters as shown by green line, the LCOE of the optimized system would increase to $ 0.41/kWh i.e., a 40% uncertainty in diesel fuel price presents a 17% uncertainty in LCOE)

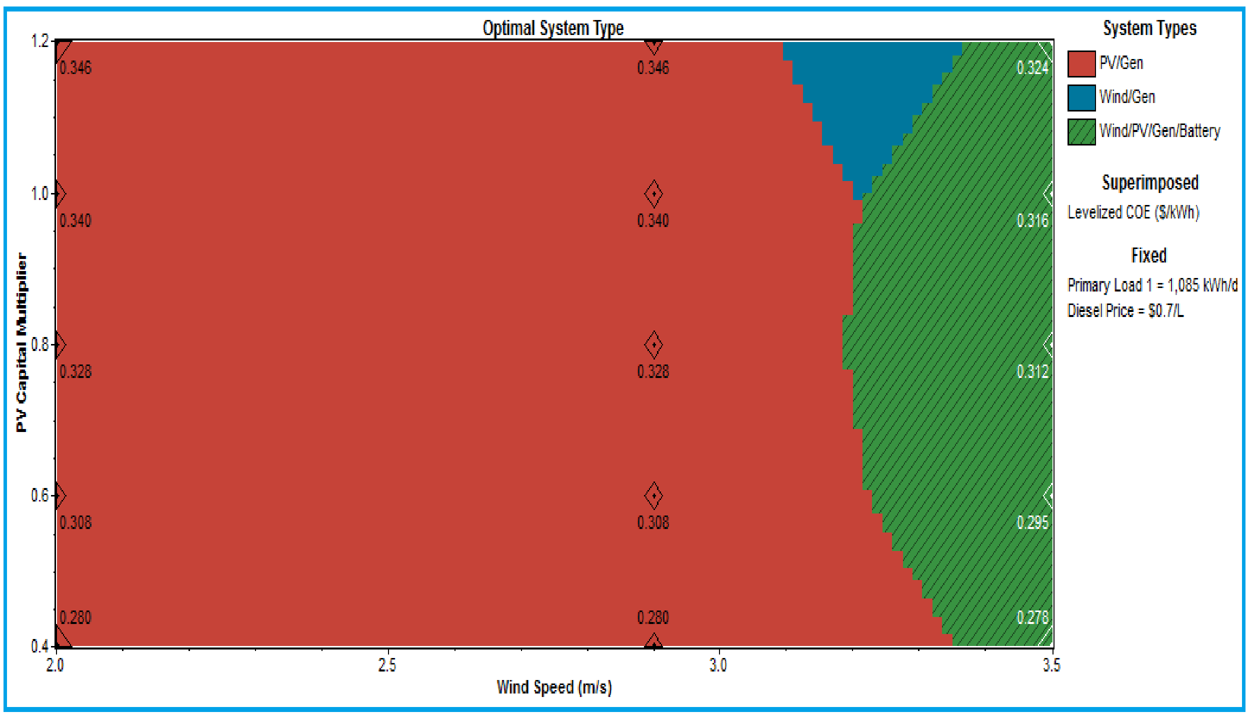


Figure 6. 7: Effects of PV capital multiplier and wind speed increment on operational system

The sensitivity results for the optimal system with fixed primary load, diesel price superimposed with LCOE is illustrated in Figure 6.7. It can be seen from the figure above that average wind speed of 2.9m/s and PV capital cost multiplier one lead to LCOE of about $0.34/kWh for a PV/generator hybrid configuration system. But when the wind speed increased to 3.4 m/s and the PV capital cost multiplier at 0.4 wind/PV/generator/battery hybrid configuration becomes the most cost effective solution. LCOE varies $0.28/kWh to $0.346/kWh when the wind speed is at 2m/s with PV capital cost multiplier of 0.4 and also varies to a favorable $0.278/kWh for wind speed above 3.4 and PV capital cost multiplier 0.4.

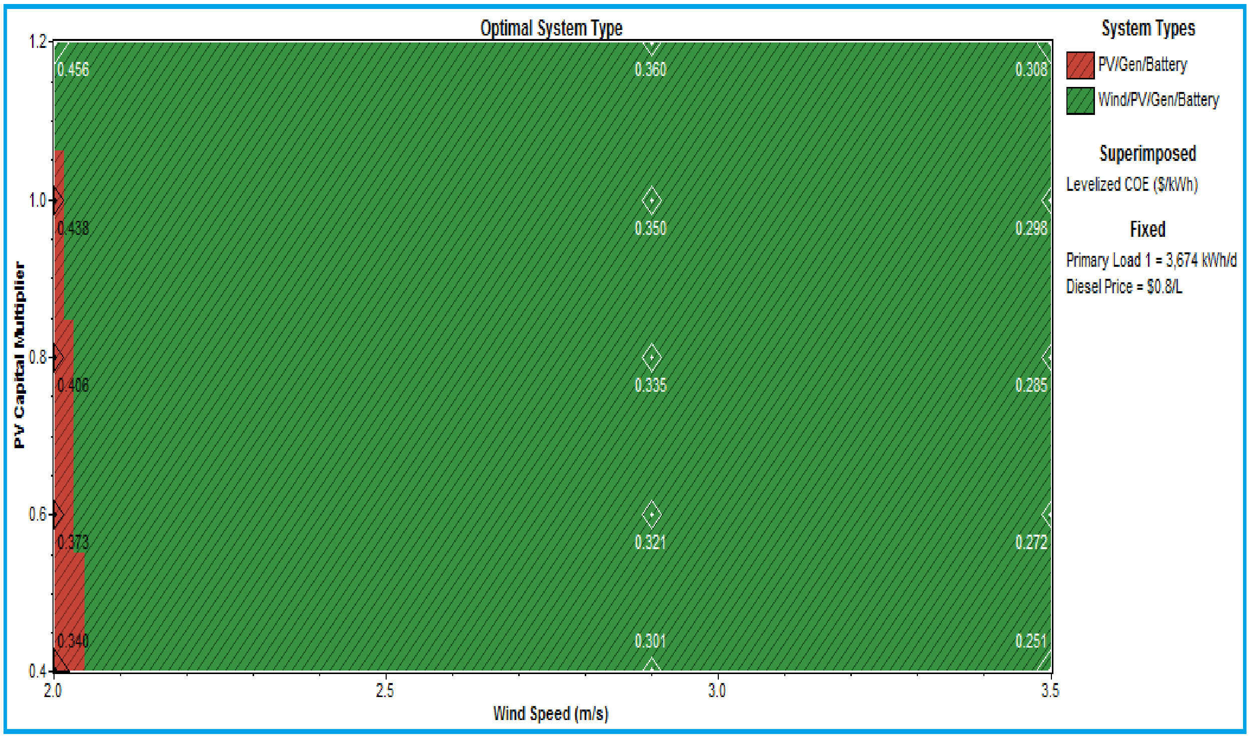


Figure 6. 8: Optimal system with 30% load increase

The sensitivity analysis result for the 30% load demand increment with high diesel fuel price is illustrated in the Figure 6.8. In this case the average wind speed at 2.9 m/s and PV capital cost multiplier1.0 lead to levelized cost of energy (LCOE) of about $0.350/kWh for a wind/PV/generator/battery hybrid system with slightly increased renewable fraction of 69% and 16.5% excess electricity. The 30% increased load is still met but at high cost due to the multiple hybrid system components need to meet the increased load demand. It is also evident from Figure 6.8 that LCOE varies from a maximum of $0.350/kWh when wind speed and PV capital cost multiplier are respectively at 2.9 m/s and 1.0 to a minimum of $0.251/kWh for wind speed 3.5 m/s and PV capital cost multiplier 0.4. In addition to this beyond PV capital cost multiplier 1.0 with wind speed at 2.9 m/s, further the LCOE gets increased to $0.360/kWh.

Figure 6.9 indicates the result for the breakeven distance for grid extension. It shows that the distance varies from 7.5km to 10.5km depending on the total net present cost and LCOE. The hybrid power generating total net present cost line comes out be a lower value than the breakeven distance for grid extension at a distance of 8.8km, meaning that a decentralized hybrid power generating system is a better option than the grid extension for a community of the village which is at a distance greater than 8.8 km far from the national grid. It is clearly evident from the line graph that as the wind speed increases with a diesel cost at a fixed cost of $0.8/L, total net present cost of the system decreases.

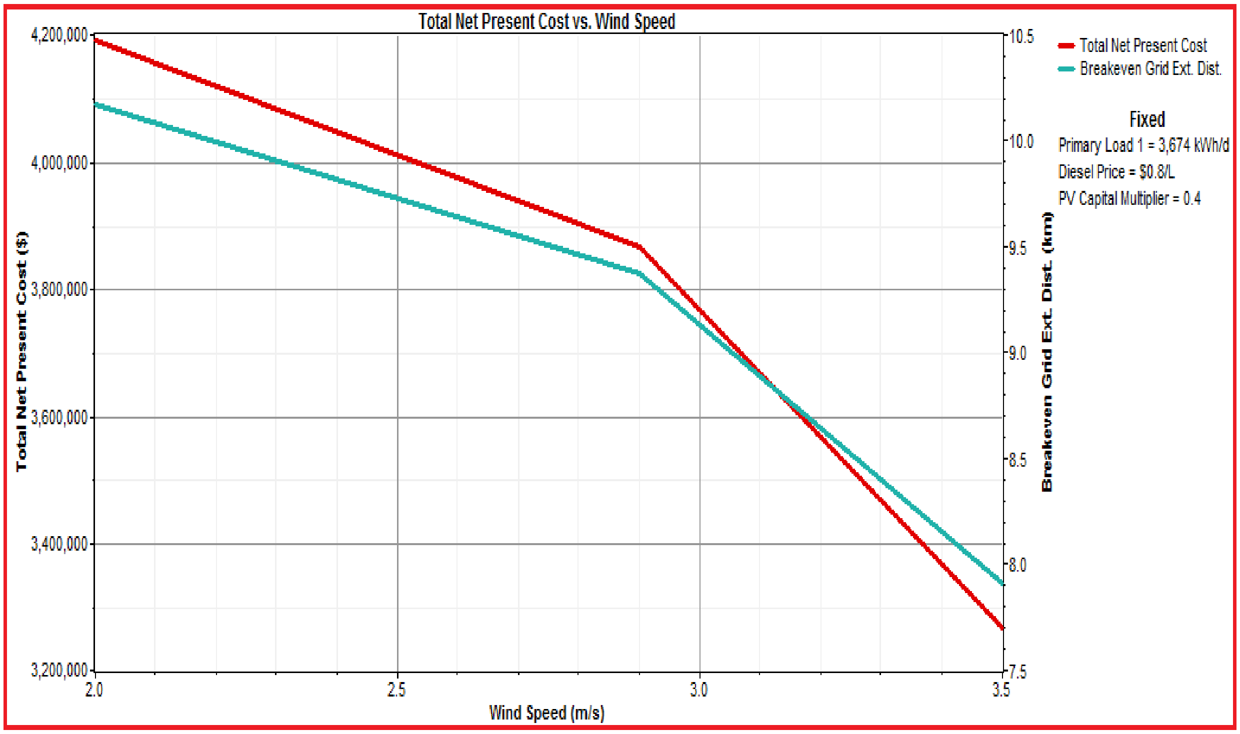


Figure 6. 9: Line graph for total NPC vs. wind speed and breakeven grid extension distance

6.4 Grid Comparison Result

Breakeven grid extension distance (BGD) is the point at which the total NPC curve of grid extension and optimal hybrid off-grid power generating systems intersect each other. At this point the optimal hybrid off-grid power generating system and the extended grid to electrify the rural community load have equal total net present cost. In this case the break even grid extension distance is 3.66 km, beyond this point grid extension will not further optimal. It is only feasible below the break even grid extension distance (i.e.3.66 km). Hybrid off-grid power generating systems is feasible for electrification of rural community beyond the BGD.

The actual distance of the national grid from the location of study community of Deleta village is 27kms. Therefore from the simulation result given in Figure 6.10 standalone hybrid system is feasible over grid extension to electrify the community.

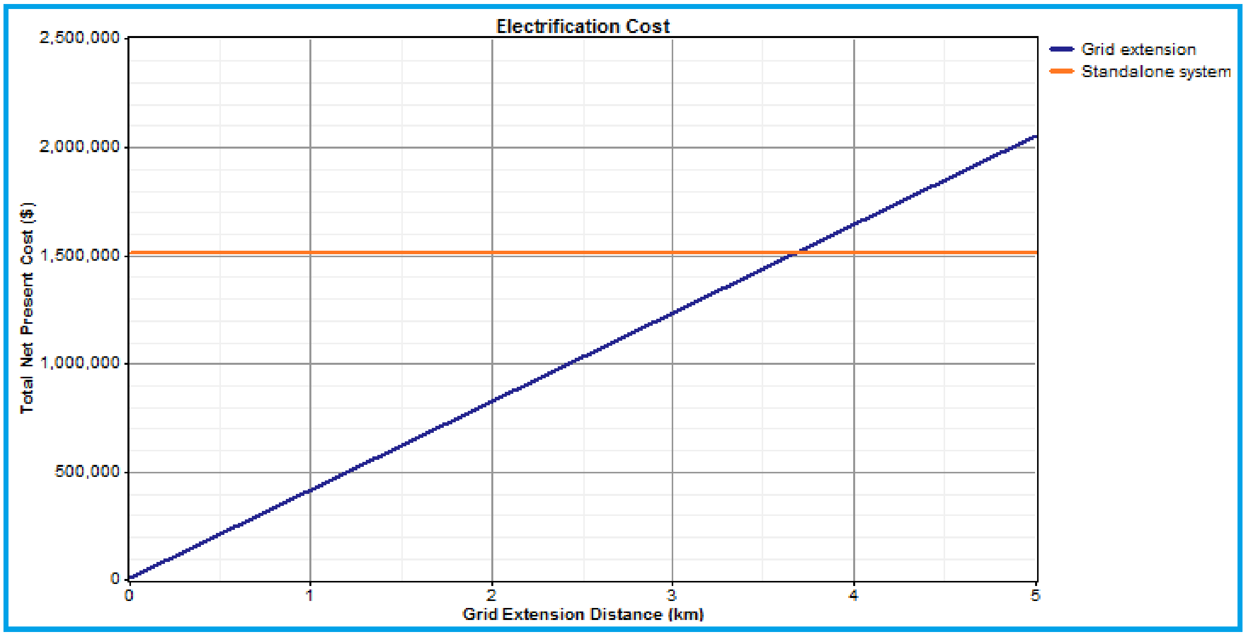


Figure 6. 10: Grid comparisons with standalone hybrid systems

6.5 Post HOMER Analysis

Development of rural electrification scheme based on hybrid power generation system in Deleta village requires an initial capital investment of approximately $647,240. This system can supply power for 795 households including public service centers. Although HOMER suggests technical feasibility of such system and indicates the breakeven cost at which the investment can be recovered. The post HOMER analysis is required to develop a complete understanding of the business case.

Since the investment volume is not large either for any convectional lender such as banks or for any utility investor, significant risks can be involved in the investment. If the project does not succeed for any reason, the investment will be a sunk cost for the investor and will become bad investment. Second the electricity market in the area is not developed and the assumptions related to the demand may not materialize or may take longer to realize. This will adversely affect the cost recovery process. Third the business environment may be affected by political, regulatory and government challenges. Fourth there are practical difficulties (e.g. availability of skilled manpower, managing supply logistics and poor transport facilities) that can add to costs, delay project delivery and reduce profitability of the projects.

In such cases, appropriate incentives and support mechanisms will play an important role to attract investment and mitigate risks. A related issue that requires careful consideration is the choice of an appropriate business model for delivering the project. While a private investor brings expertise and innovative ideas the cost of supply can be higher. Moreover, a private investor will essentially be profit driven and unless the business case suggests profitability, it is unlikely that private investment will flow. On the other hand, state utility services have not been successfully in providing electricity in the remote areas.

Tariff issue will play a crucial role but there are challenging task in the rural context due to the following factors. First investors will be interested in recovering the investment over a shorter period of time and very few lenders will consider a loan period of 25 years. As the cost recovery period reduces, the cost of supply will increase which may in turn make the project less attractive to the users. Second, the discount rate used for business decisions depends on the investor. For example, a private investor is likely to use a higher discount rate to reflect the cost of capital, riskiness of the investment and its desire to recover the investment quickly. On the other hand, state agencies or local communities may use a low discount considering the social nature of the investment. Third, the grid based electricity supply in other areas may be subsidized and consumers in the off-grid area may expect similar tariff treatments.

However, the cost of supply for the off-grid case may be quite different from the grid based supply and the consumer base is significantly small. Therefore, there is very limited cross subsidy potential in the off-grid case and unless there is a direct subsidy support from the government, price parity with grid based supply can only jeopardize the viability of the project. In this particular case, the state allows subsidy for rural areas and the support is available for off-grid consumers at a fixed rate.

Generally, the basic rule in the electrification project is that the tariff structure must cover at least the capital and the lifetime O&M cost of the project. The LCOE is the indicator that presents the flat electricity tariff that can cover the capital and the O&M cost of the project during the lifetime. In contrast to financial scheme, proper O&M scheme must be developed to ensure the sustainable operation of the rural electrification project. Local people can be trained for doing basic maintenance of the system and even for collecting the monthly fees from the consumer. O&M cost can be brought down by incorporating well trained local people. However, the service of skilled technicians will be required for major maintenance activities especially in the diesel generator.

CHAPTER SEVEN

7. CONCLUSION, RECOMMENDATION AND SUGGESTION FOR FUTURE WORK

7.1 Conclusion

The main objective of this thesis was to find a best techno-economic hybrid off-grid power generation systems for the electrification of rural areas of Deleta village in Meta Robi district. In this thesis first the electric load is estimated and forecasted for the study community within 25 years of the project lifetime. The electrical load estimated for the study community is 1085kWh/day and the forecasted load demand is about 3674kWh/day.

For the study site renewable energy wind and solar potential data for simulation is obtained from NASA. The data shows the study site have an average wind speed of 2.9 m/s at 10m anemometer and solar radiation of $5.81\text{kWh}/\text{m}^2/\text{day}$.

Off-grid renewable power generation system cannot provide an efficient and continuous supply of electricity without a storage medium. Consequently batteries are added to the hybrid system. In order to ensure the continuity of power supply without severe stress on the battery bank for a reduced overall cost, a diesel generator is also incorporated. After selecting the appropriate components and studying their characteristics, hybrid system that consists of PV/wind/diesel generator/battery has been modeled in HOMER using the estimated electrical load, renewable energy potential and the costs of the hybrid system components. Then the simulation made to determine the best optimal hybrid configuration system that can supply the village load with the required level of availability.

The optimization simulation result by HOMER shows that on the basis of lowest total net present cost (NPC) and cost of energy (COE) an optimal hybrid system configuration of PV-diesel generator system has been identified as the cheapest dependable solution with a NPC and COE of $1,386,562 and $0.340/kWh respectively. However, the optimal hybrid system cannot supply affordable and reliable power with required availability to meet the village load and it emits high GHG when compared with other feasible hybrid configuration system. Therefore, for the study area a hybrid configuration system of 250 kW solar PV, 4 wind turbine, 44 kW diesel generator and100 batteries that have a total NPC of $1,506,689 and COE of $0.360/kWh with renewable fraction of 0.6 is selected as the best reliable and continuous power supply solution. The resulting annually a carbon dioxide emission from the system is about 195,974kg/year.

The sensitivity analysis result further reveals that due to varying wind speed and PV capital cost multiplier, COE varies from a minimum of $0.298/kWh to a maximum of $0.301/kWh and 30% load demand increased is also met by the hybrid configuration of (solar PV-wind-diesel-battery) system with renewable fraction of 0.69.

The grid comparison result revealed that both grid extension and standalone system have equal total net present cost of $1,500,000 at a breakeven distance of 3.66 km. Since grid-extension is only feasible below this breakeven distance, hybrid off-grid power generation is suitable for electrification of study village. The study area is located far away 27 km from the nearby substation; therefore, the use of grid extension is not worthwhile due to the high capital cost of grid extension, sparsely populated and low energy demand of the rural community.

In summary, the simulation result prove that the hybrid power generation system consisting of solar photovoltaic-wind-diesel generator-battery configuration is the best solution to guarantee the reliable and affordable electric power supply without interruption of the load under the climatic data change.

7.2 Recommendation

For further research and development relating to the electrification of rural areas by using hybrid renewable power generation systems the following points are recommended. To determine the appropriate wind turbine siting and to determine the prevailing wind direction wind data recorded for more than a year is very important for a given wind regime area. Therefore, the author of this thesis recommends that collecting of wind speed data for the actual site at different locations using a wind mast equal to the hub height of the selected wind turbine for at least one complete year.

The inclusion of off-grid solution under the GTP-II has been accompanied by a restructuring of energy sector and the development of a national electrification strategy and off-grid master plan for rural electrification by using renewable resources. However, there are challenges like low purchasing power of the rural community, unfavorable conditions towards the utilization of renewable resources for the off-grid power generation and the absence of awareness how to use these resources. Therefore, the government, non-government and private sector should make combined efforts to overcome these challenges by using flexible approaches to improve the current poor rural electrification status in Ethiopia.

7.3 Suggestion for Future Work

- ✓ The exact measurement of renewable energy resources such as solar radiation and wind speed at different local time of the site.
- ✓ Detailed electrical design and power quality analysis of hybrid system
- ✓ Addressing the possibility of replacing the convectional diesel generator in the hybrid power generating system by locally generated biofuels.

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9. APPENDIXES

Appendix 4A. 1: Household load profile and energy demanded per day

Domestic load						
Type	Number of household	Type of Appliances	Ratting (W)	Number of appliance	Run Time (hr/day)	Total Energy (kWh/day)
High class household	210	CFL	11	4	4	36.96
		Outdoor CFL	11	2	4	18.48
		Cell phone	5	1	2	2.1
		Radio	10	1	4	8.4
		Television	100	1	8	168
		DVD Player	25	1	4	21
		Refrigerator	100	1	24	504
					Total	**758.94kWh/day**
Medium class household	275	CFL	11	3	4	36.3
		Outdoor CFL	11	2	4	24.2
		Cell phone	5	1	2	2.75
		Radio	10	1	4	11
		Television	65	1	8	143
		DVD Player	25	1	4	27.5
					Total	**244.75kWh/day**
Lower class household	310	CFL	11	2	4	27.28
		Outdoor CFL	11	1	4	13.64
		Cell phone	5	1	2	3.1
		Radio	10	1	4	12.4
		DVD player	25	1	4	31
					Total	**87.42Wh/day**
Total Energy demand for all household						**1091kWh/day**

Appendix 4A. 2: Estimated electric appliances and their run time for public load

School				
Appliances	Ratting (W)	Number of appliance	Run time (h/day)	Total Power (kWh/day)
CFL	11	52	3	1.716
Outdoor CFL	11	3	12	0.396
Radio receiver	10	4	6	0.24
Health Extension center				
CFL	11	4	5	0.22
Outdoor CFL	11	2	12	0.264
Vaccine refrigerator	100	1	24	2.4
Radio receiver	10	1	8	0.08
Animal clinic				
CFL lamp	11	2	5	0.11
Outdoor CFL	11	1	12	0.132
Vaccine refrigerator	100	1	24	2.4
Radio receiver	10	1	8	0.08
Keble Administration				
CFL lamp	11	4	6	0.264
Farmers Training Centers (FTC)				
CFL lamp	11	4	4	0.176
			Total	**6.938 kWh/day**

Appendix 4A. 3: Population growth and load forecasted result for the study area

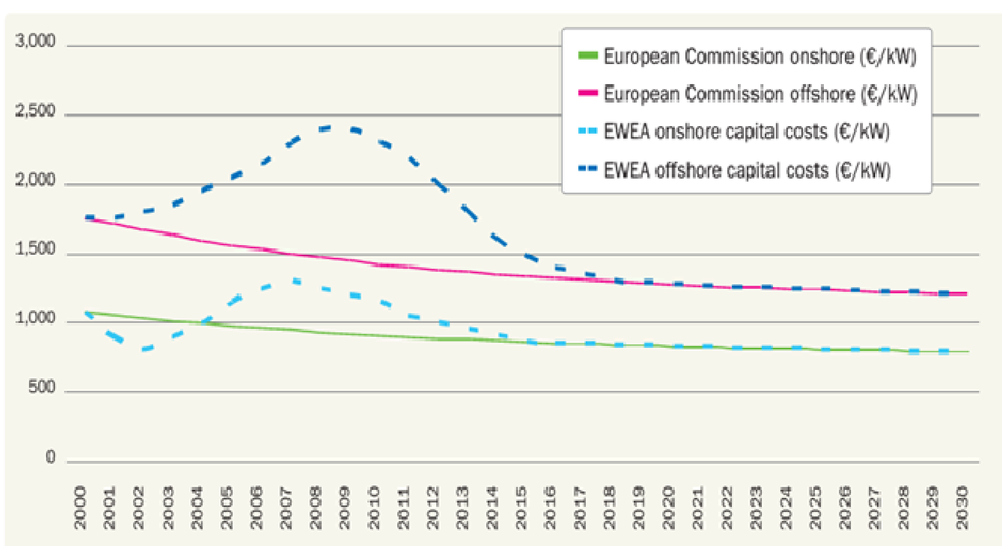
Year (G.C)	Population	Household	Primary Load	Deferrable Load
2016	4770	795	1085	15
2017	4860	810	1139.3	15.75
2018	4952	825	1196.2	16.54
2019	5047	841	1256.0	17.36
2020	5142	857	1318.8	18.23
2021	5240	873	1384.7	19.14
2022	5340	890	1454.0	20.1
2023	5441	906	1526.7	21.1
2024	5545	924	1603.0	22.16
2025	5650	941	1683.2	23.26
2026	5757	959	1767.4	24.43
2027	5867	977	1855.7	25.65
2028	5978	996	1948.5	26.94
2029	6092	1015	2045.9	28.28
2030	6208	1034	2148.2	29.69
2031	6326	1054	2255.6	31.18
2032	6446	1074	2368.4	32.74
2033	6564	1094	2486.8	34.38
2034	6693	1115	2611.2	36.1
2035	6820	1136	2741.7	37.9
2036	6950	1158	2878.8	39.8
2037	7082	1180	3022.7	41.79
2038	7216	1202	3173.9	43.88
2039	7354	1225	3332.6	46.1
2040	7493	1248	3499.2	48.37
2041	7636	1272	3674.2	50.79

Appendix 5A. 1: Technical specification of 30kWrated power Fuhrlander wind turbine

Description	**Specification**
Power	
Rated power	30kW
Rated wind speed	12m/s
Cut-in wind speed	2.5m/s
Cut-out wind speed	25m/s
Maximum wind speed the turbine can withstand	55m/s
Dimension	
Rotor weight	640kg
Rotor diameter	13m
Swept area	133m^2
Height of the mast	18/27m
Other information	
Life time	25years
Upwind or downwind	Up wind

Source: www.fuhrlaender.com.

Appendix 5A. 2: Cost/price of onshore and offshore wind (€/kW). Source (EWEA, 2007)



Appendix 5A. 3: Diesel generator technical specification

Model	Standby Power		Prime Power		Engine	Dimension	Weight
	kVA	kWe	kVA	kWe		mm	KG
MC20S-1	22	18	20	16	4B3.9-G1	2600×1130×1615	1230
MC20S-1	22	18	20	16	4B3.9-G2	2600×1130×1615	1230
MC25S-1	28	22	25	20	4B3.9-G1	2600×1130×1615	1230
MC25S-1	28	22	25	20	4B3.9-G2	2600×1130×1615	1230
MC30S-1	33	26	30	24	4BT3.9-G1	2600×1130×1615	1230
MC30S-1	33	26	30	24	4BT3.9-G2	2600×1130×1615	1330
MC40S-1	44	35	40	32	4BT3.9-G1	2600×1130×1615	1330
MC40S-1	44	35	40	32	4BT3.9-G2	2600×1130×1615	1330
MC55S-1	61	48	55	44	4BTA3.9-G2	2800×1130×1615	1480

Source: http://www.Cummins diesel generator power.com.

Appendix 5A. 4: Technical parameter and cost of sunny-boy inverter

Peak Power Watts	Min. Quant.	Total Wattage	Cost US per Solar Panel	Total Cost	Voltage	Off/On Grid	Price per Watt	Vendor
1300	1	1300	$949.97	$949.97	12	GT/OG	$0.73	The Solar Biz
1300	1	1300	$979.97	$979.97	12	GT/OG	$0.75	The Solar Biz
1400	1	1400	$979.97	$979.97	48	GT/OG	$0.70	The Solar Biz
1400	1	1400	$979.97	$979.97	48	GT/OG	$0.70	The Solar Biz
2000	1	2000	$1,623.97	$1,623.97	12	OG	$0.81	The Solar Biz
2000	1	2000	$1,303.97	$1,303.97	12	GT/OG	$0.65	The Solar Biz
2000	1	2000	$1,297.97	$1,297.97	12	OG	$0.65	The Solar Biz
2000	1	2000	$1,297.97	$1,297.97	24	OG	$0.65	The Solar Biz

Source:http://www.ecobusinesslinks.com/surveys/sma-inverters-price-survey-sunnyboy-inverters